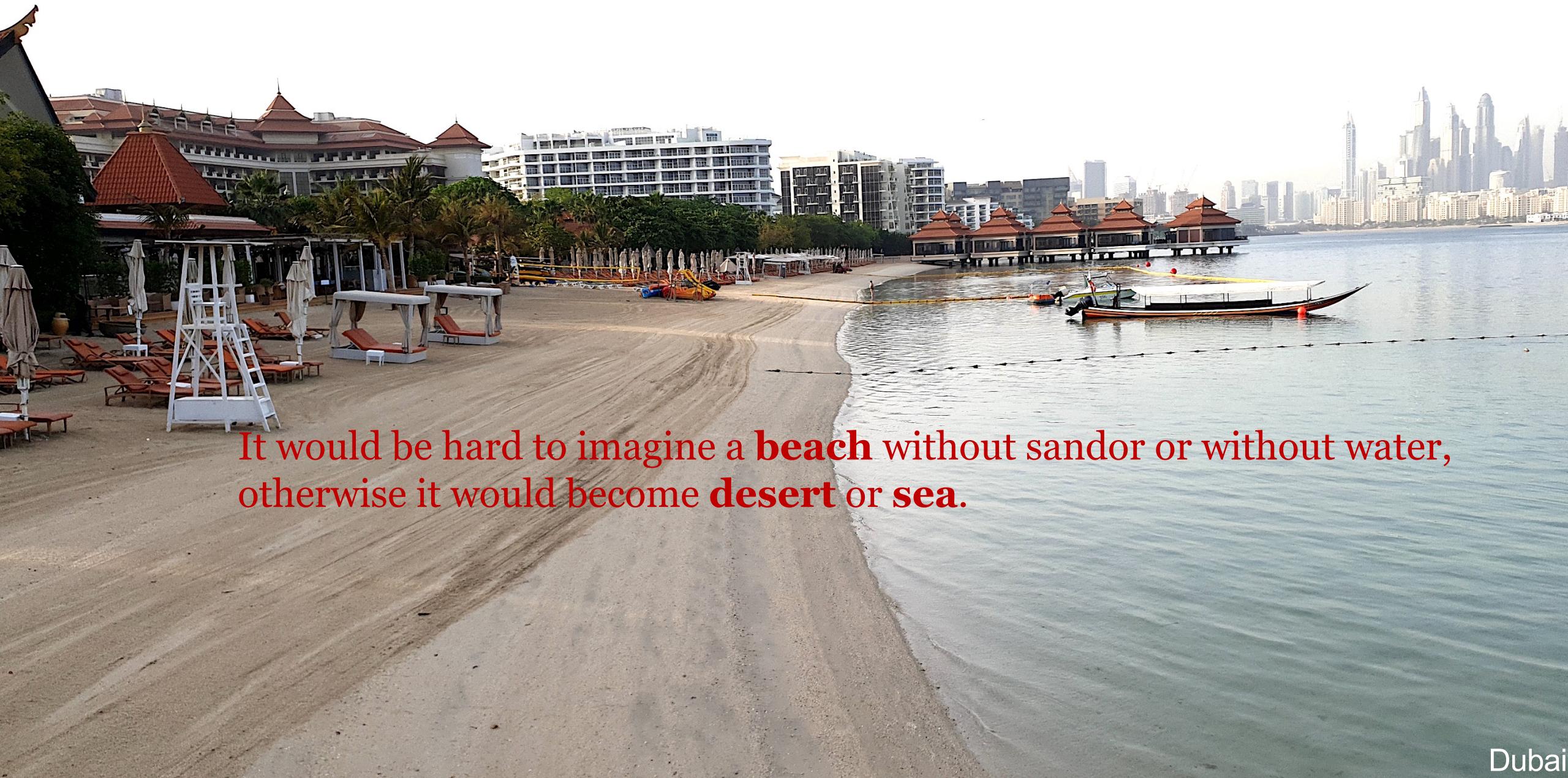


**Morphology Decoder:
Untangling Heterogeneous Porous Media Texture
and Quantifying Permeability and Capillary
Pressure by Semantic Segmentation**

Dr. Omar Alfarisi

| Advisor Data Architecture at ADNOC | Visiting Lecturer at Khalifa University |
| Adjunct Professor at China University of Petroleum |
| VP SPWLA Abu Dhabi Chapter |
| Reviewer at SPE Reservoir Evaluation and Engineering Journal |
oalfarisi.embadj2016@london.edu

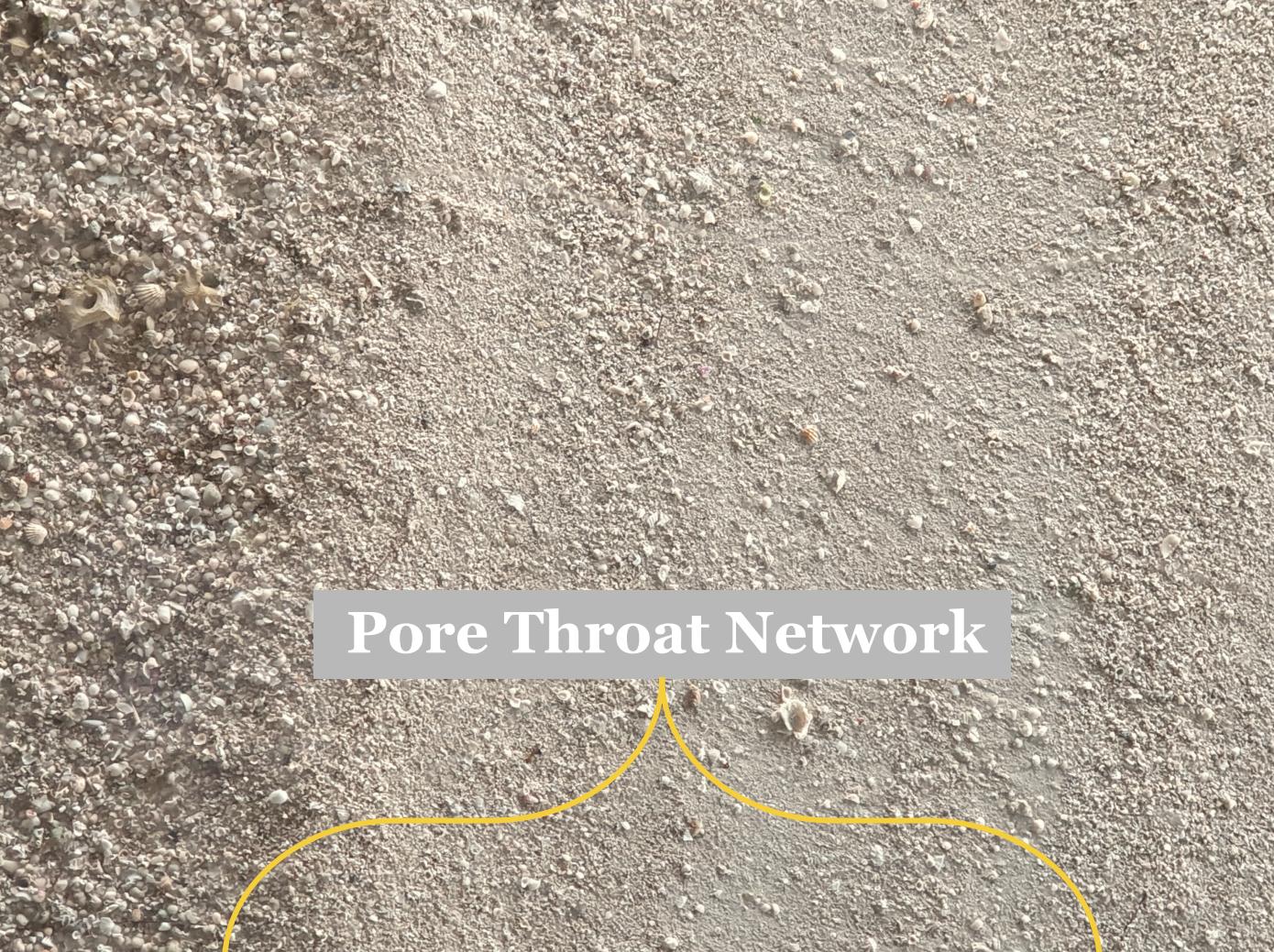


It would be hard to imagine a **beach** without sand or without water, otherwise it would become **desert** or **sea**.



Permeability

Capillarity



Dubai



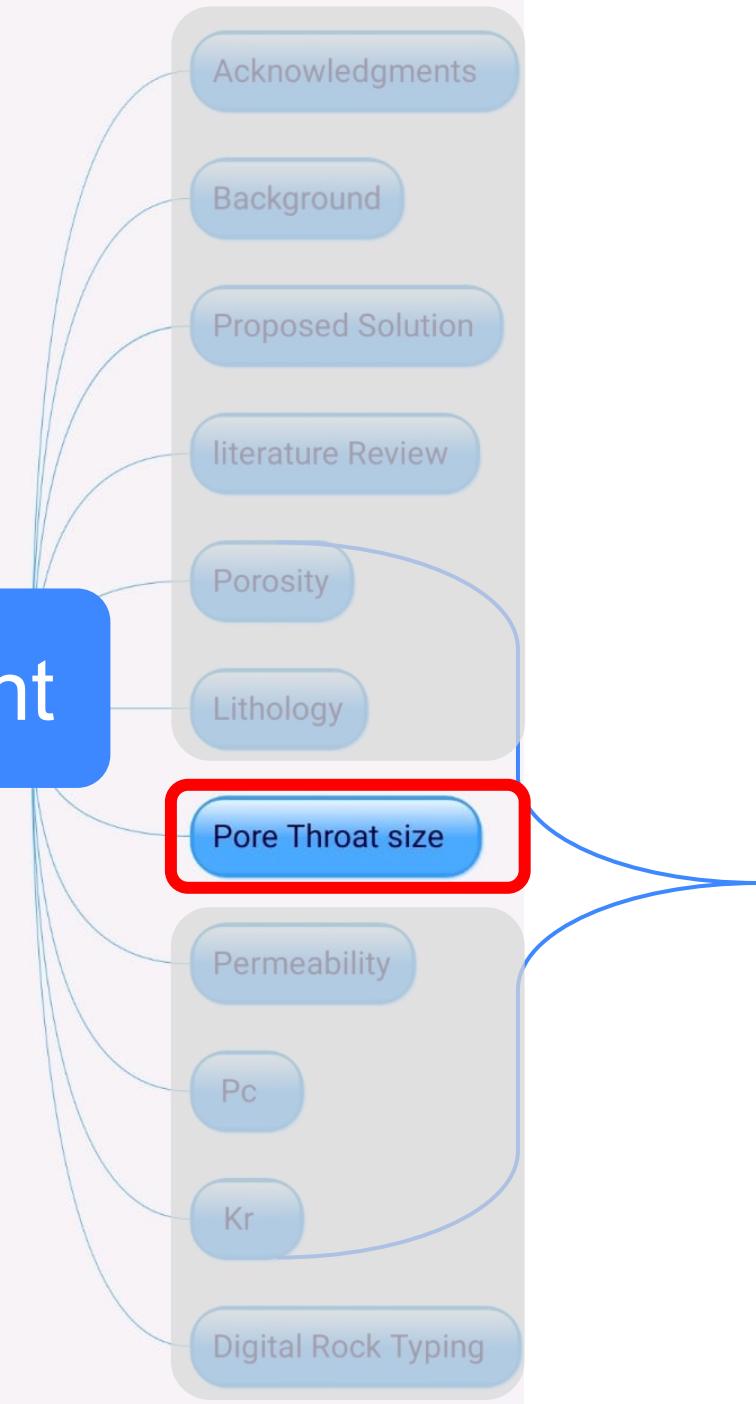
Content



Machine
Learning
3D Image
Recognition



Content



Machine
Learning
3D Image
Recognition

Research Options

PorThN Pore Throat Identification and Quantification

1. Analytical

2

2. Machine Learning

2

3. Image Processing

2

4. Experimental

2

5. Simulation

2

The Conventional Research Approach

PorThN Pore Throat Identification and Quantification



Novel - Morphology Decoder

PorTh: Pore Throat Identification and Quantification

-
1. Analytical
 2. Machine Learning
 3. Image Processing
 4. Experimental
 5. Simulation

2

2

2

2

2

Research Options

DimAmp:Pore Throat Identification and Quantification

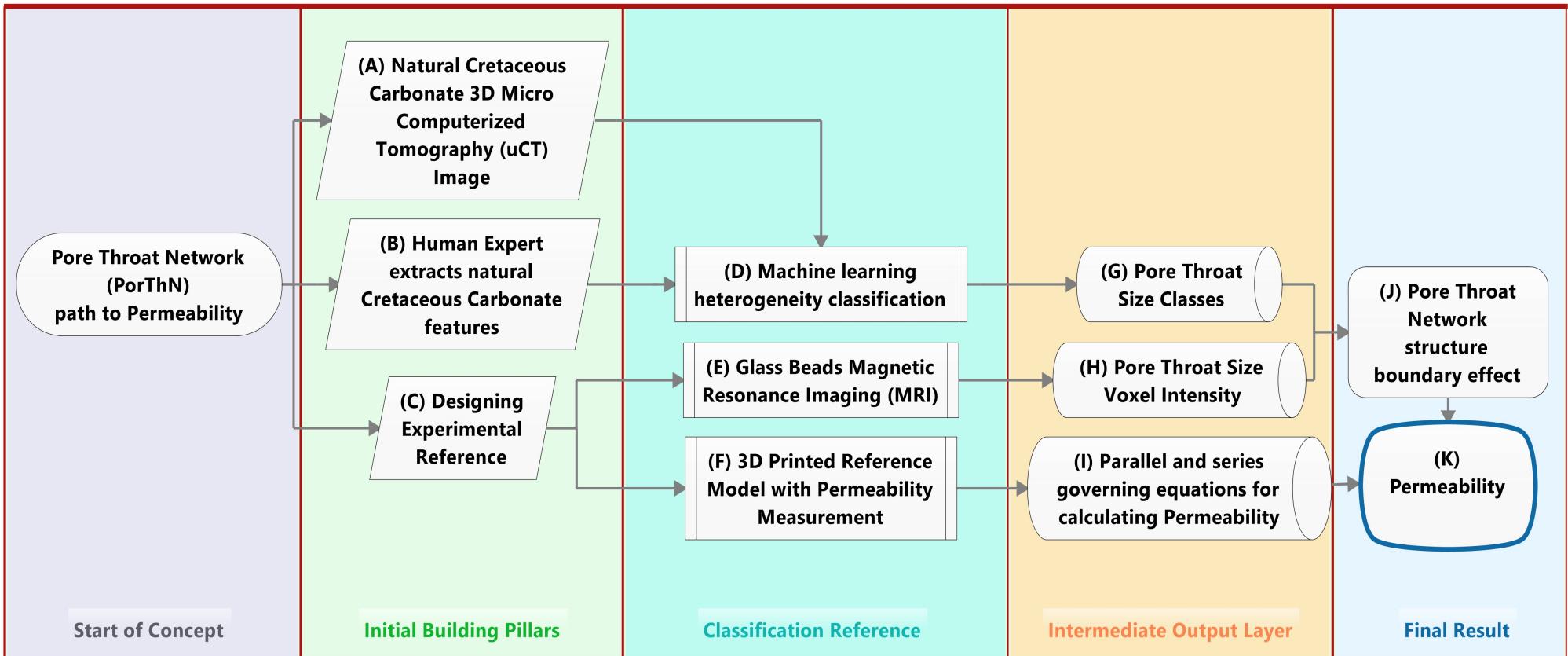
1. Analytical

2. Machine Learning

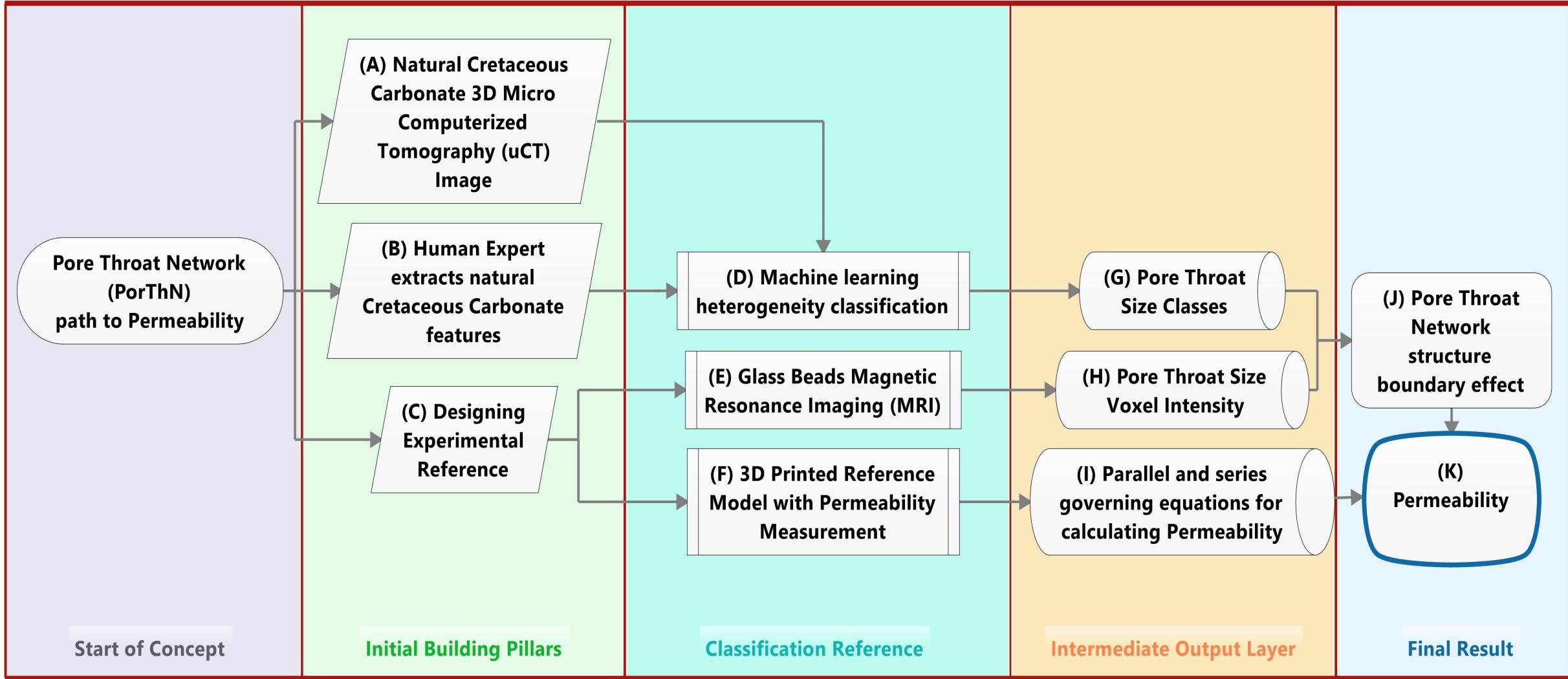
3. Image Processing

4. Experimental

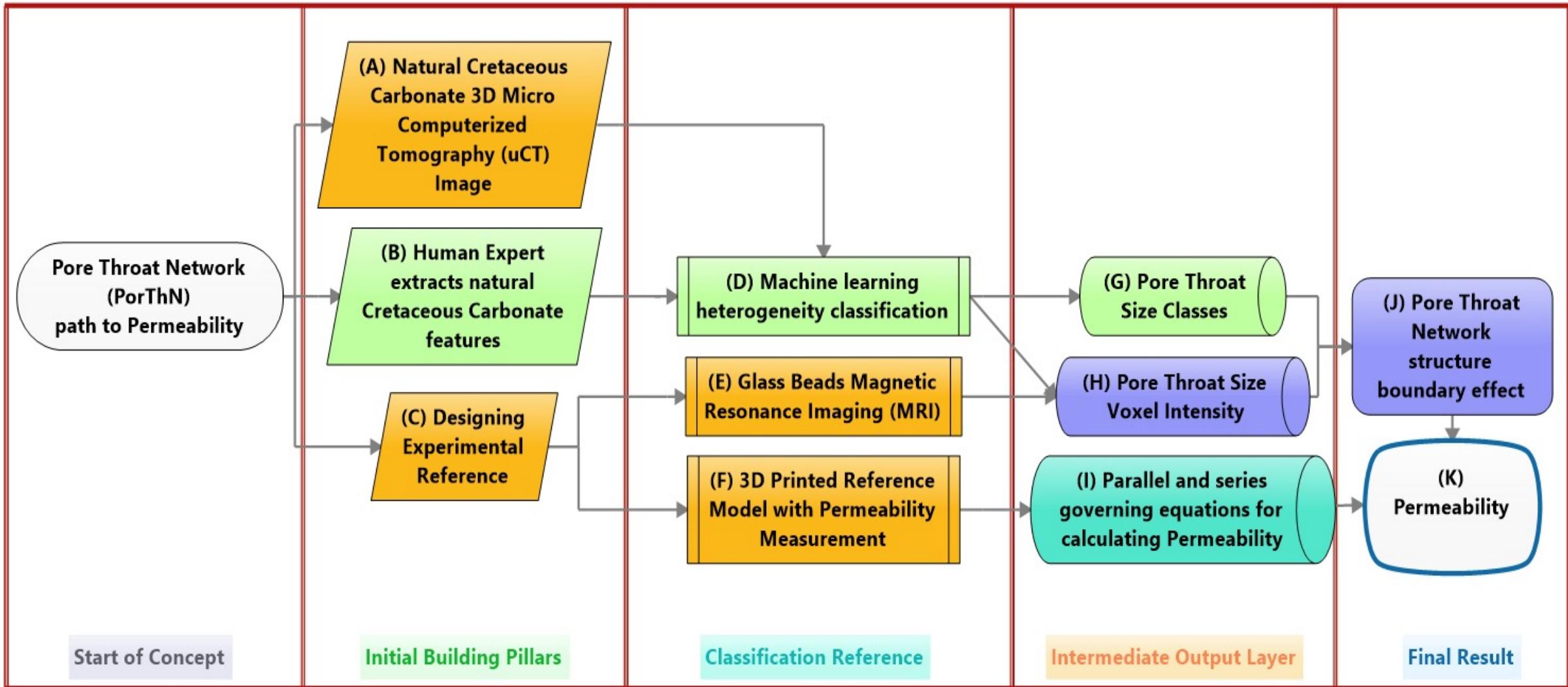
5. Simulation



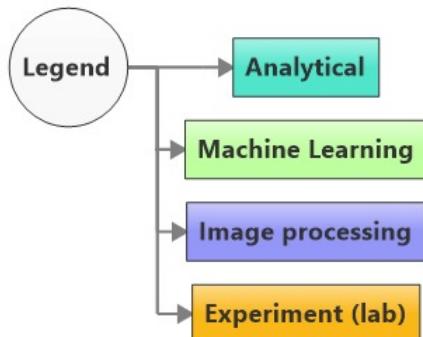
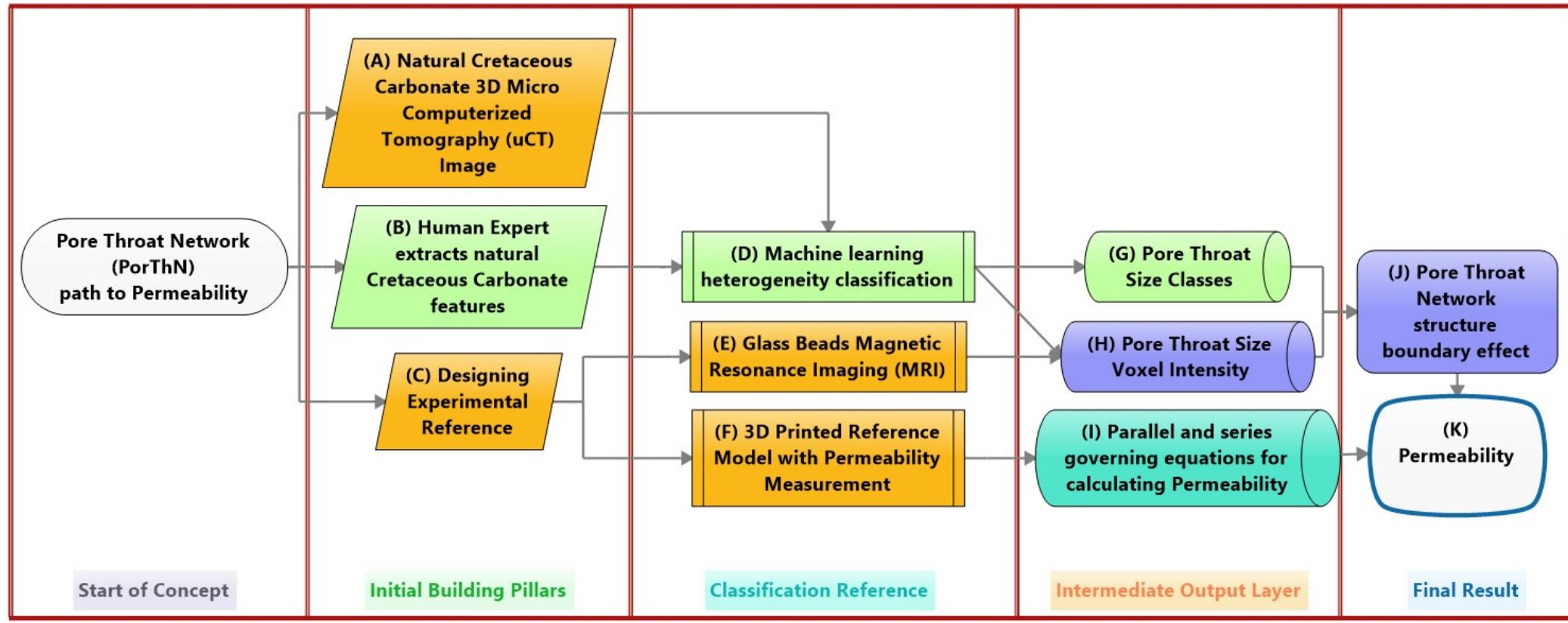
Pore Throat Network (PorThN) path to Permeability determination flow chart



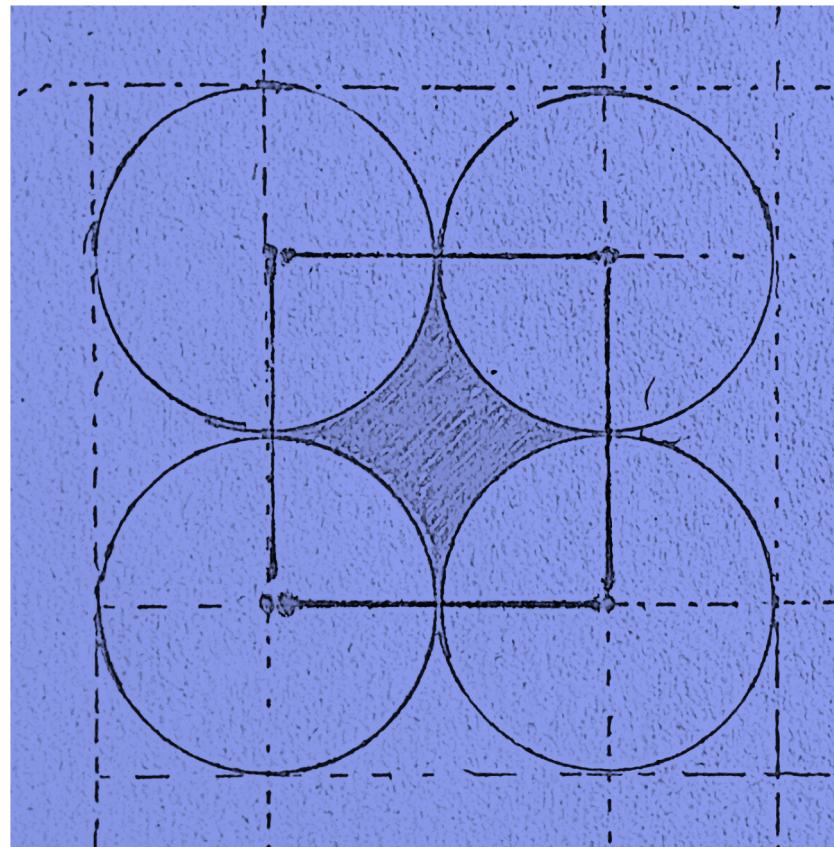
Pore Throat Network (PorThN) path to Permeability determination flow chart



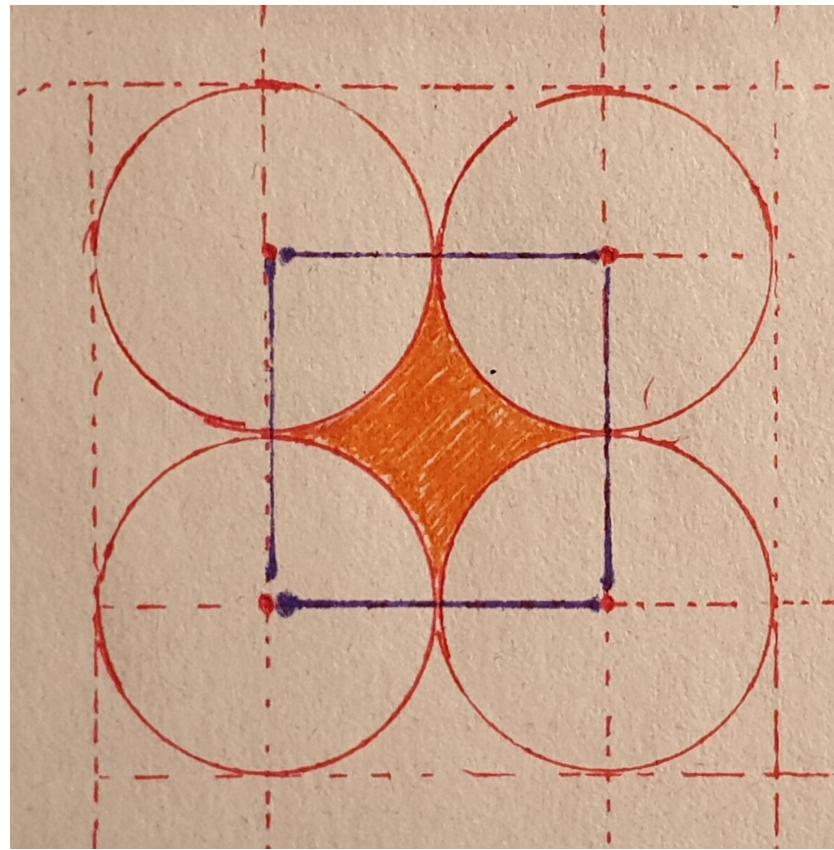
Pore Throat Network (PorThN) path to Permeability determination flow chart



Geometrical Analysis

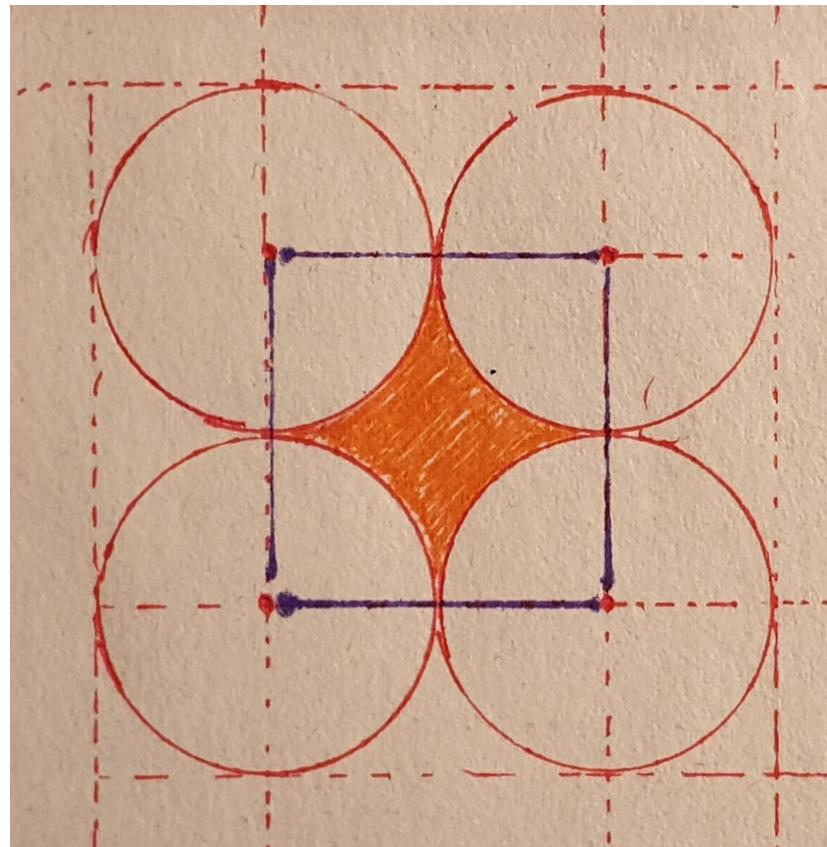


Geometrical Analysis



Geometrical Analysis

Axiom 0: Pore Throat has enclosure from all directions.

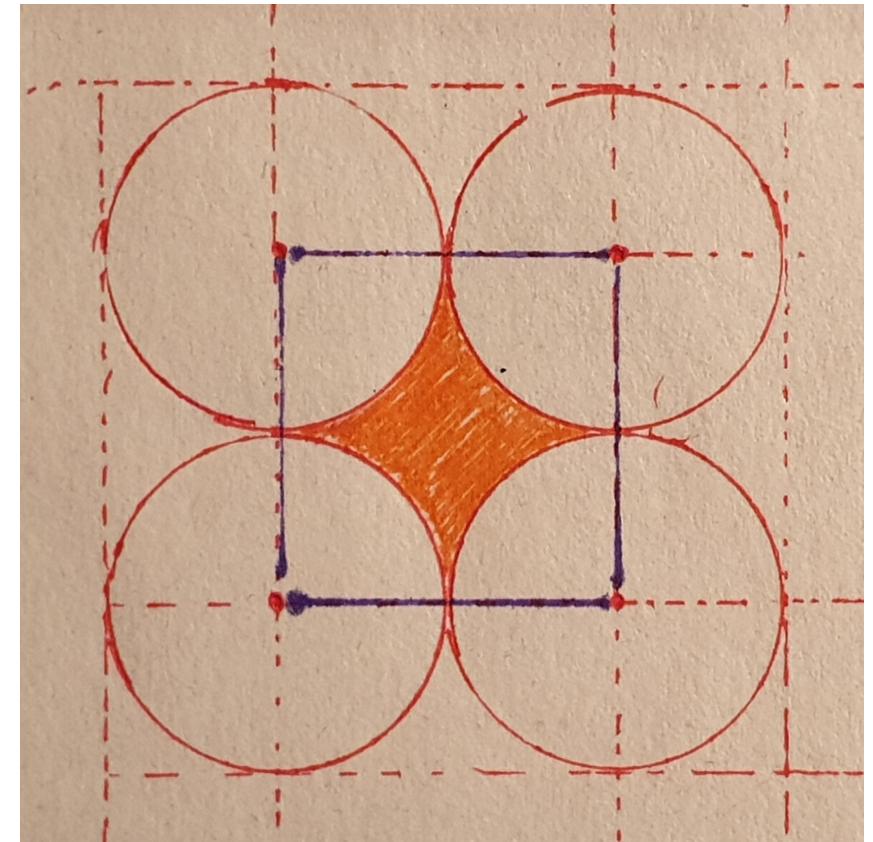


Geometrical Analysis

Axiom 0: Pore Throat has enclosure from all directions.

$$\text{Pore Size} = \text{Small Blue Square Area of Figure 3.4} = 4r^2 \quad (3.2)$$

where r is the grain size



Geometrical Analysis

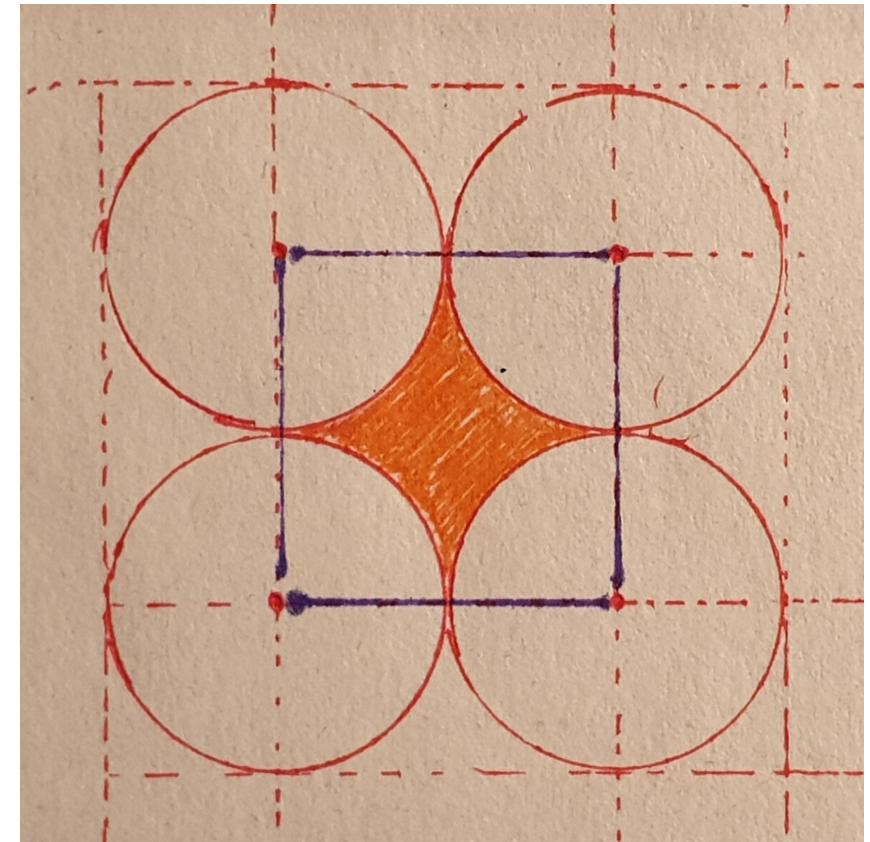
Axiom 0: Pore Throat has enclosure from all directions.

$$\text{Pore Size} = \text{Small Blue Square Area of Figure 3.4} = 4r^2 \quad (3.2)$$

Pore Throat Size = Small Square Area - Circle Area

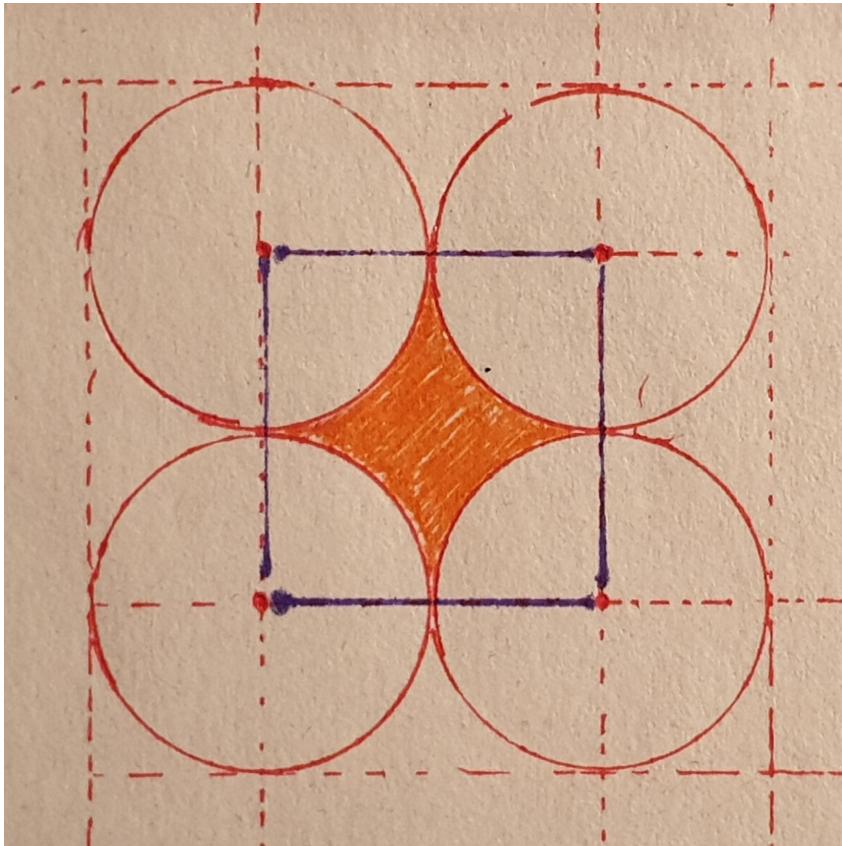
$$\text{Pore Throat Size} = 4r^2 - \pi r^2 = (4 - \pi)r^2 = 0.858 r^2 \quad (3.3)$$

where r is the grain size

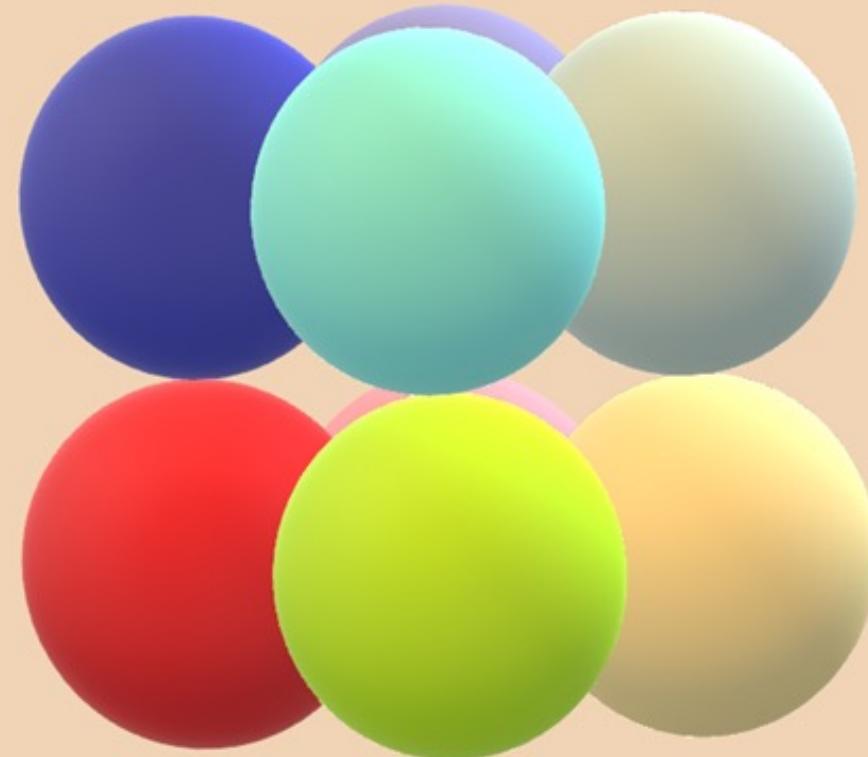


Geometrical Analysis

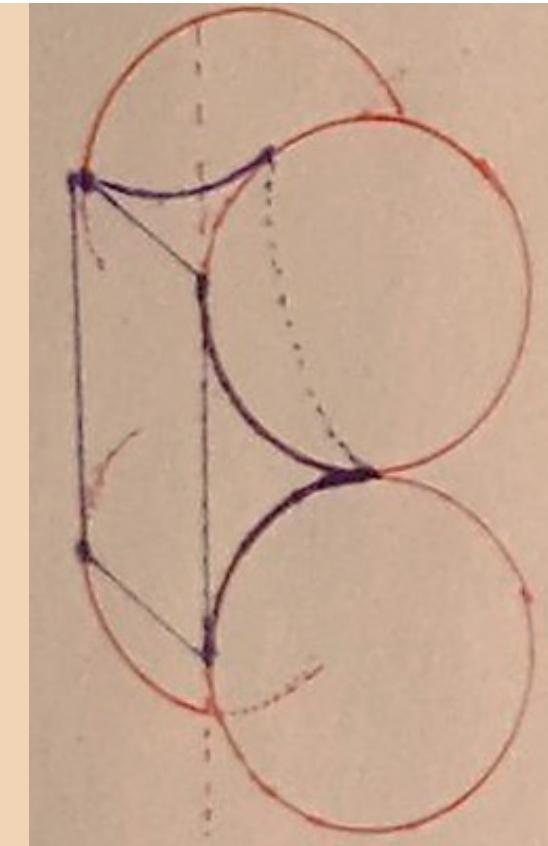
2D



3D Full pore

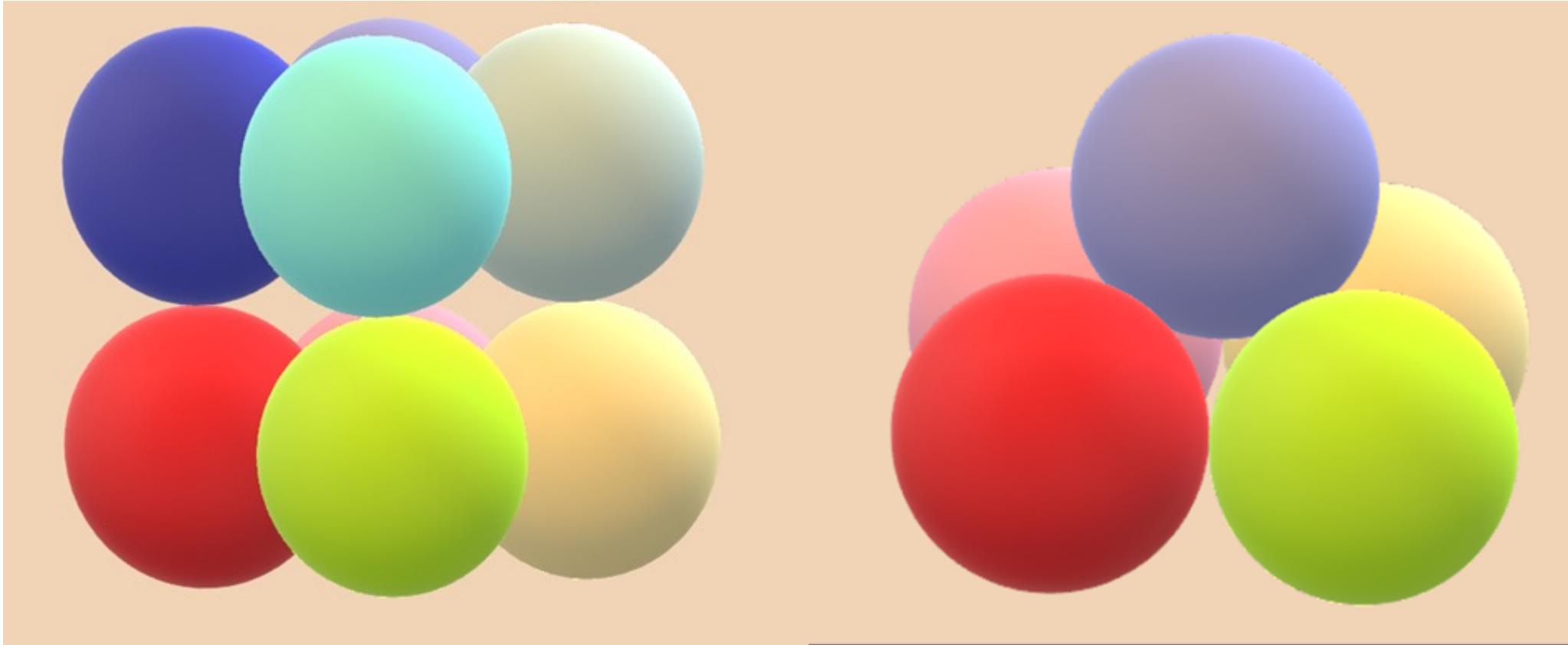


3D Half pore



Geometrical Analysis

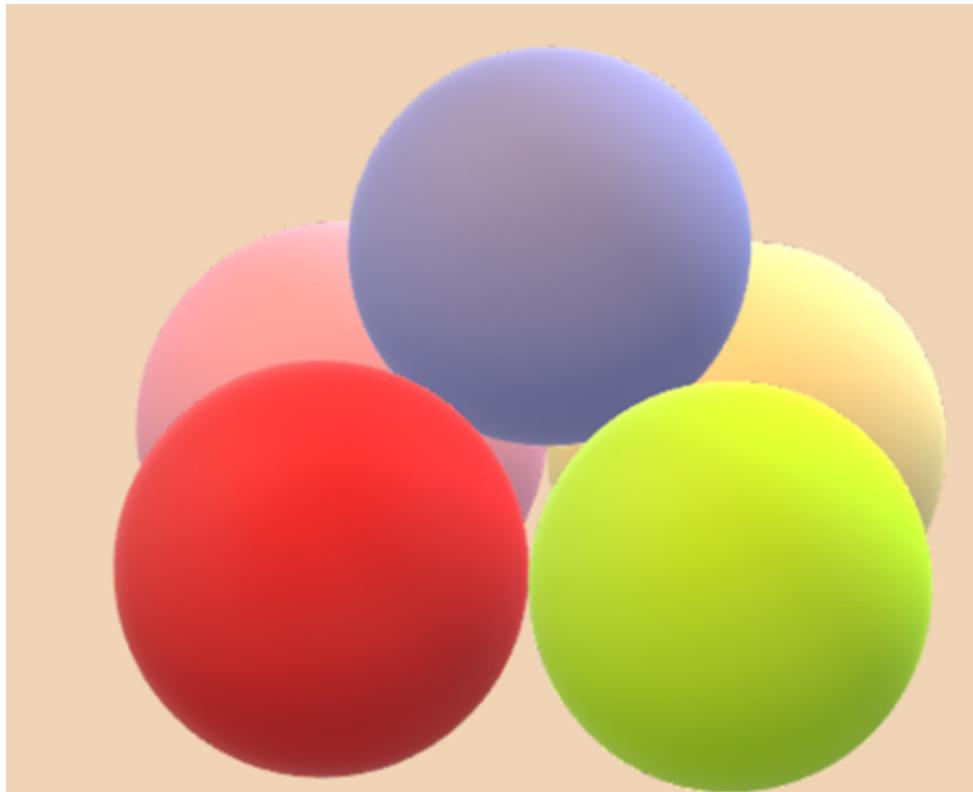
Natural Rock will be a form of below:



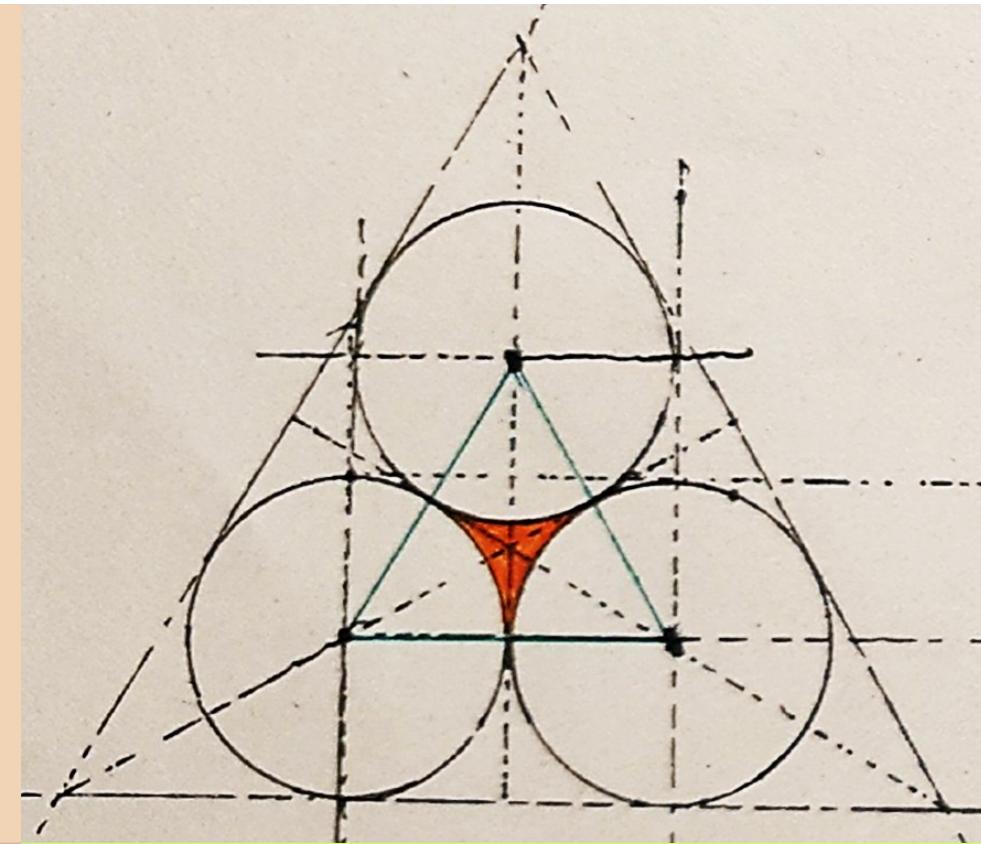
Rhombohedral

Geometrical Analysis

We started with easier Configuration:



Rhombohedral



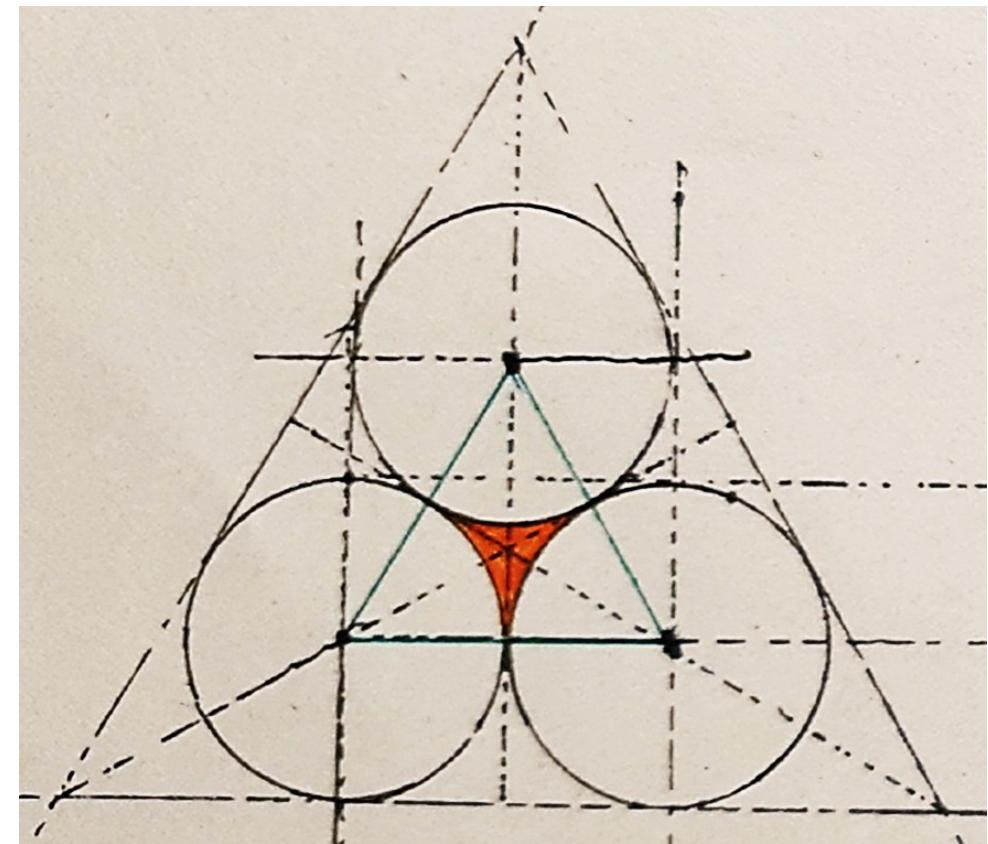
Triclinic

Geometrical Analysis

$$\text{Pore Size} = \text{Triangle Area} = \sqrt{3} r^2 \quad (3.5)$$

where r is the grain size

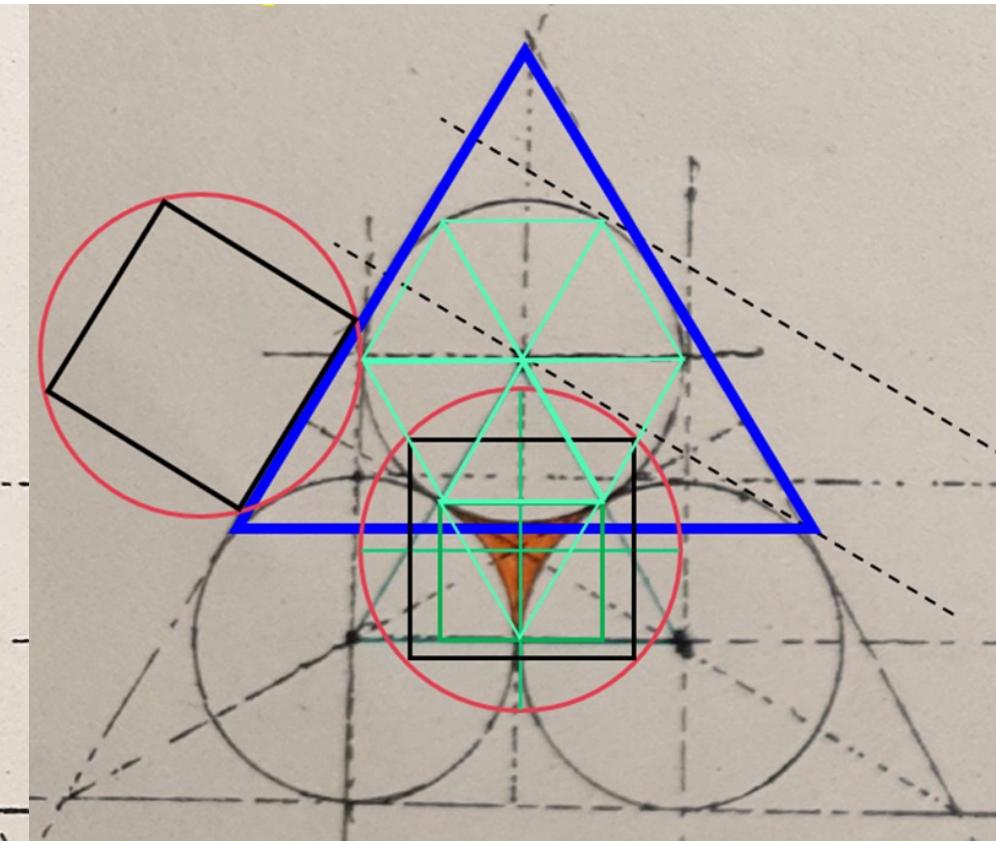
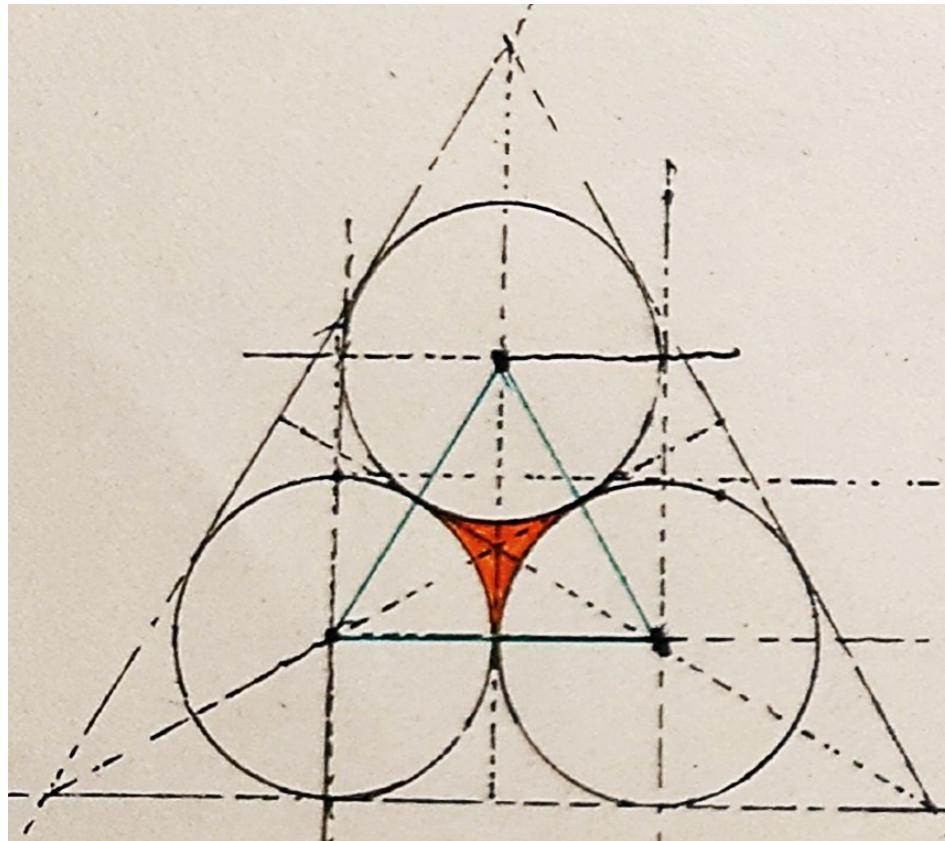
We started with easier Configuration:



Triclinic

Geometrical Analysis

Found Pore throat size geometrically



Triclinic

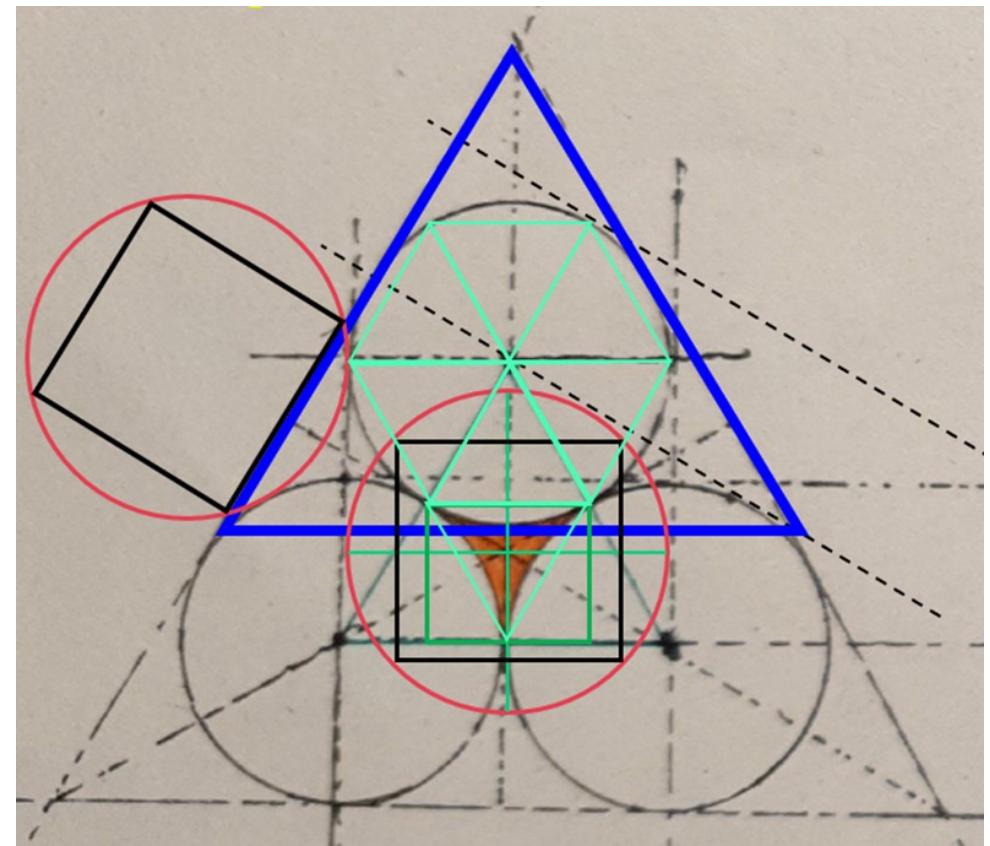
Geometrical Analysis

$$\text{Pore Size} = \text{Triangle Area} = \sqrt{3} r^2 \quad (3.5)$$

$$\text{PorTS}_{\text{Triclinic}} = \sqrt{3} r^2 - \frac{\pi}{2} r^2 = (\sqrt{3} - \frac{\pi}{2}) r^2 = 0.162 r^2 \quad (3.6)$$

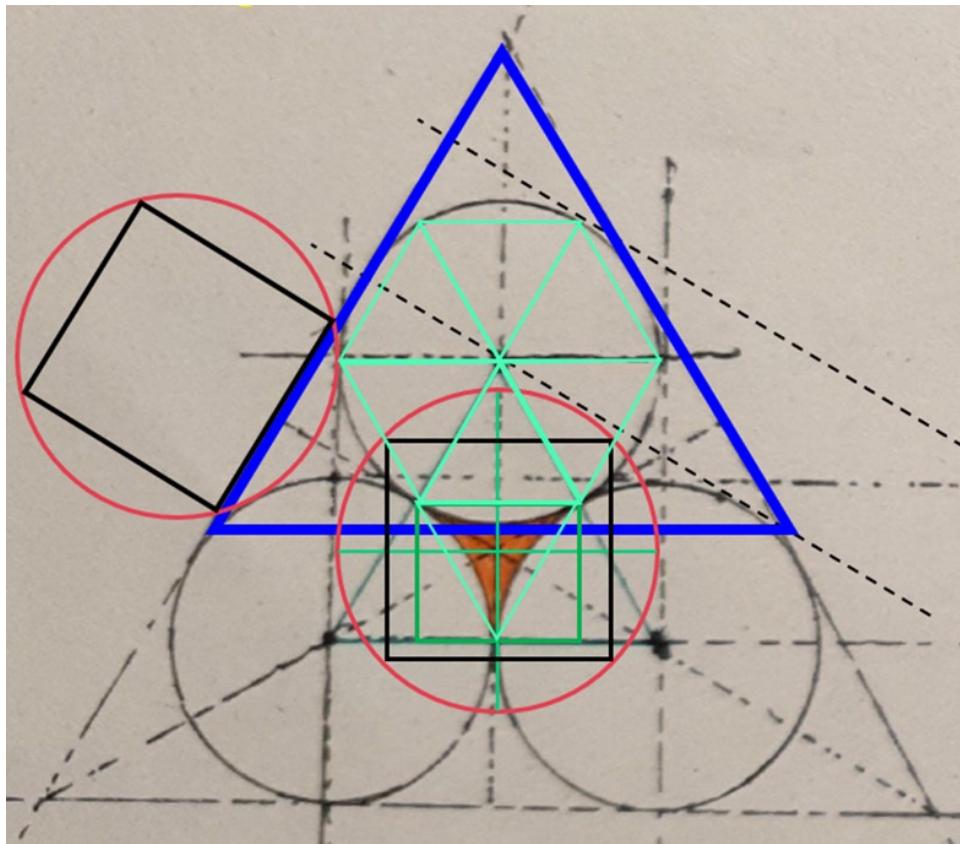
where r is the grain size

Found Pore throat size geometrically



Triclinic

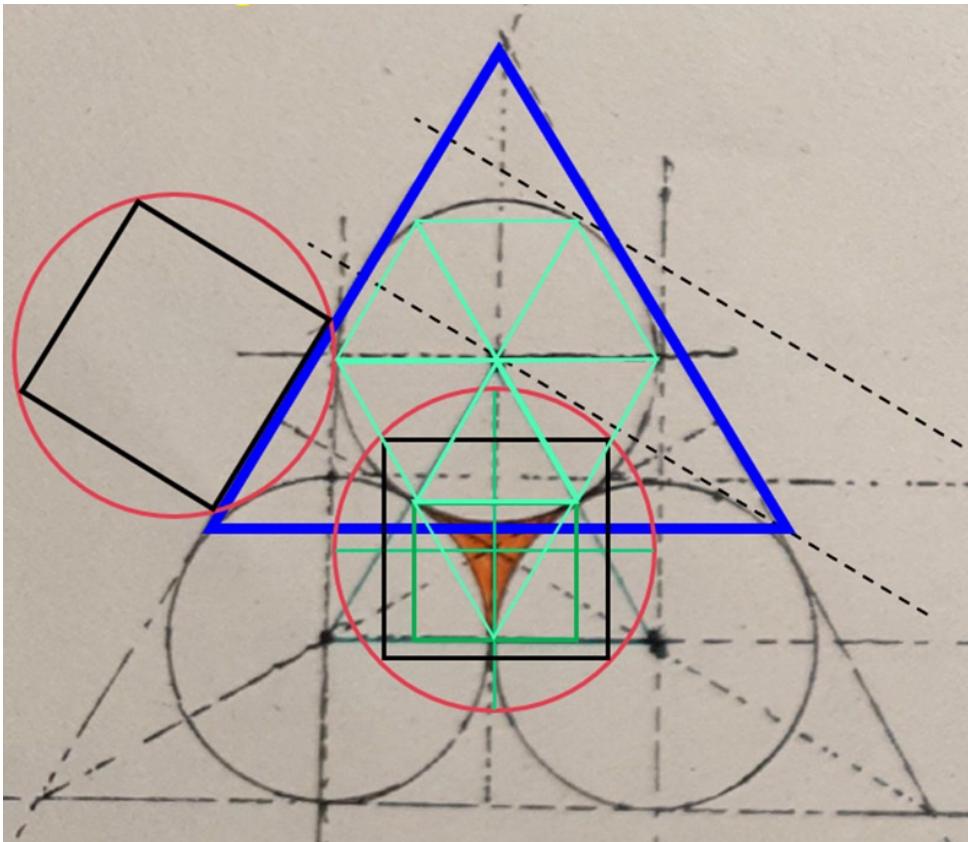
Geometrical Analysis



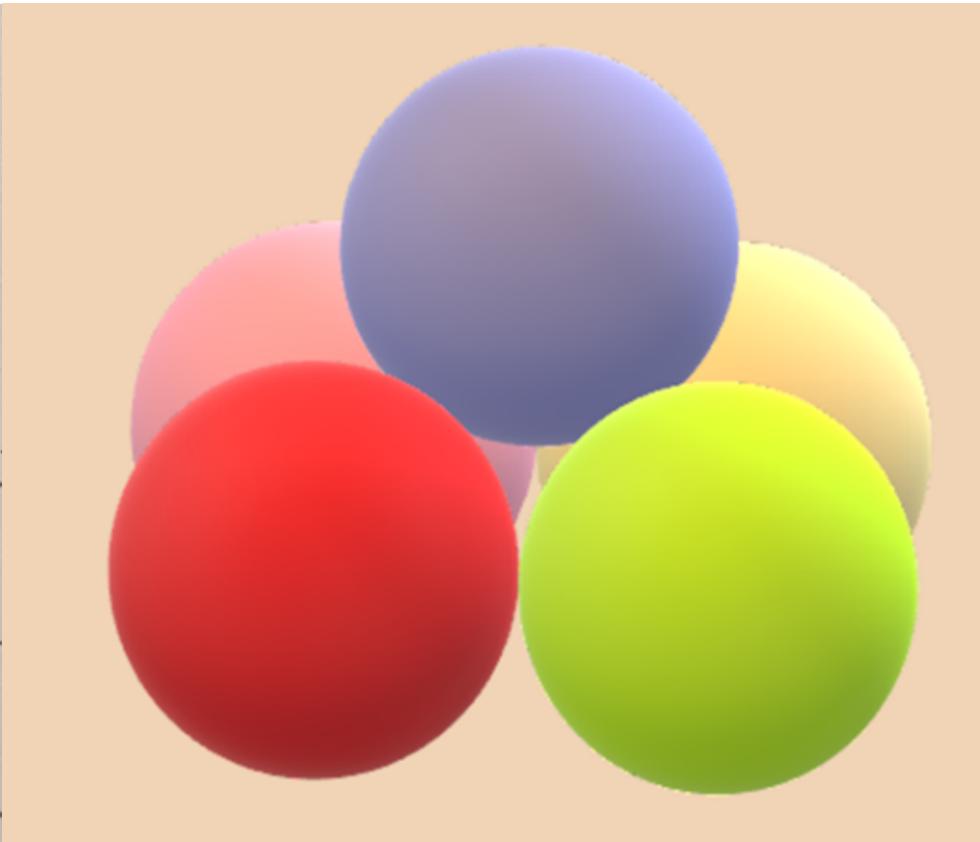
Triclinic

Geometrical Analysis

We need to upgrade Triclinic Equation to Rhombohedral



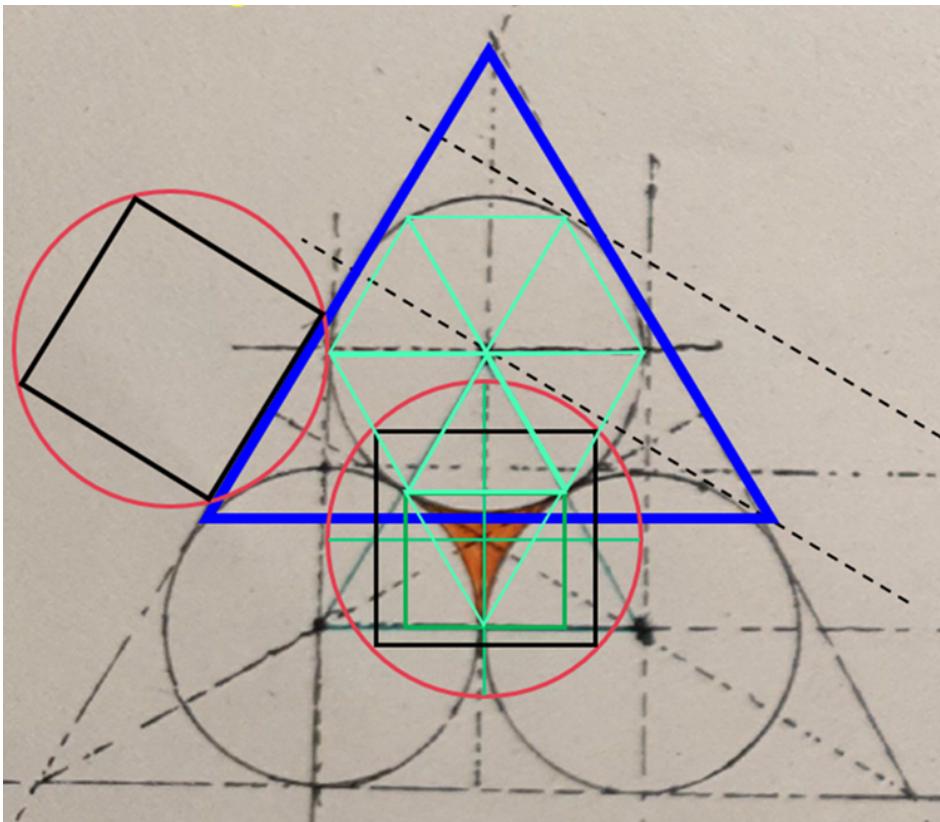
Triclinic



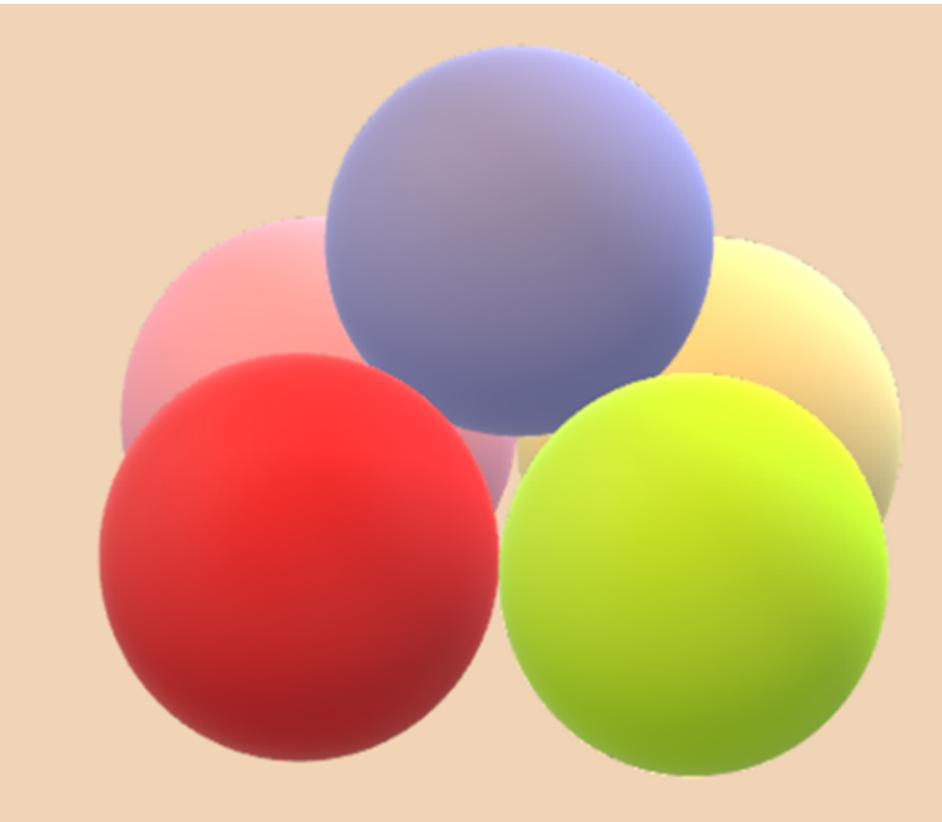
Rhombohedral

Geometrical Analysis

Ratio



Triclinic



Rhombohedral

Experimental and Analytical (Cubic)

than triclinic (Fig. 5, A). The 3D cubic configuration of eight spheres shown in Fig. 4, B consists of six faces: top, bottom, and four slides. A pore throat shape of a concaved diamond on each face, like the yellow area shown in Fig. 3. Therefore, the 3D pore throat area of cubic configuration is the sum of six concaved diamonds areas, Eq. 2, to be $5.148r_g^2$.

Then we calculate the Effective 3D Pore Throat Size of cubic configuration ($PorTS_{cubic3DEffective}$) as shown in Eq. 6 below:

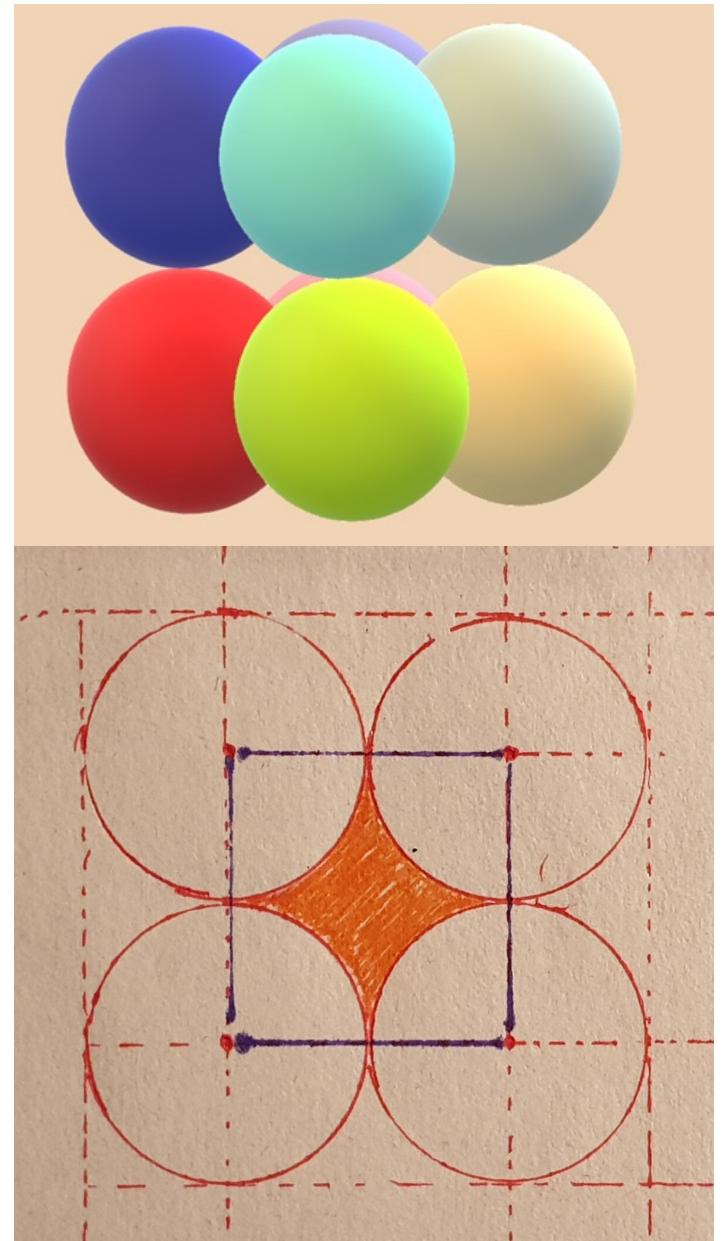
$$PorTS_{cubic3DEffective} = \frac{A_{cubicPorT}}{N_{PorT} \cdot N_{C_{V\text{inets}}}} r_g^2 = \frac{5.148}{6 * 2} r_g^2 = 0.429r_g^2$$

where,

$A_{cubicPorT}$: The area of all pore throats of cubic configuration,

N_{PorT} : The number of pore throats in a 3D configuration,

$N_{C_{V\text{inets}}}$: The number of outlets of the fluid flow control volume.



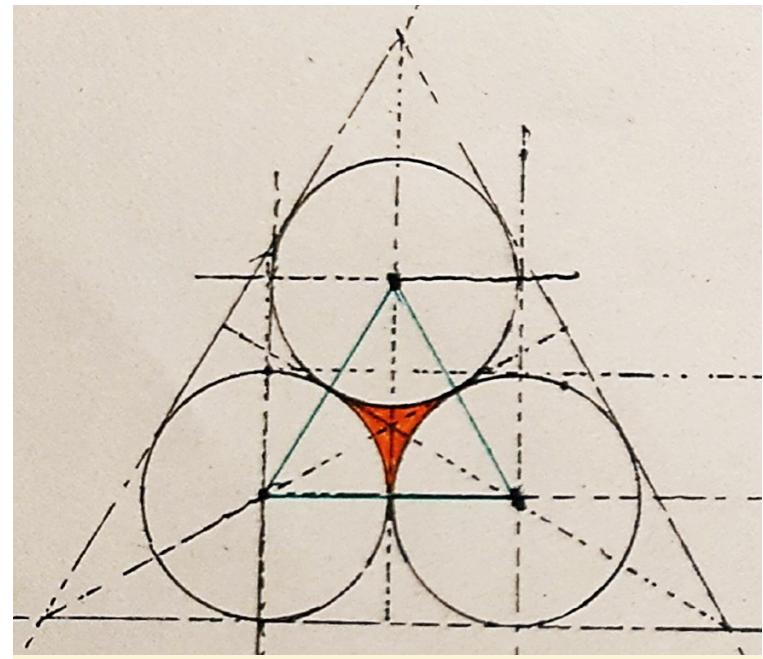
Experimental and Analytical (Triclinic)

The 3D triclinic configuration of eight spheres consists of six faces that hold two different shapes of pore throats; the top, bottom, and two sides have a pore throat shape of a concaved diamond. The other two sides hold a concaved triangle pore throat shape: two-pore throats per side. Therefore, the 3D pore throat area of triclinic configuration is the sum of four concaved diamonds and four concaved triangles, Eq. 2 and 5 to be $4.08r_g^2$. Then we calculate the Effective 3D Pore Throat Size of triclinic configuration ($PorTS_{triclinic\ 3D\ Effective}$) as shown in Eq. 7, below:

$$PorTS_{triclinic\ 3D\ Effective} = \frac{A_{triclinic\ PorT}}{N_{PorT} \cdot N_{Cavities}} r_g^2 = \frac{4.08}{8 * 2} r_g^2 = 0.255 r_g^2$$

where,

$A_{triclinic\ PorT}$: The area of all pore throats for triclinic configuration.



Triclinic

Experimental and Analytical (Rhombohedral)

The 3D rhombohedral configuration of eight spheres consists of six faces that hold two different shapes of pore throats; the top and bottom faces hold a pore throat shape of a concaved diamond. The four sides have a concaved triangle pore throat shape: two-pore throats per side. Therefore, the 3D pore throat area of rhombohedral configuration is the sum of two concaved diamonds and eight concaved triangles areas, Eq. 2 and 5, to be $1.716r_g^2$.

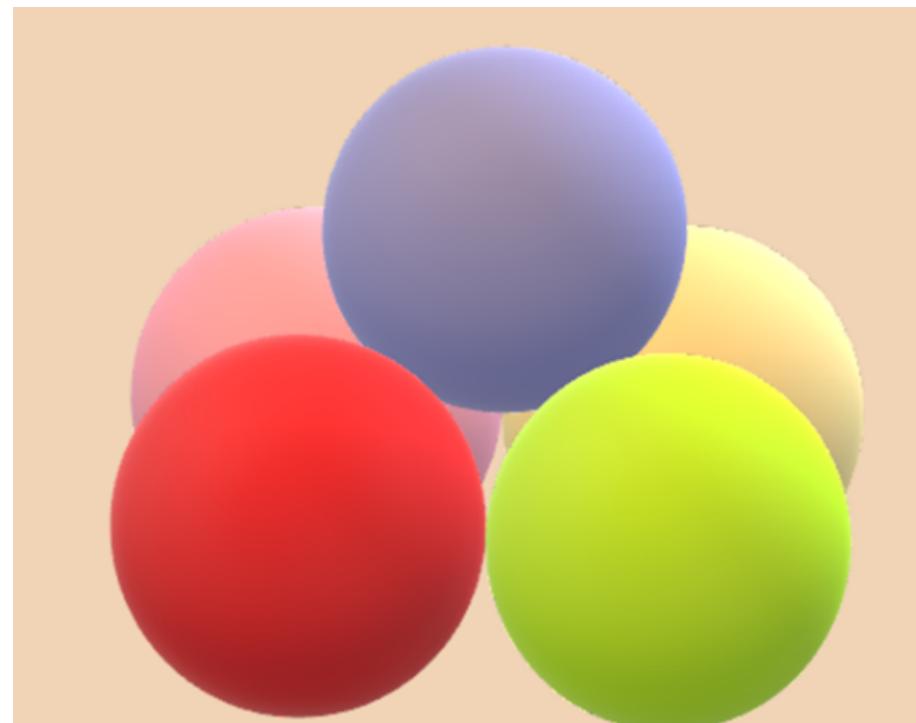
Then we calculate the Effective 3D Pore Throat Size of rhombohedral configuration ($PorTS_{rhombohedral\ 3D\ Effective}$) as shown in Eq. 8 below:

$$PorTS_{rhombohedral\ 3D\ Effective} = \frac{A_{rhombohedralPorT}}{N_{PorT} \cdot N_{Cavities}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858r_g^2 \quad (8)$$

where,

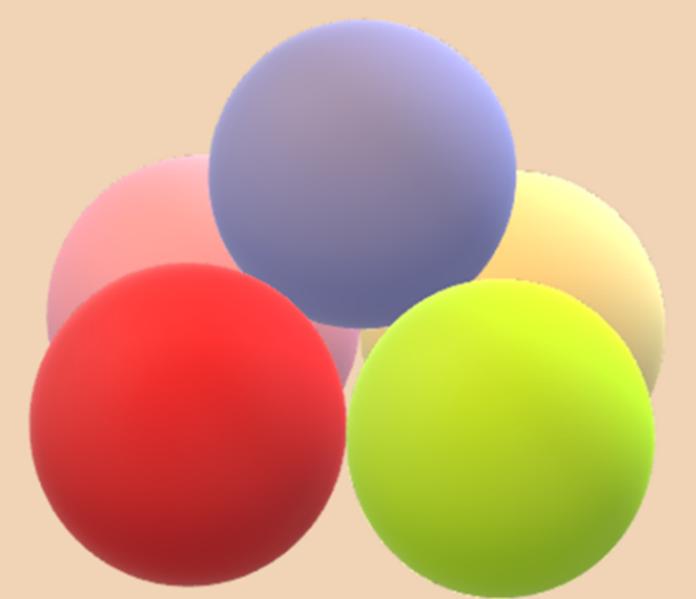
I

$A_{rhombohedralPorT}$: The pore throats area of rhombohedral configuration.

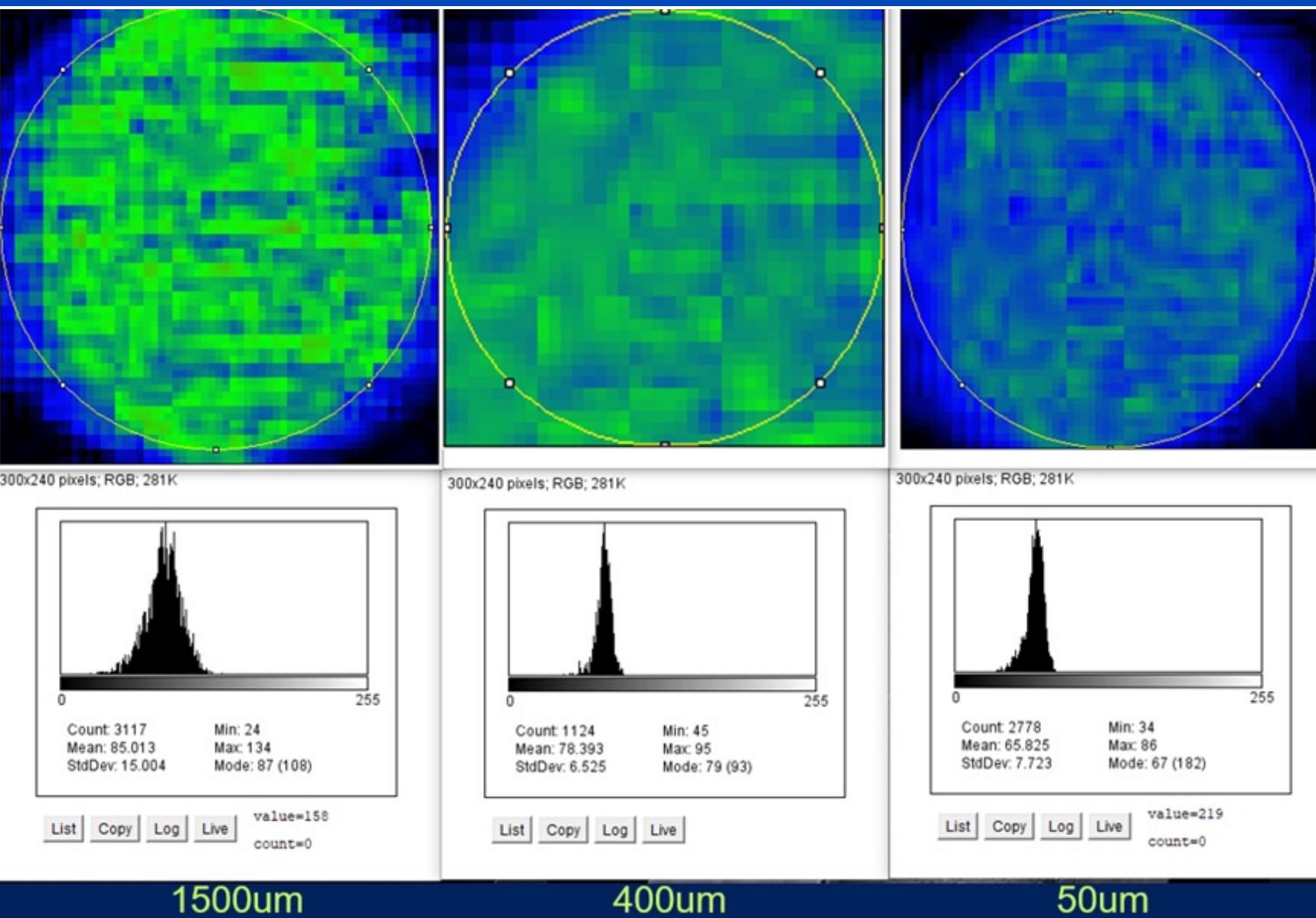


Rhombohedral

Experimental (MRI) – Different sizes of Glass Beads

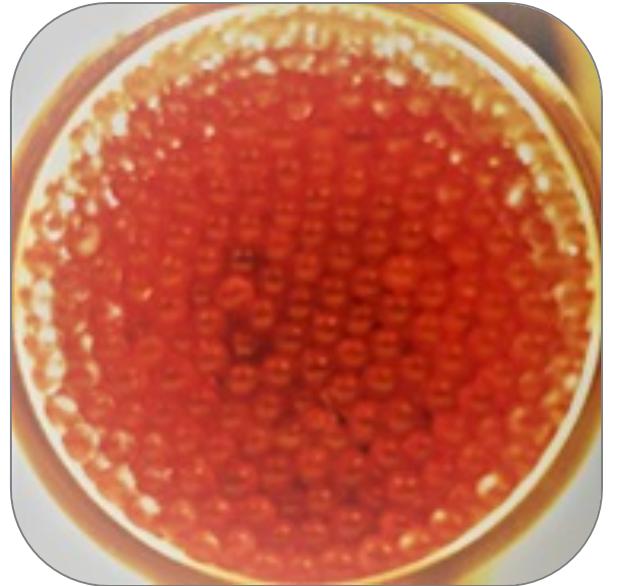


Rhombohedral

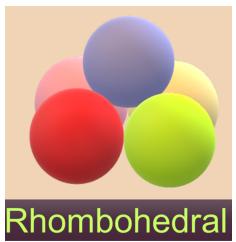


$$PortS_{rhombohedral\ 3DEffective} = \frac{A_{rhombohedral\ Port}}{N_{Port} \cdot N_{C_{V_{inets}}}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \quad (8)$$

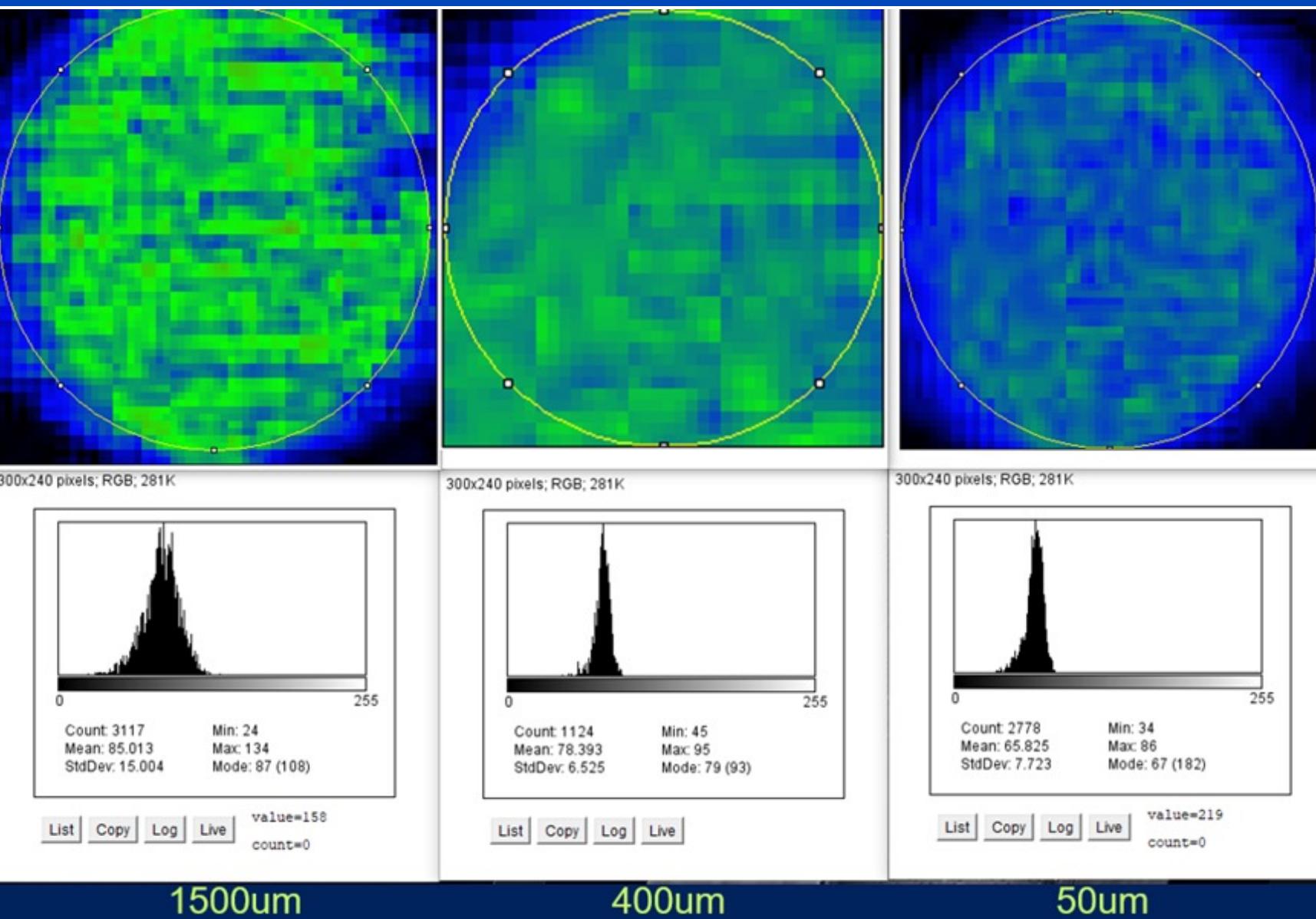
Experimental (MRI) – Different sizes of Glass Beads



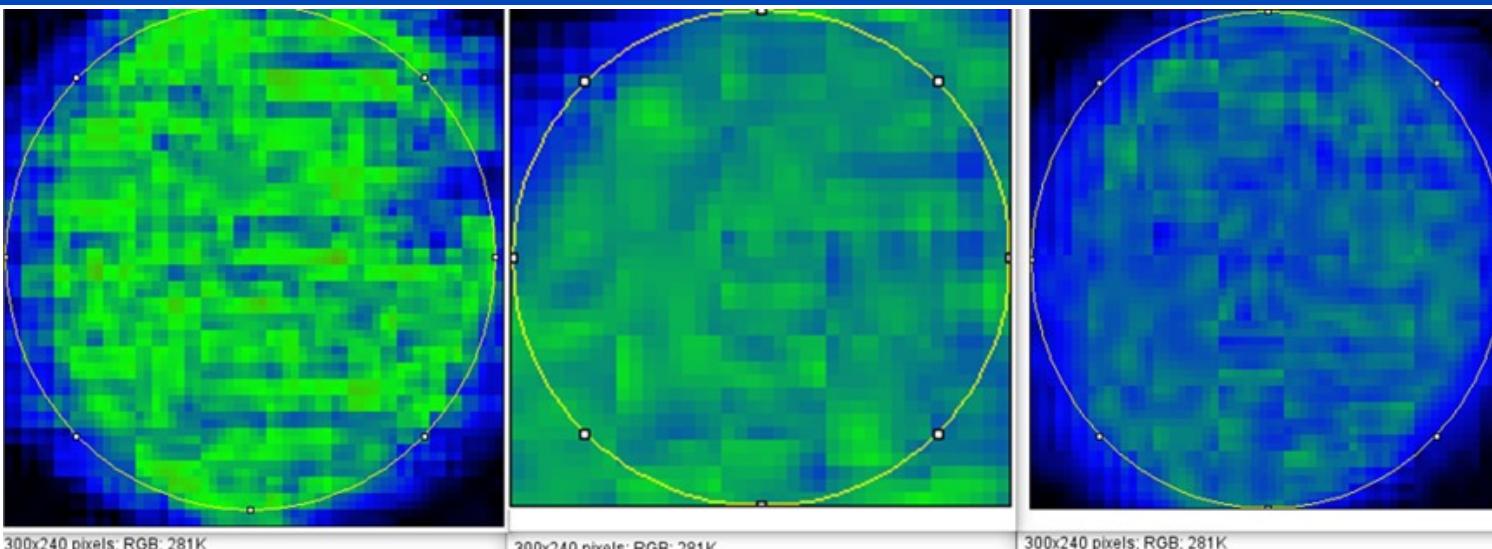
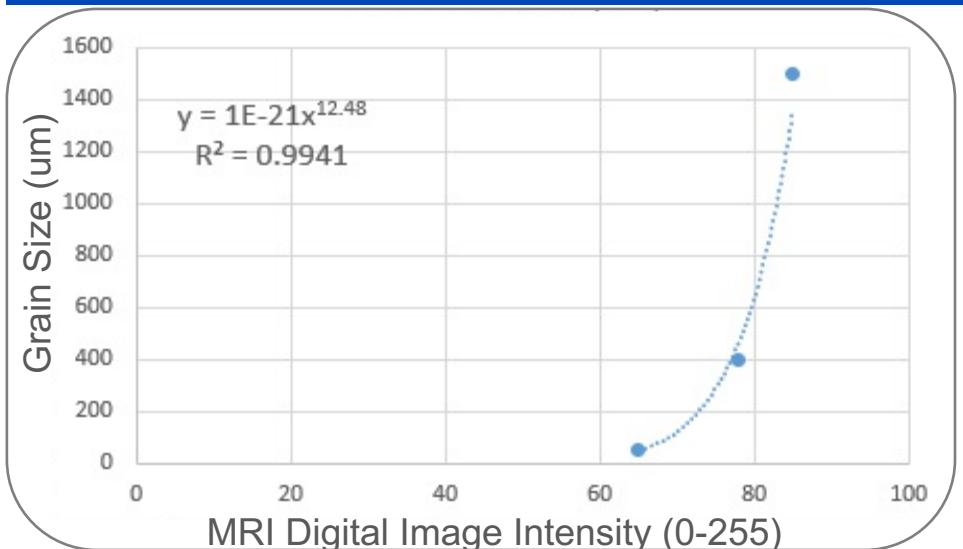
Glass Beads



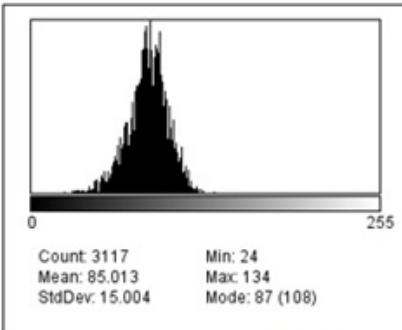
$$PortS_{rhombohedral\ 3D\ Effective} = \frac{A_{rhombohedral\ Port}}{N_{Port} \cdot N_{Cylinders}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \quad (8)$$



Experimental (MRI) – Different sizes of Glass Beads

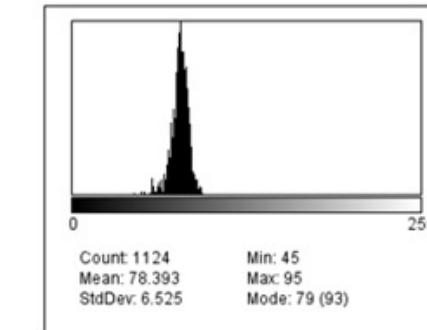


MRIII_Slices	Grain Diameter (um)
85	1500
78	400
65	50



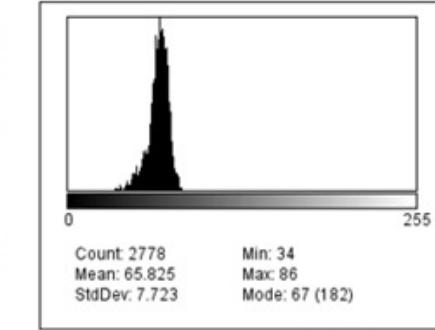
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1500um



List Copy Log Live

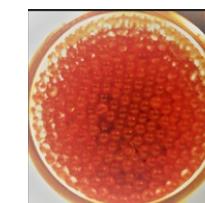
400um



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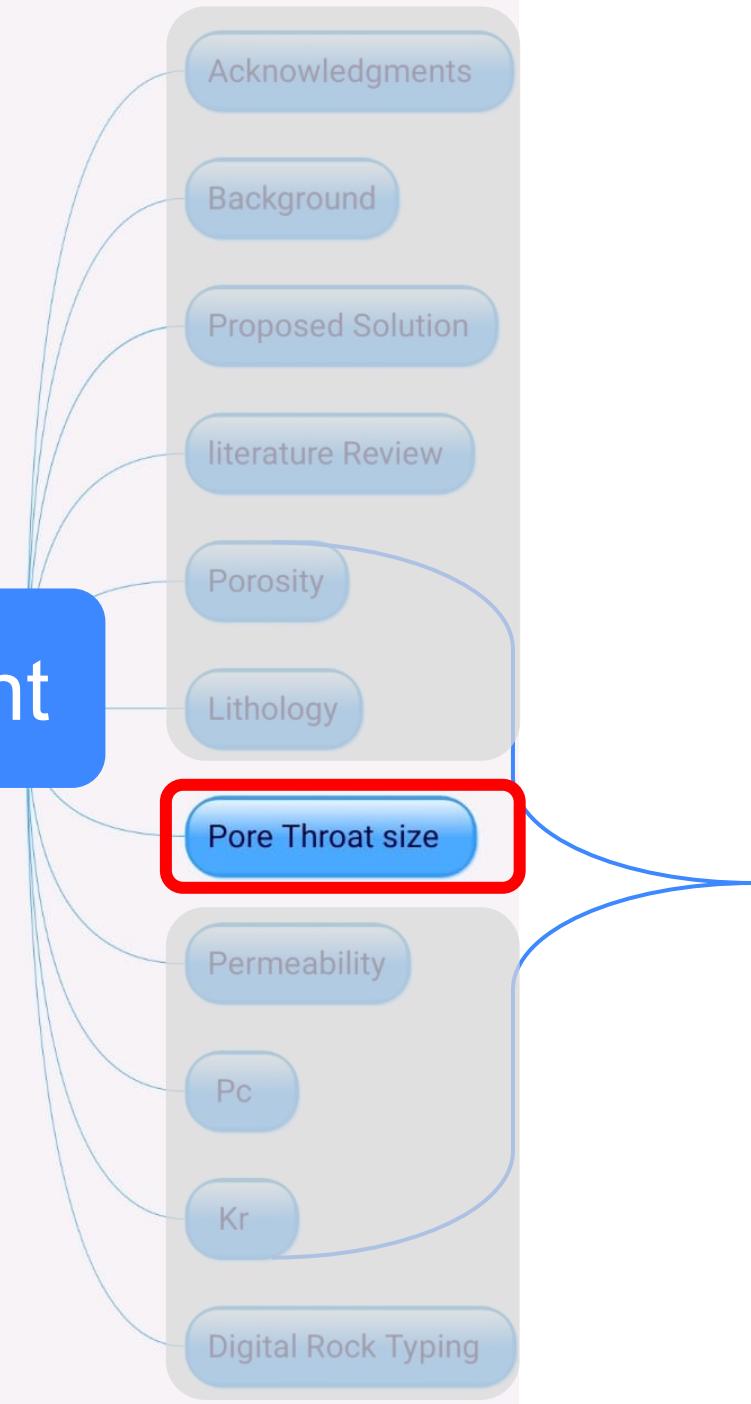
50um

$$PorTS_{rhombohedral\ 3D\ Effective} = \frac{A_{rhombohedral\ porT}}{N_{PorT} \cdot N_{Cavities}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \quad (8)$$





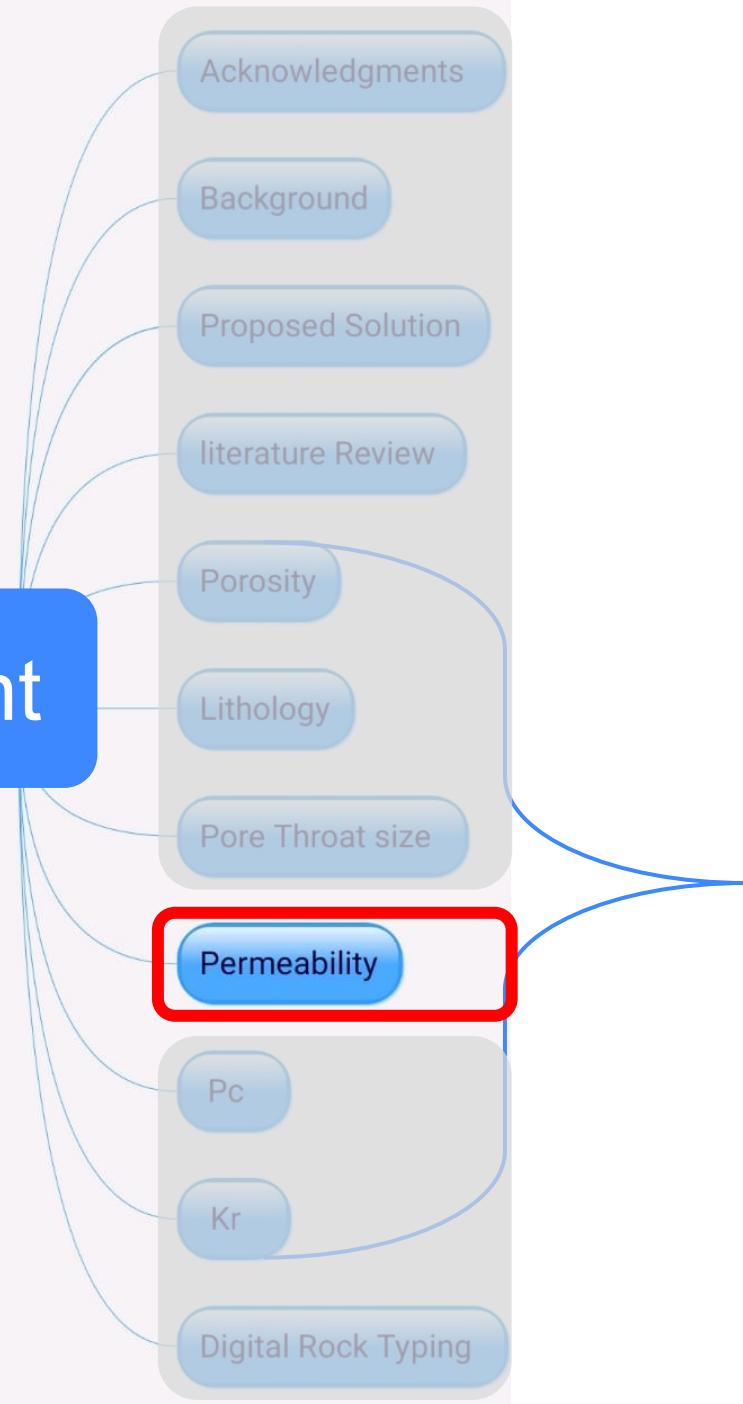
Content



Machine
Learning
3D Image
Recognition



Content

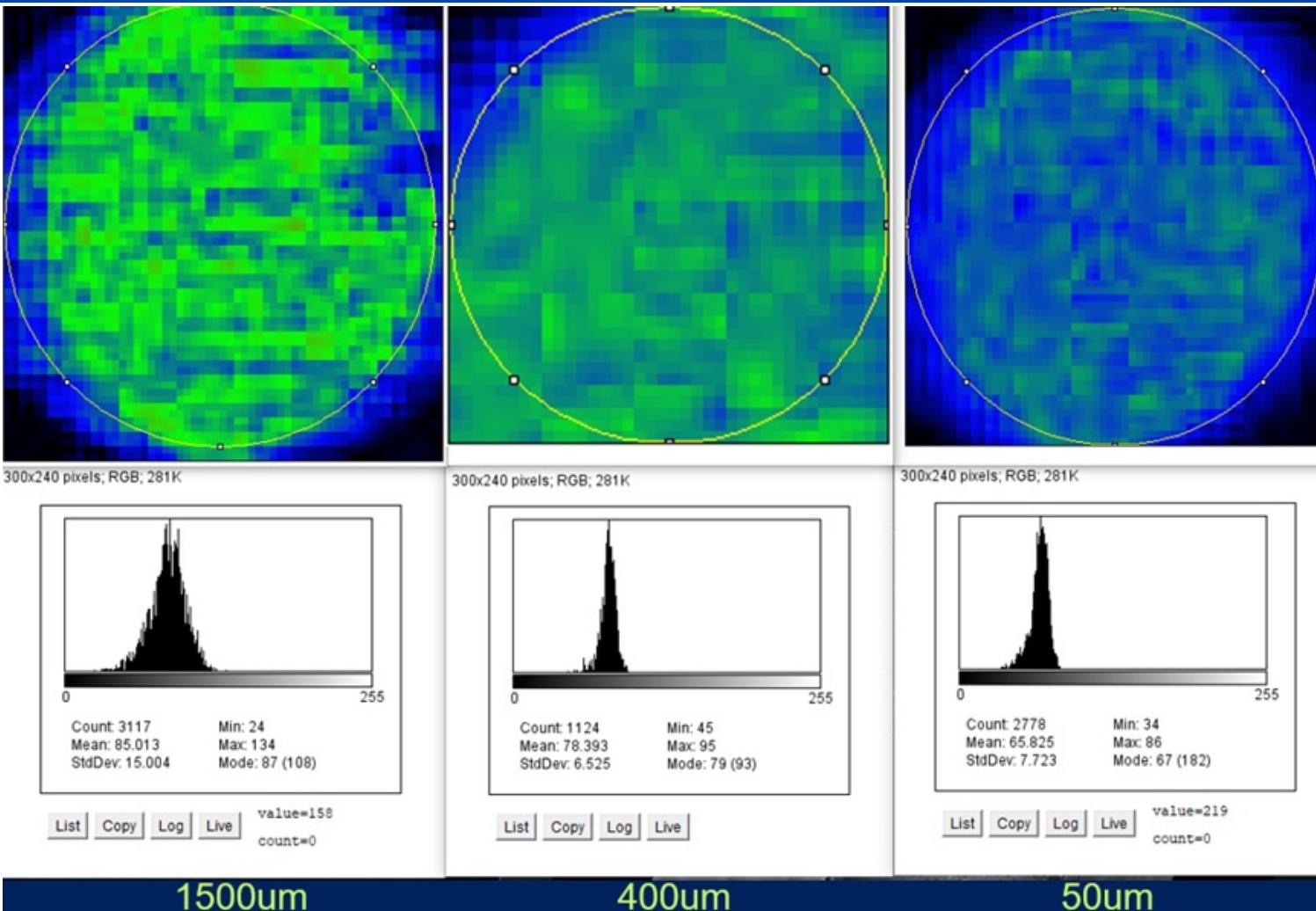


Machine
Learning
3D Image
Recognition

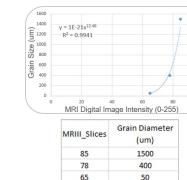
Experimental (MRI) – Different sizes of Glass Beads



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78	400
65	50

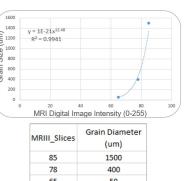
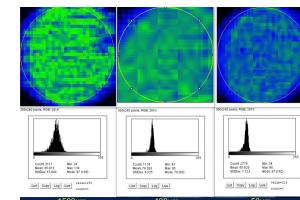
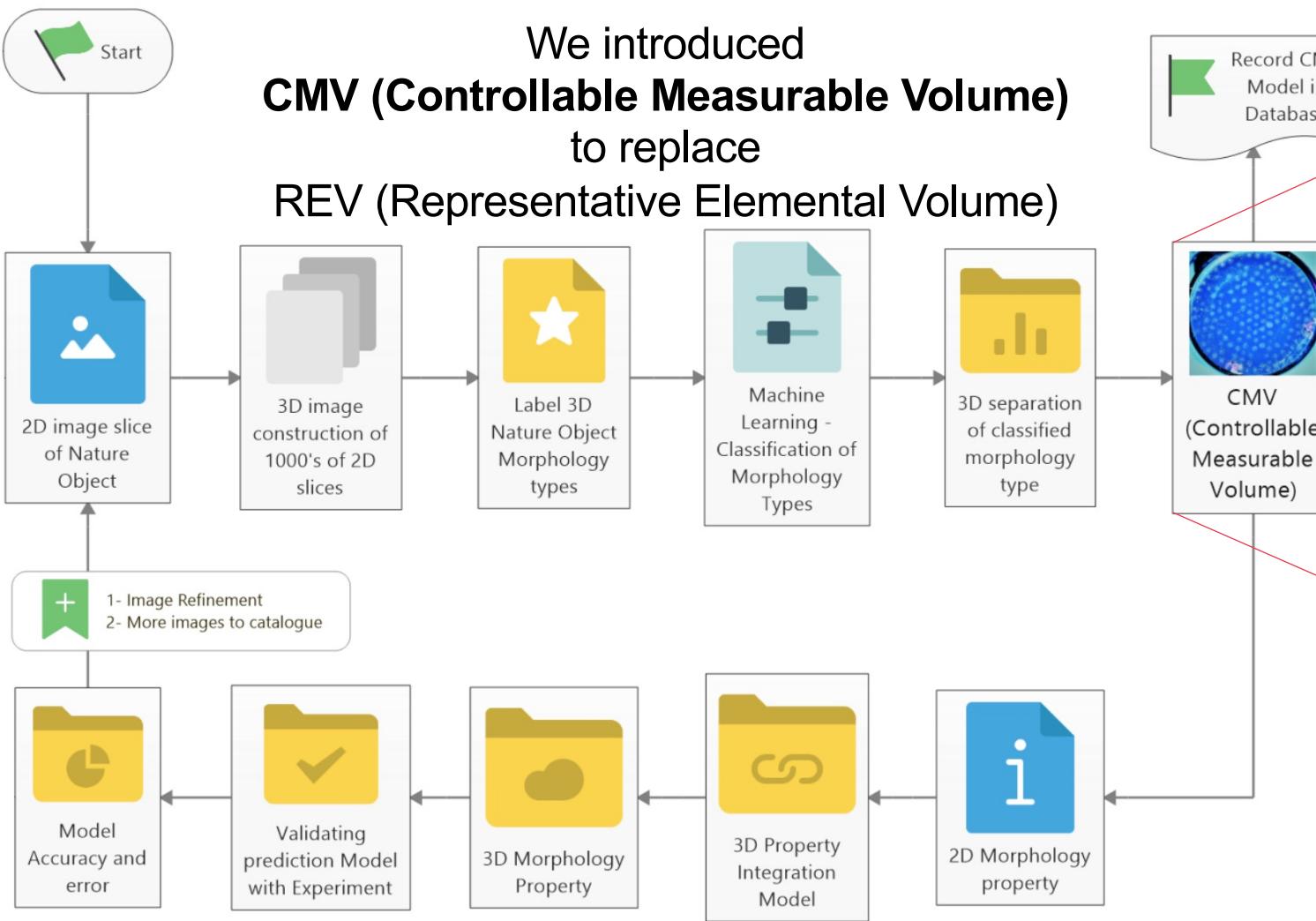


$$PortS_{rhombohedral\ 3D\ Effective} = \frac{A_{rhombohedral\ Port}}{N_{Port} \cdot N_{Cavities}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \quad (8)$$



CMV – Controllable Measurable Volume

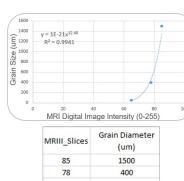
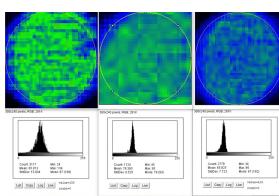
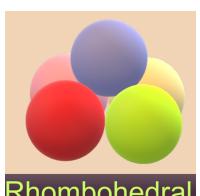
We introduced
CMV (Controllable Measurable Volume)
to replace
REV (Representative Elemental Volume)



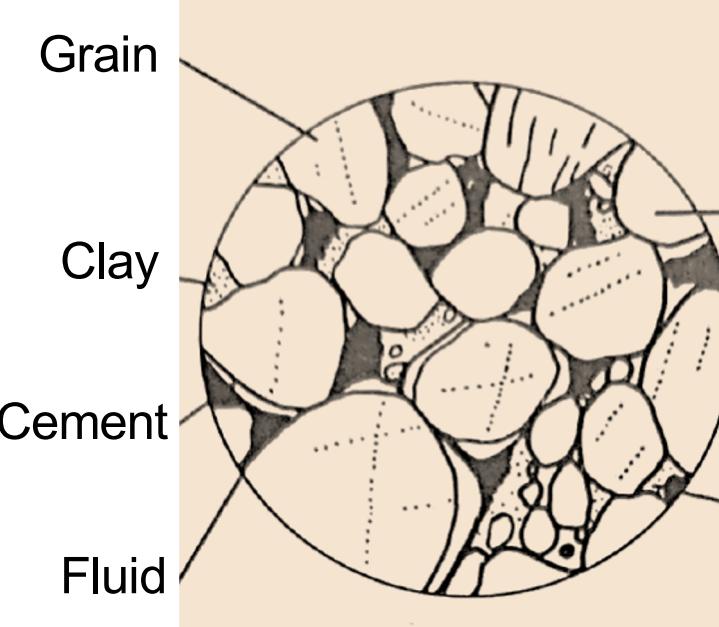
CMV – Controllable Measurable Volume



Al-Farisi, O., Belgaeid, A., Elhami, M., Kadada, T., Aljefri, G., & Barkawi, A. N. (2004, January). Electrical Resistivity and Gamma-Ray Logs: Two Physics for Two Permeability Estimation Approaches in Abu Dhabi Carbonates. In Abu Dhabi International Conference and Exhibition. Society of Petroleum Engineers.



CMV (Controllable Measurable Volume)
provides
heterogenous rock morphology segmentation



Serra, O. (1985). Sedimentary environments from wireline logs. Schlumberger Limited.

Porosity & Diagenetic Model

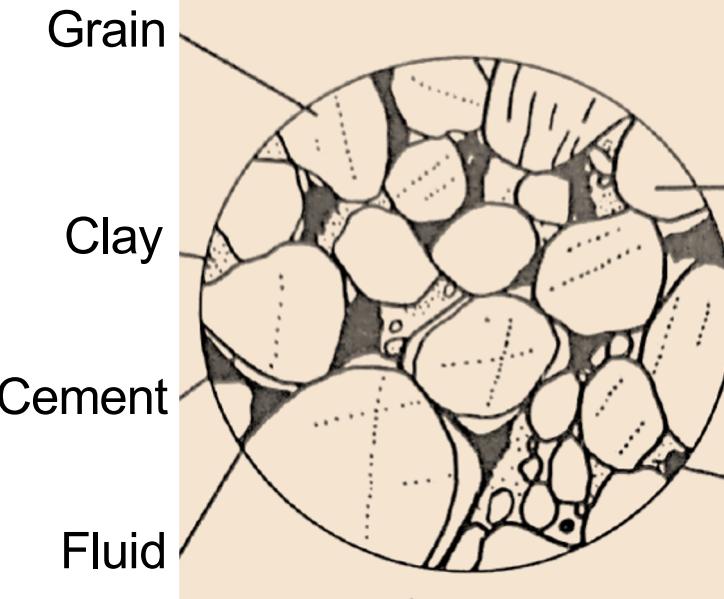
- Intergranular



- Intragranular

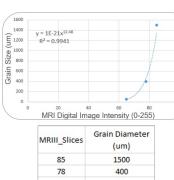
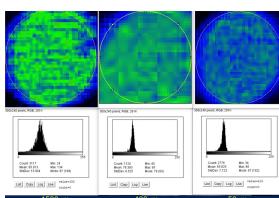
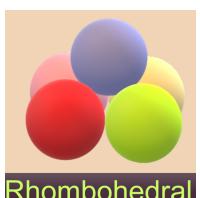


CMV (Controllable Measurable Volume) provides
heterogenous rock morphology segmentation

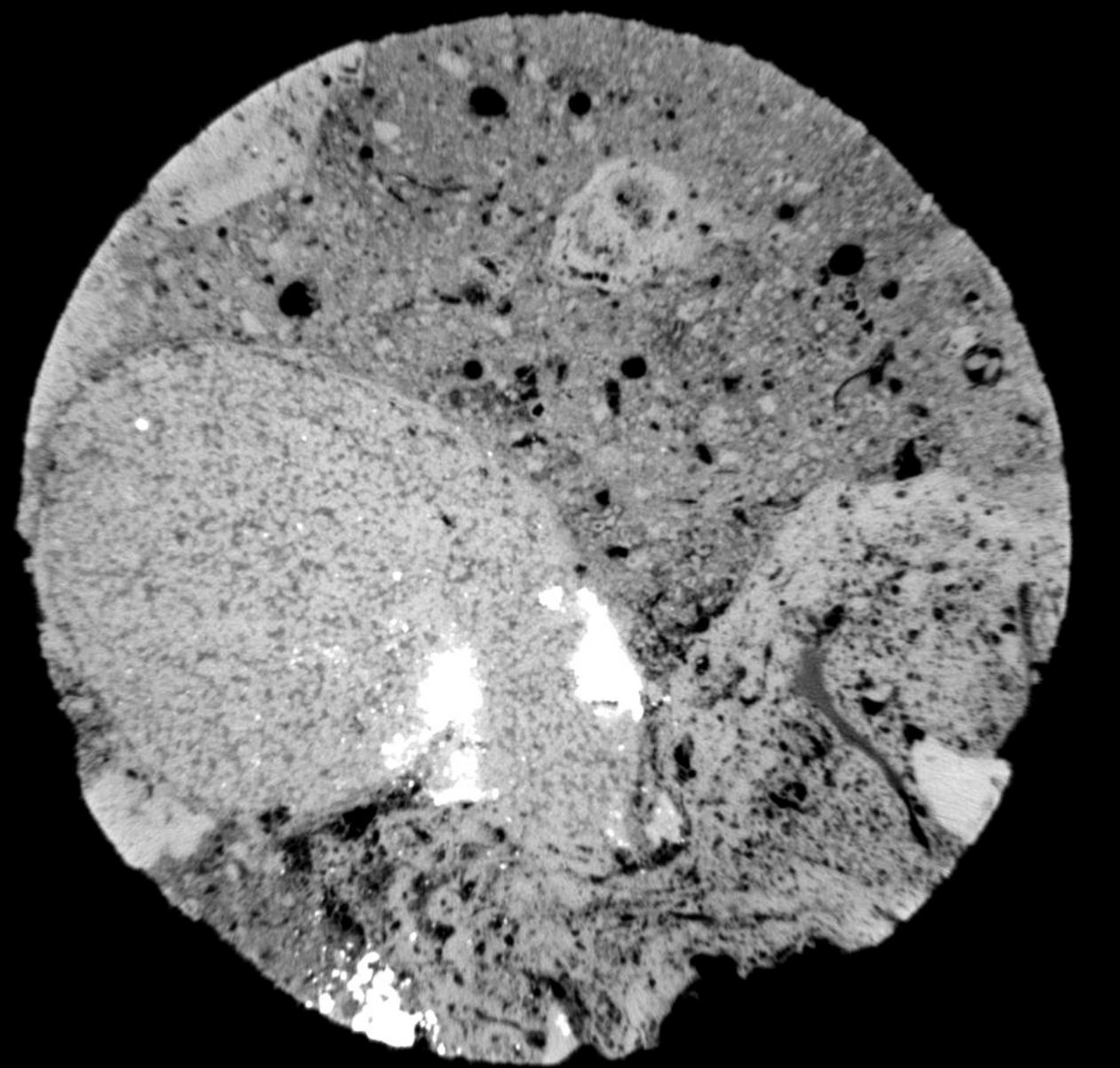


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Al-Farisi, O., Belgaid, A., Elhami, M., Kadada, T., AlJefri, G., & Barkawi, A. N. (2004, January). Electrical Resistivity and Gamma-Ray Logs: Two Physics for Two Permeability Estimation Approaches in Abu Dhabi Carbonates. In Abu Dhabi International Conference and Exhibition. Society of Petroleum Engineers.

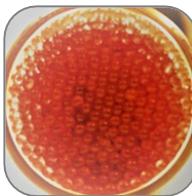
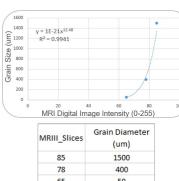


CMV– Controllable Measurable Volume

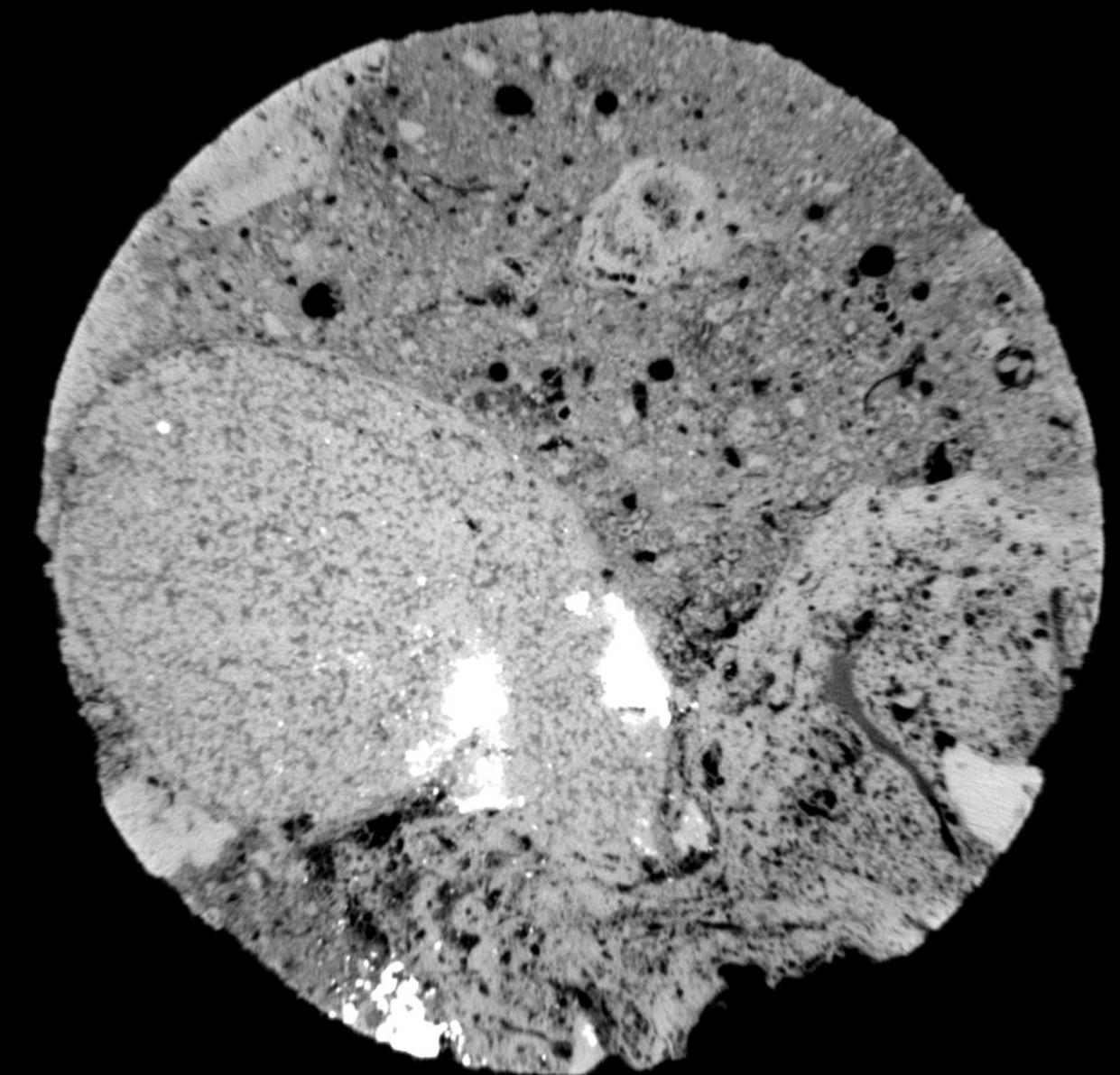


CMV (Controllable Measurable Volume)
provides
heterogenous rock morphology segmentation

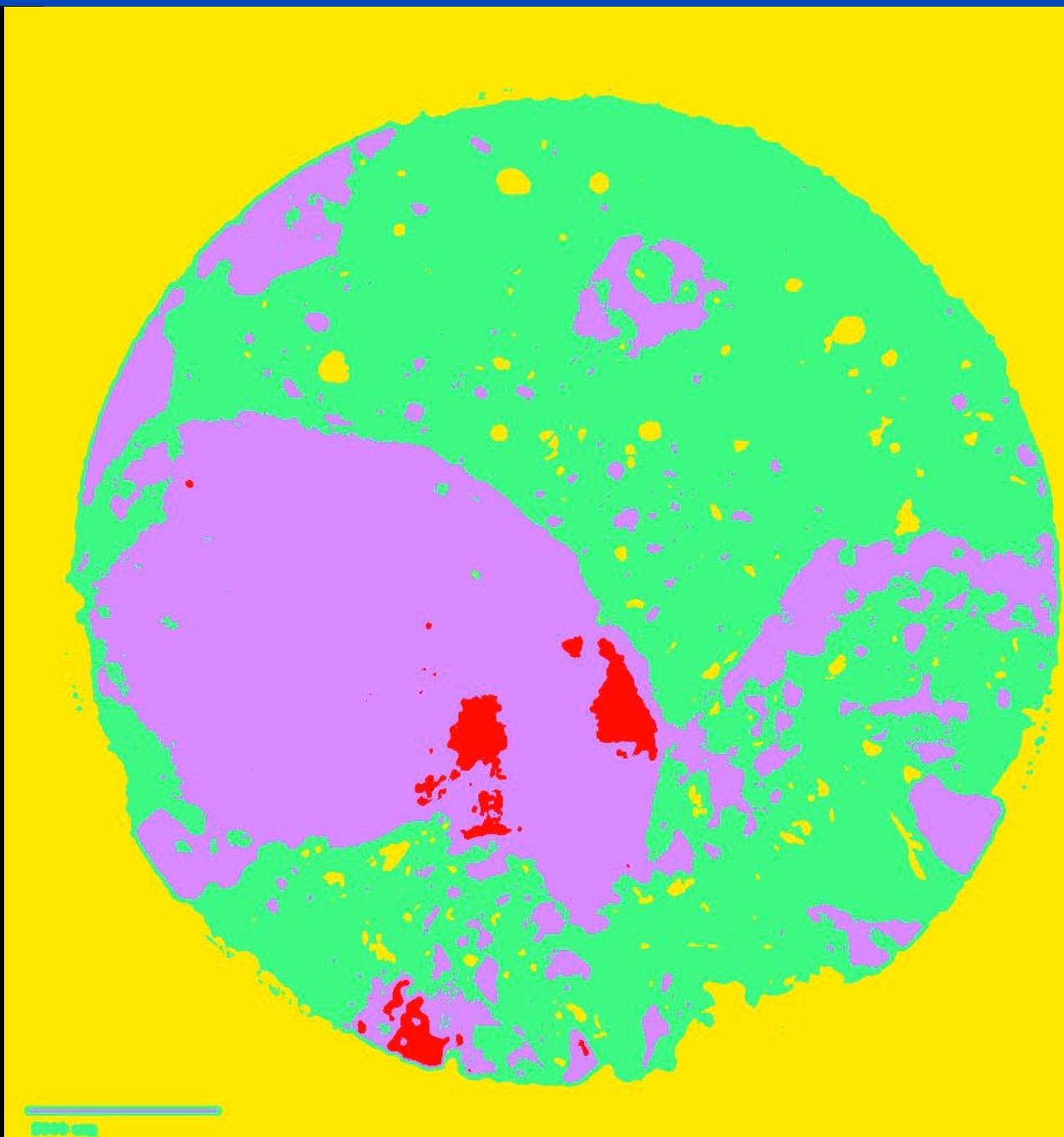
Do we have Intragranular and Intergranular?



Machine Learning Heterogenous Morphology Segmentation

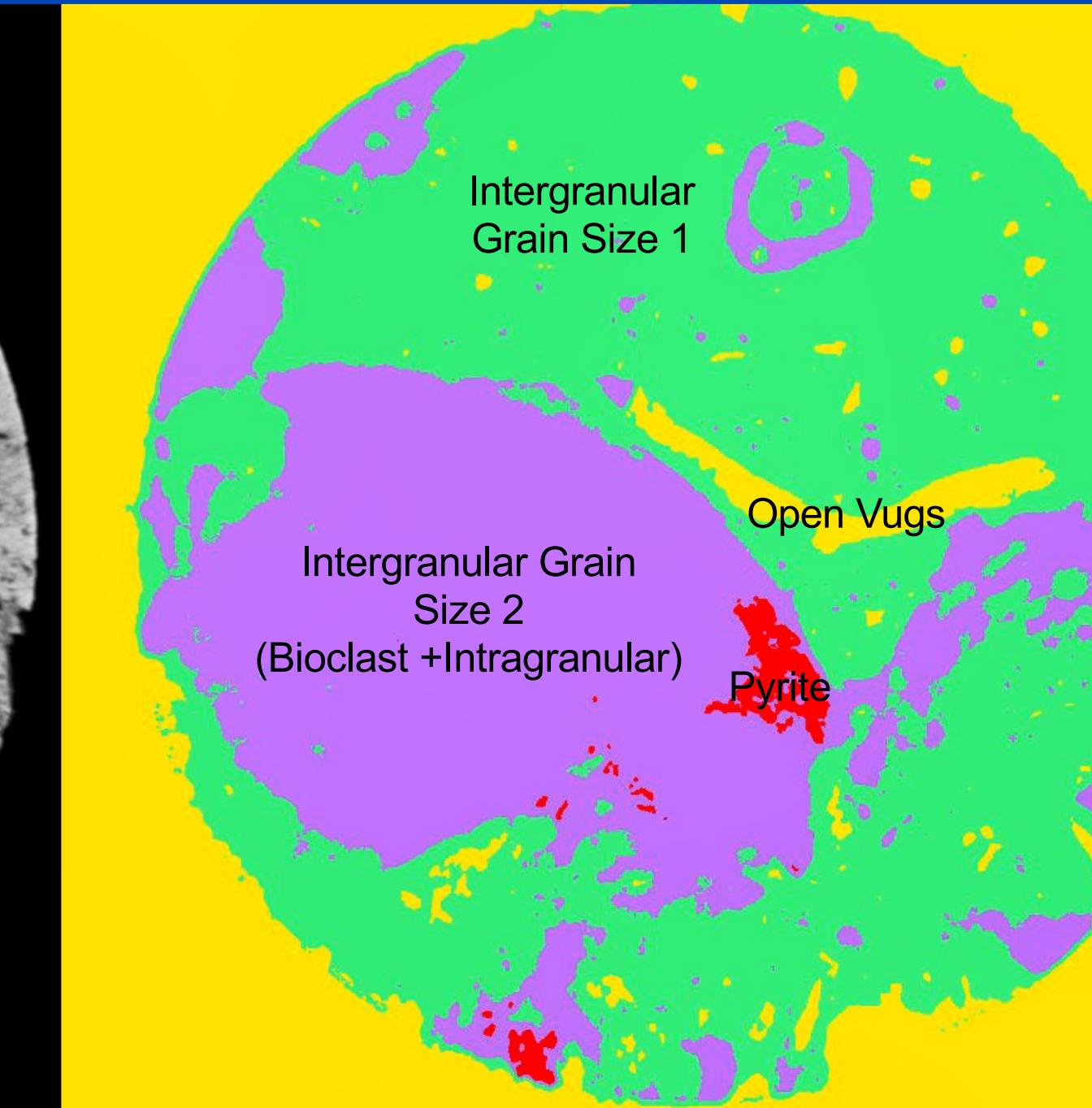
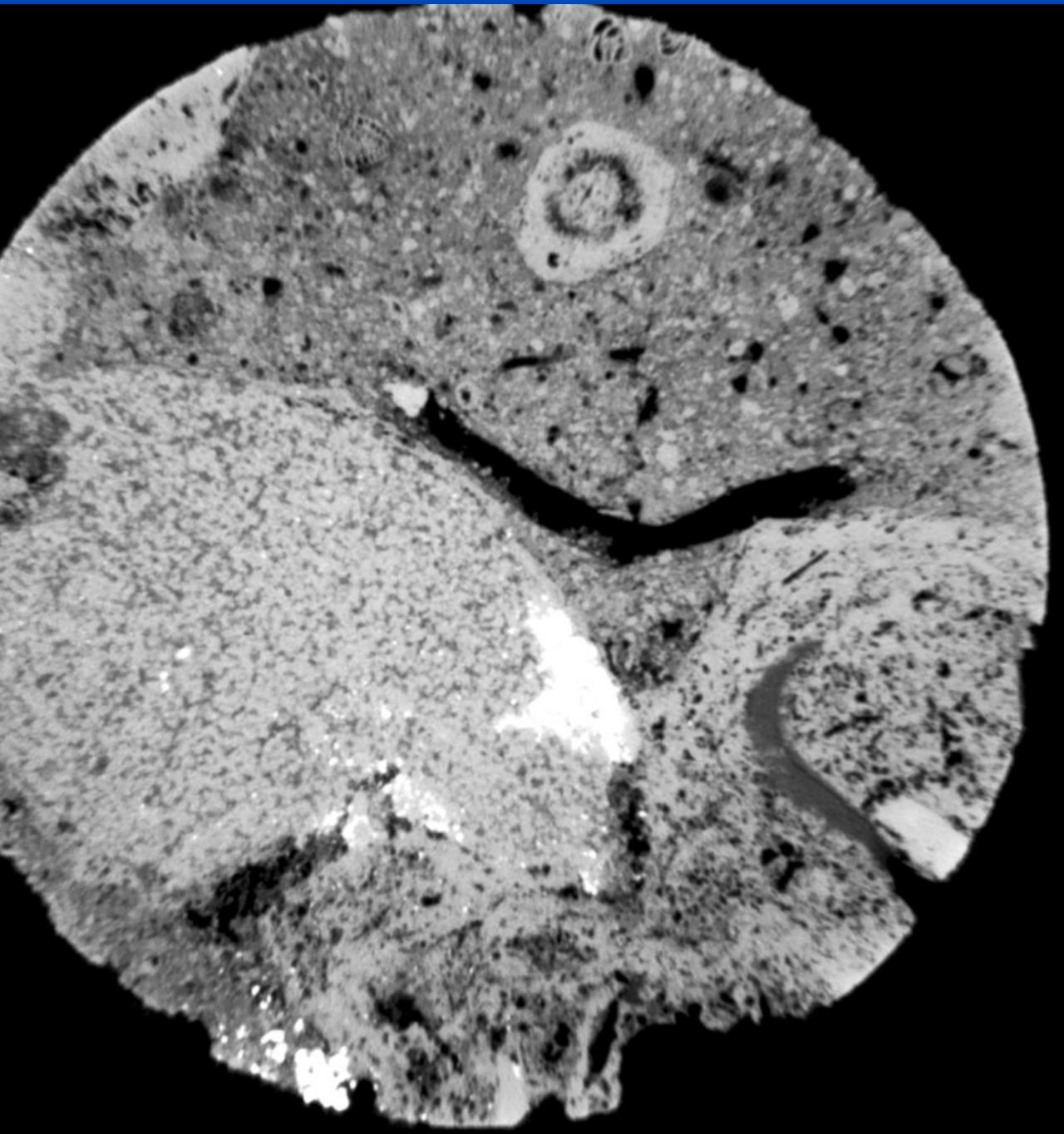


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Machine Learning Heterogenous Morphology Segmentation



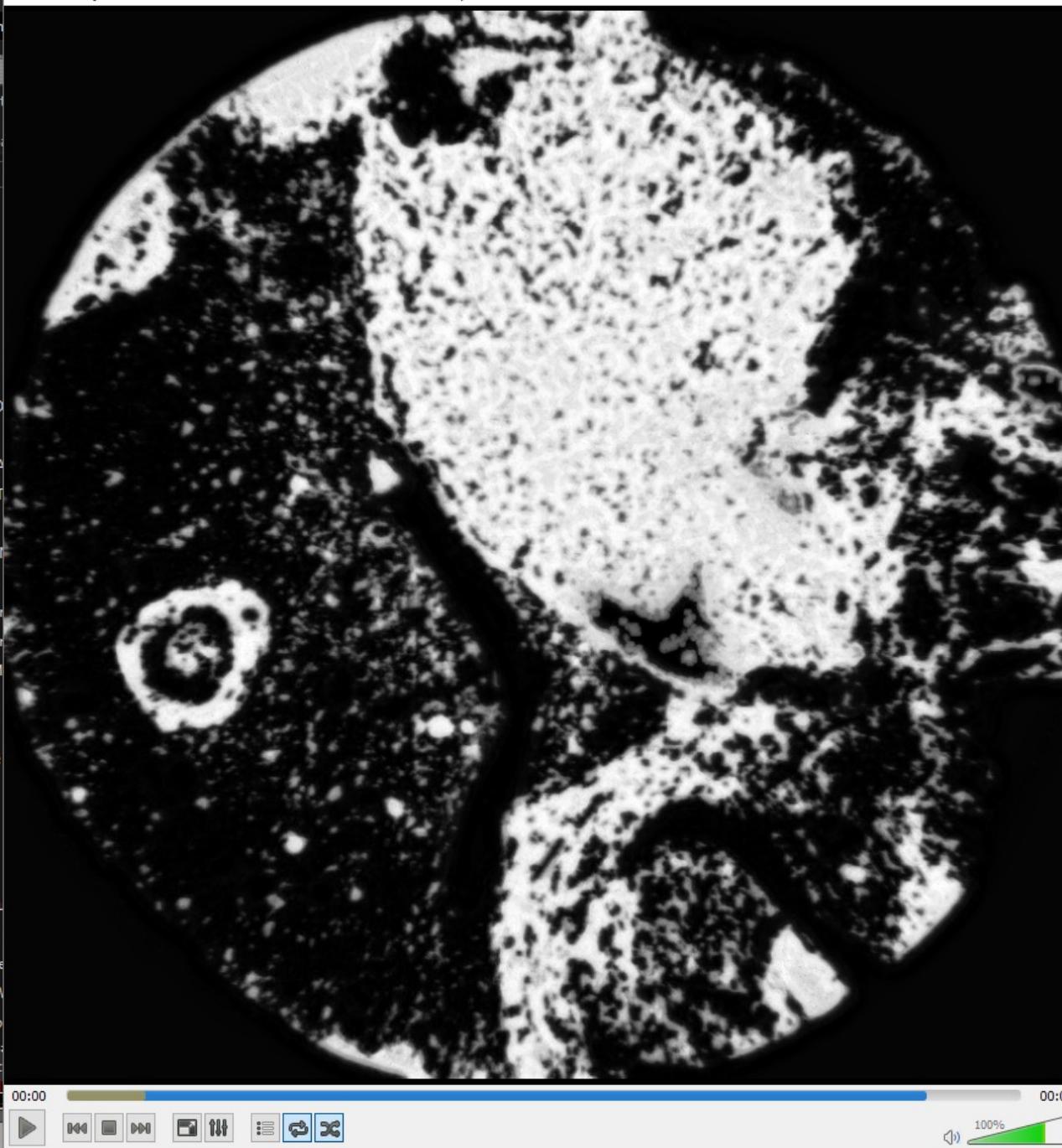
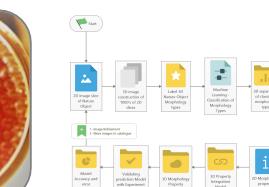
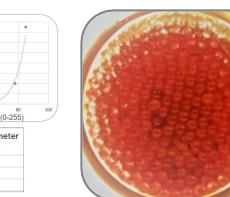
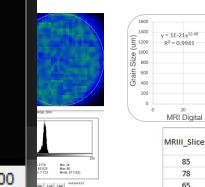
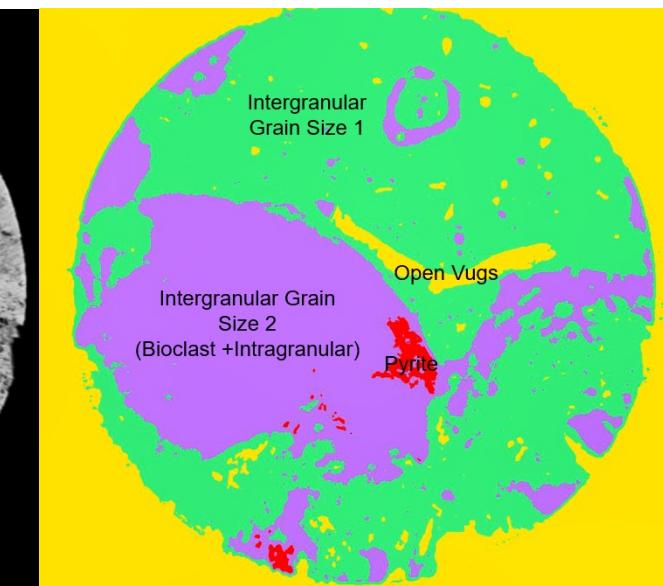
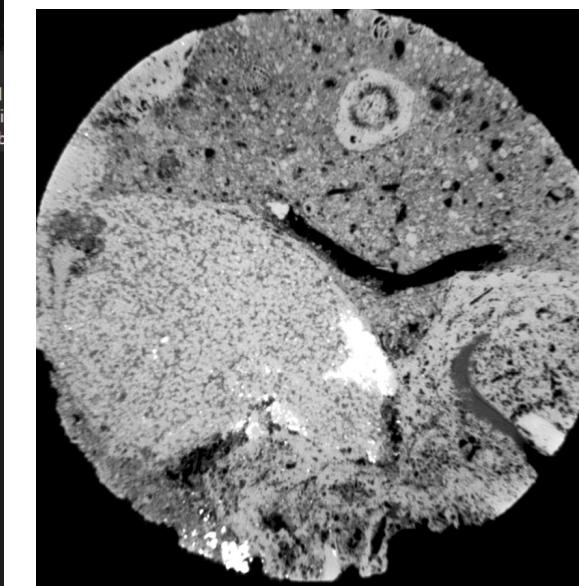


Image Processing Segregation of Morphology



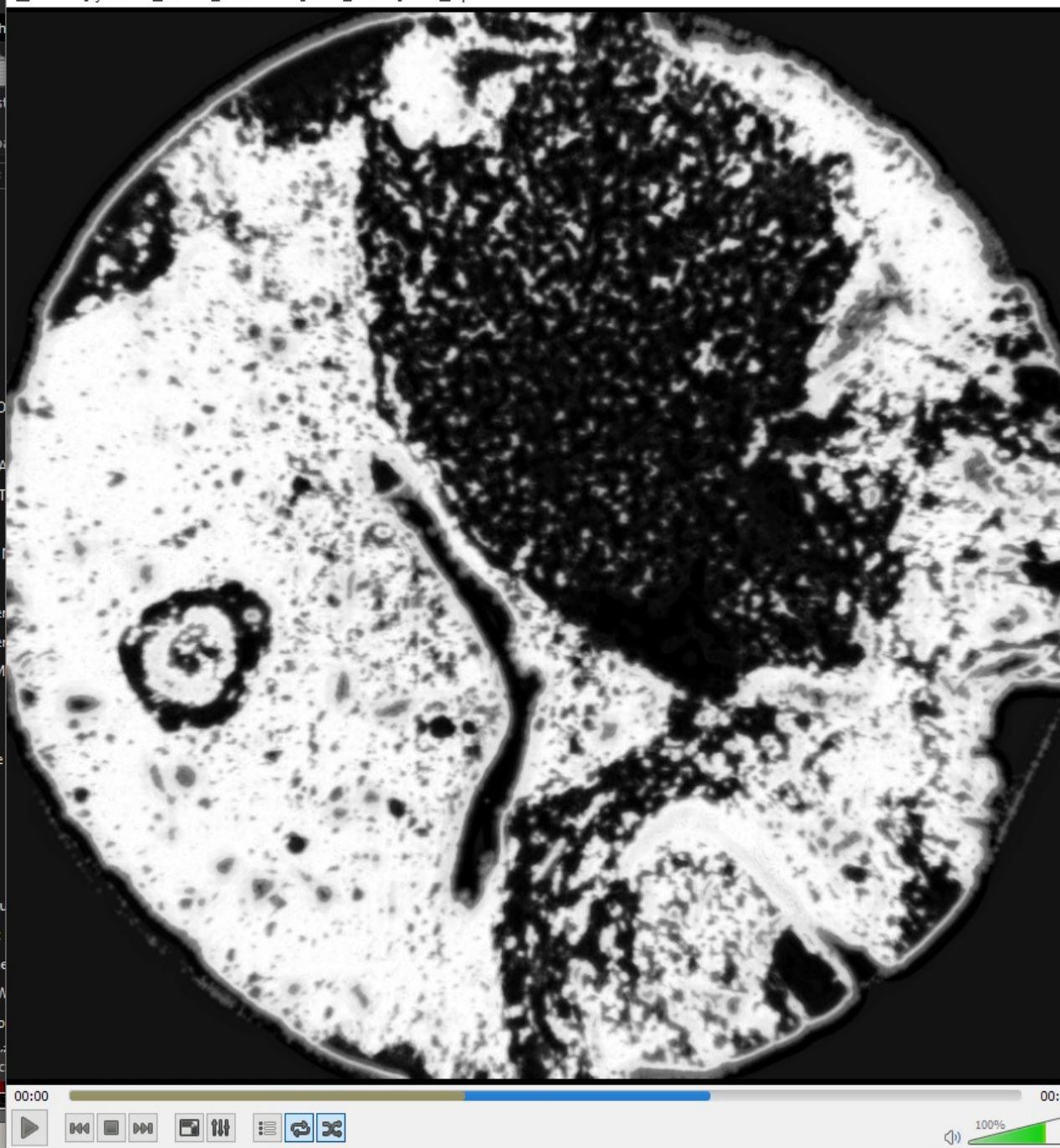
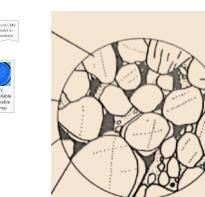
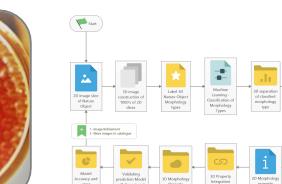
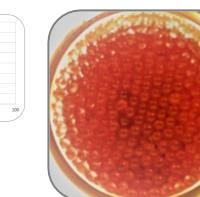
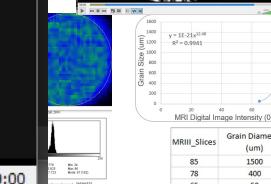
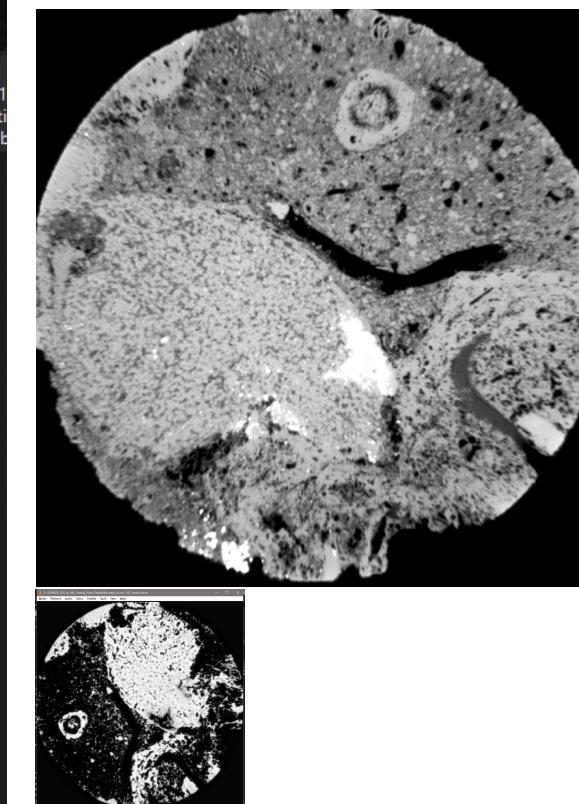


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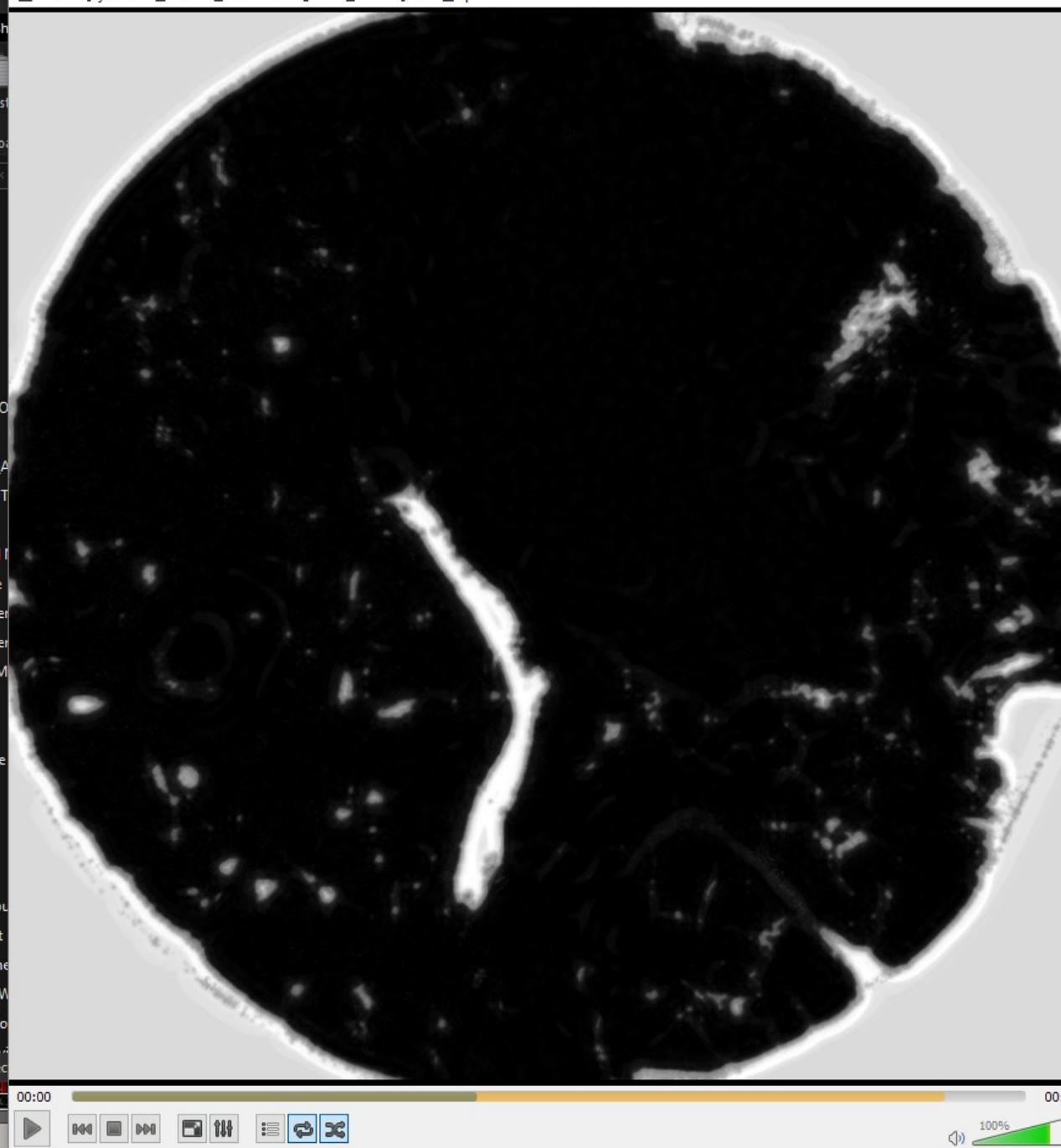


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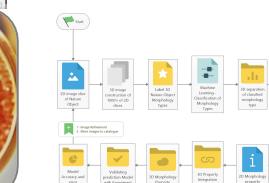
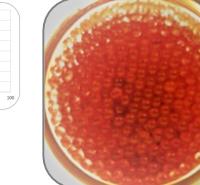
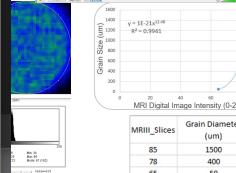
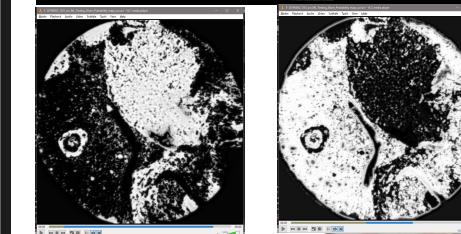
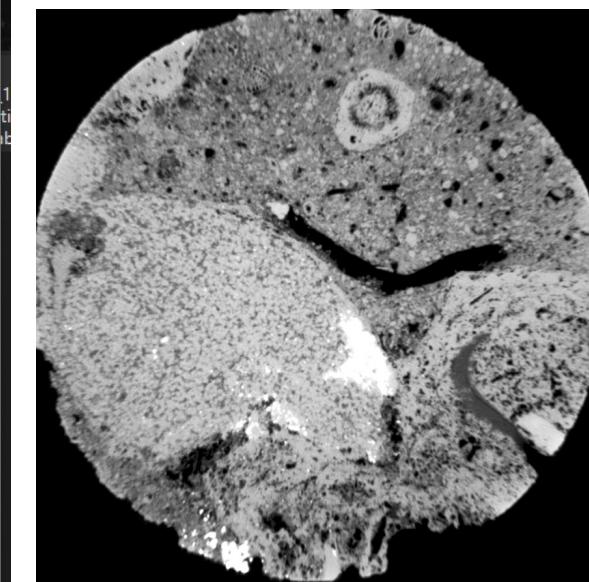


Image Processing Segregation of Morphology

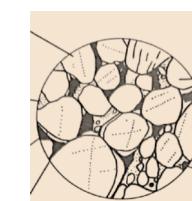
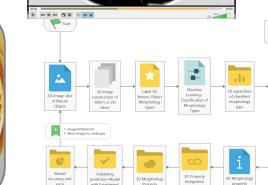
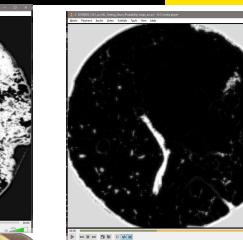
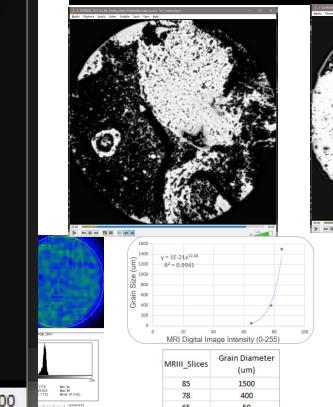
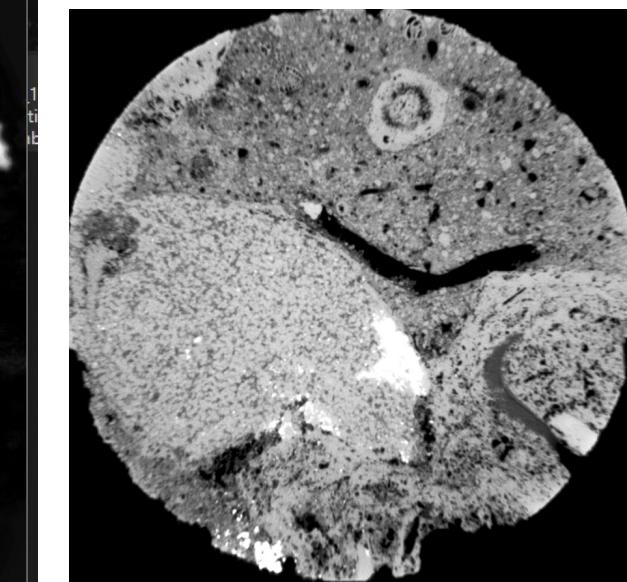
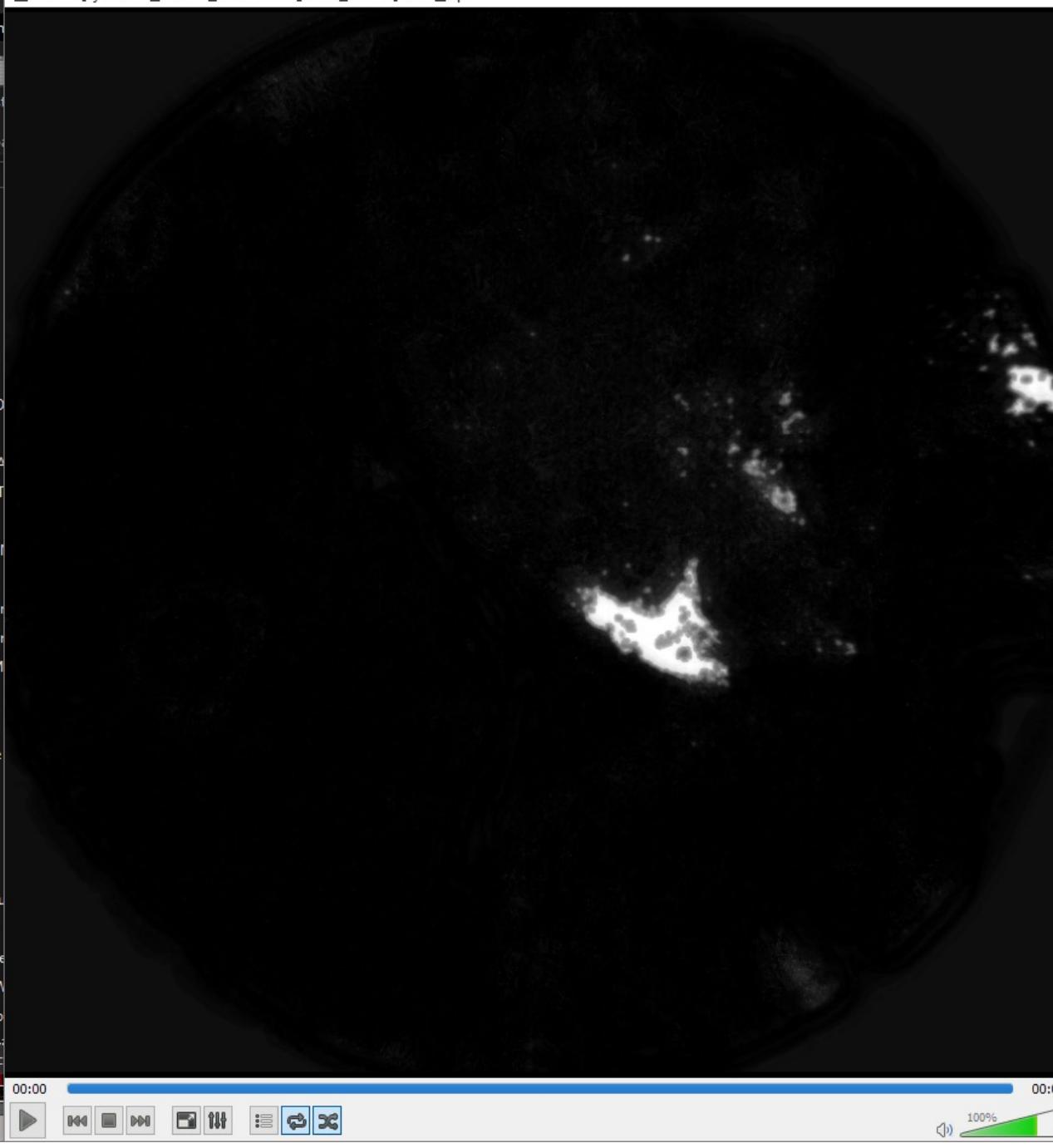
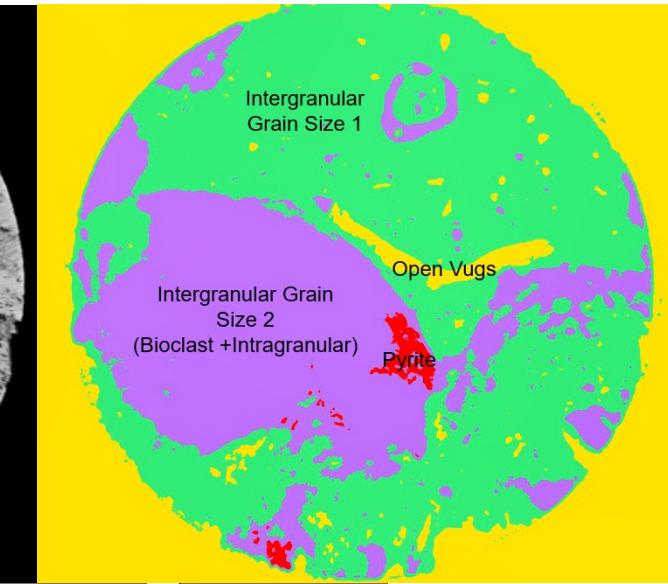
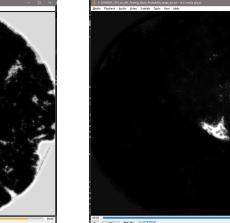
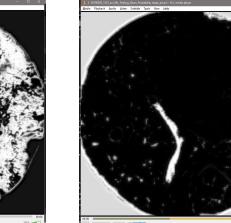
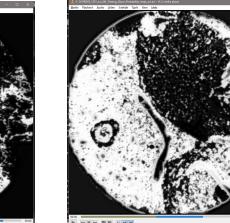
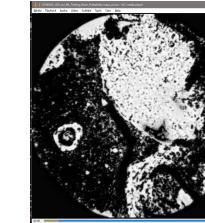
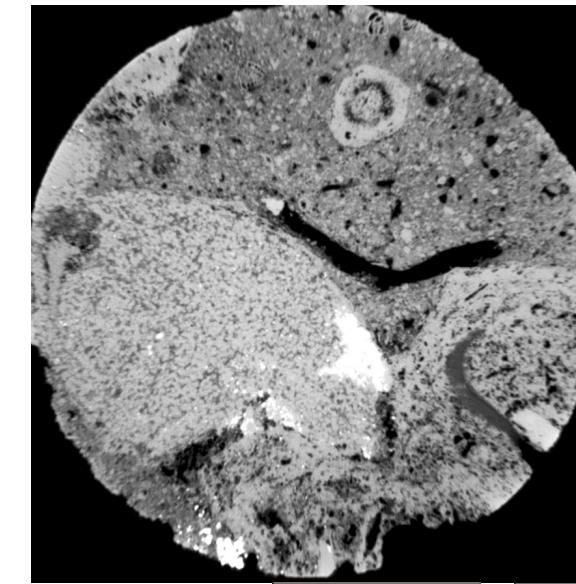
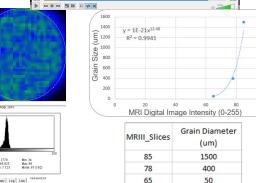
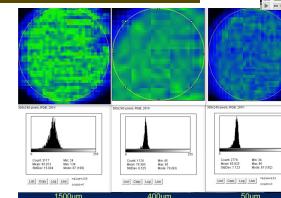
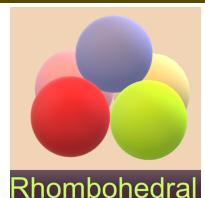
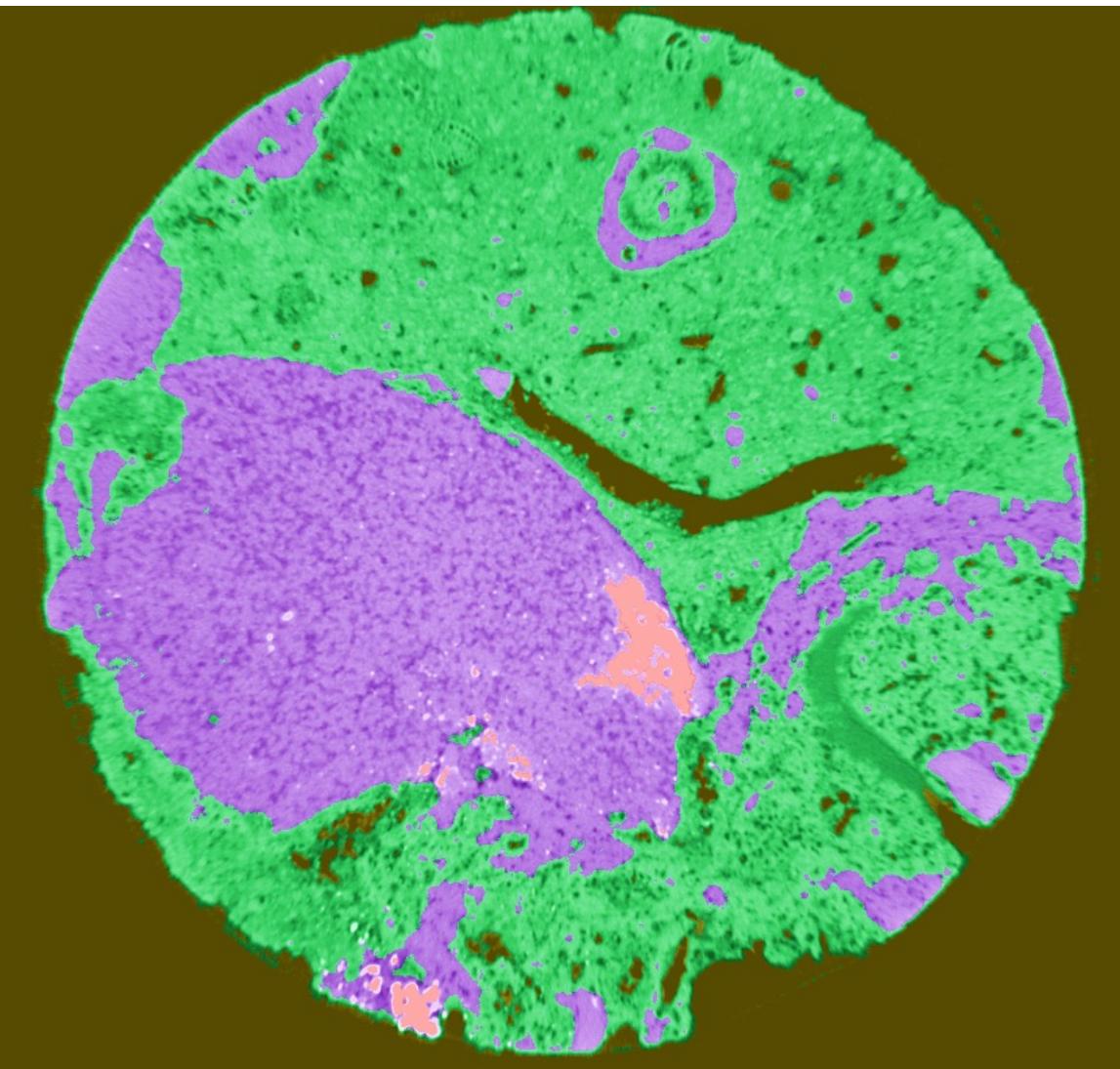


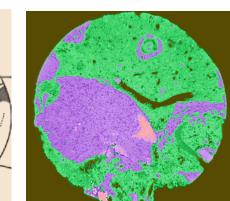
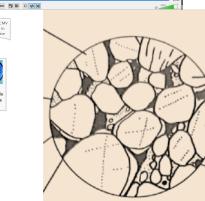
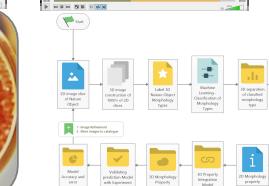
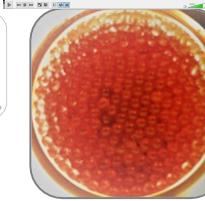
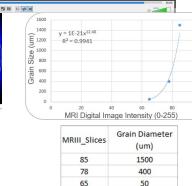
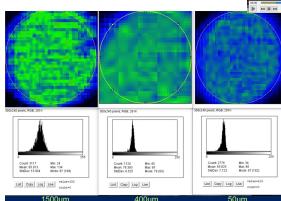
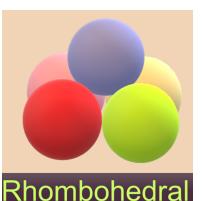
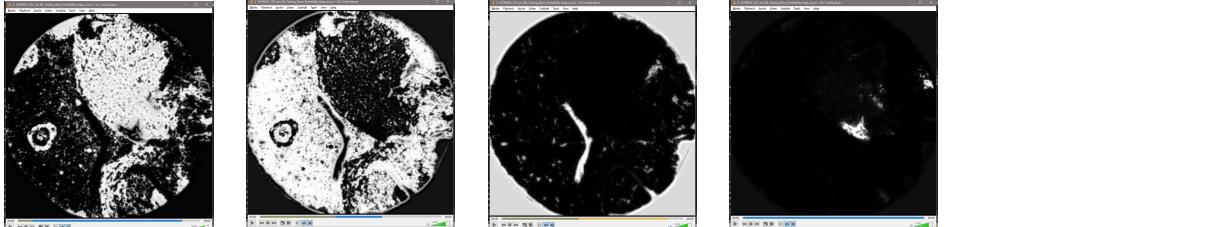
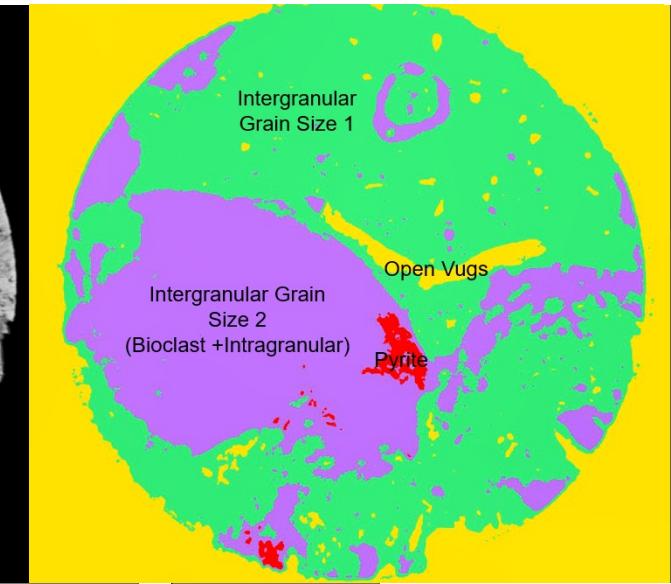
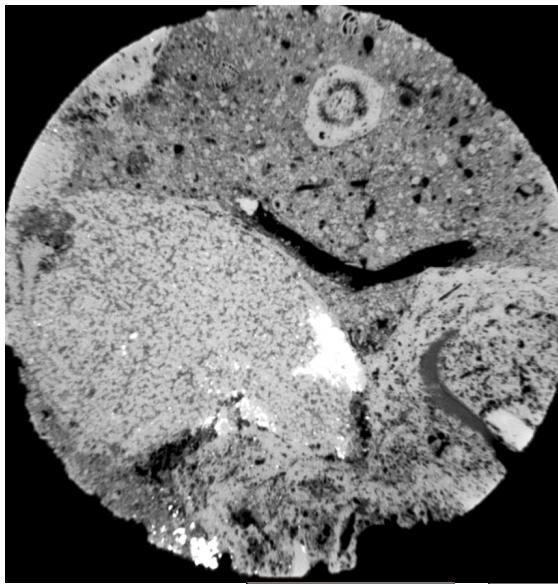
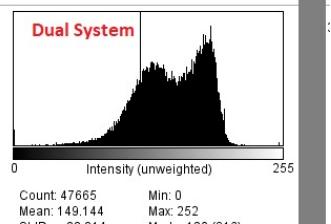
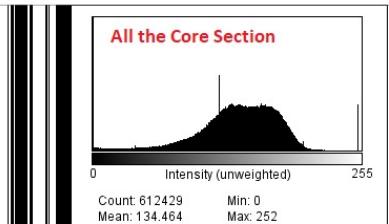
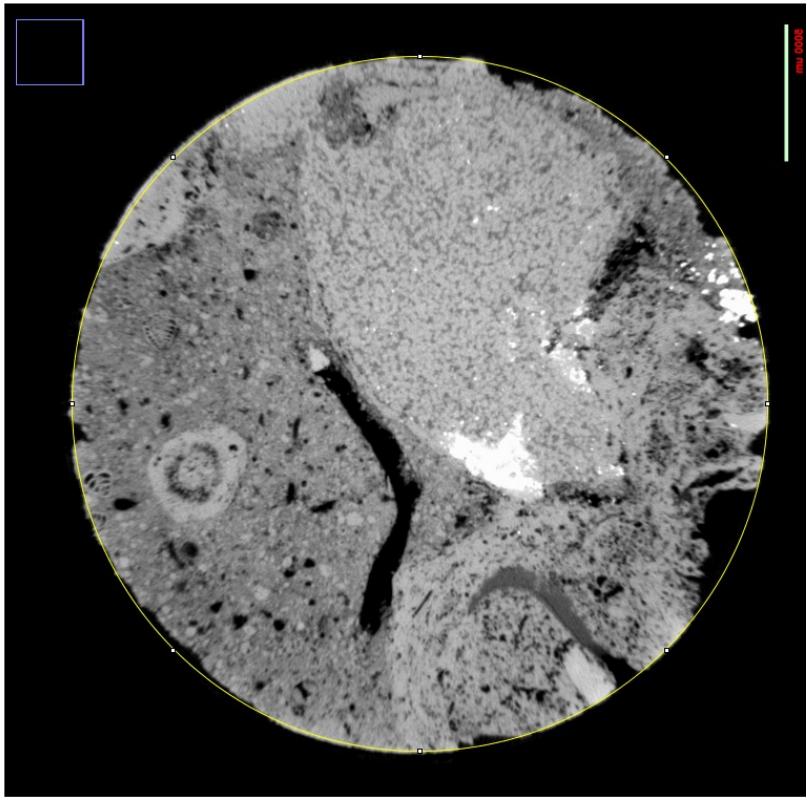
Image Processing Segregation of Morphology



(Dual Pore system) identified by Image Processing Segregation of Morphology

20190502Better_MAS-Trial-1_0p5x_A_1794_fliped and rotated_labeled_for histogram.tif (75%)

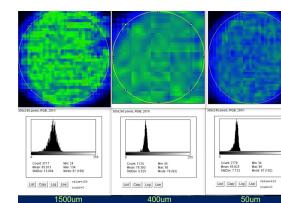
6.82x6.67 inches (1023x1000); RGB; 3.9MB



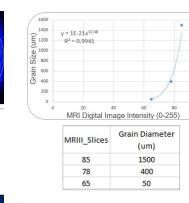
Machine Learning Heterogenous Morphology Segmentation

$$k = \left(\frac{q \cdot l \cdot \mu}{A \cdot \nabla p} \right)$$

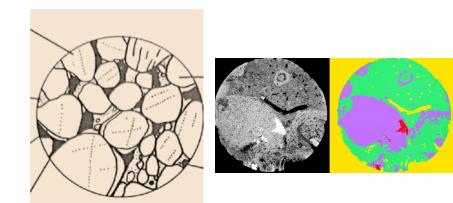
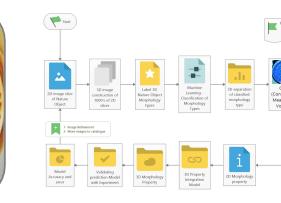
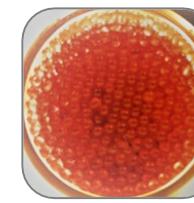
Darcy Equation



Rhombohedral



MRII_Slices	Grain Diameter (μm)
85	1500
78	400
65	50



Machine Learning Heterogenous Morphology Segmentation

$$k = \left(\frac{q \cdot l \cdot \mu}{A \cdot \nabla p} \right)$$

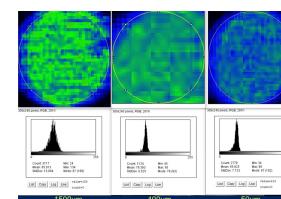
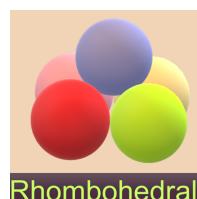
Darcy Equation

$$k = \left(\frac{q \cdot l \cdot \mu}{A \cdot \nabla p} \right) = \left(\frac{A \cdot l^2 \cdot \mu}{t \cdot A \cdot \nabla p} \right) = \left(\frac{t \cdot A \cdot l^2 \cdot F}{t \cdot A \cdot l^2 \cdot \nabla p} \right) = \left(\frac{t \cdot A^2 \cdot l^2 \cdot F}{t \cdot A \cdot l^2 \cdot F} \right) = A$$

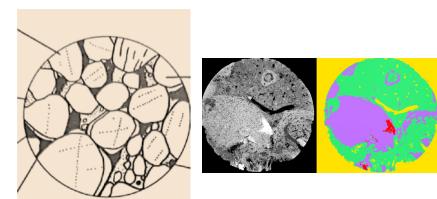
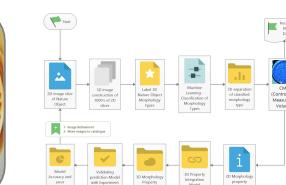
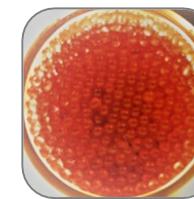
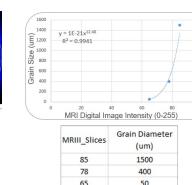
or **Permeability (mD) = Area (μm) 2**

Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education.

or $k = A$



Rhombohedral



Machine Learning Heterogenous Morphology Segmentation

$$k = \left(\frac{q \cdot l \cdot \mu}{A \cdot \nabla p} \right)$$

Darcy Equation

$$k = \left(\frac{q \cdot l \cdot \mu}{A \cdot \nabla p} \right) = \left(\frac{A \cdot l^2 \cdot \mu}{t \cdot A \cdot \nabla p} \right) = \left(\frac{t \cdot A \cdot l^2 \cdot F}{t \cdot A \cdot l^2 \cdot \nabla p} \right) = \left(\frac{t \cdot A^2 \cdot l^2 \cdot F}{t \cdot A \cdot l^2 \cdot F} \right) = A$$

or *Permeability (mD) = Area (um)²*

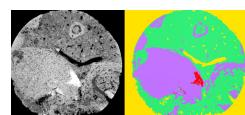
Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education.

or $k = A$

$A_{rhombohedralPorT}$: The pore throats area of rhombohedral configuration.

We rewrite Eq. 8 in terms of grain surface area, as shown in Eq. 9 below:

$$PorTS_{rhombohedral3DEffective} = A_{surface_{grain}} = 0.02731\pi r_g^2 \quad (9)$$



Machine Learning Heterogenous Morphology Segmentation

$A_{rhombohedralPorT}$: The pore throats area of rhombohedral configuration.

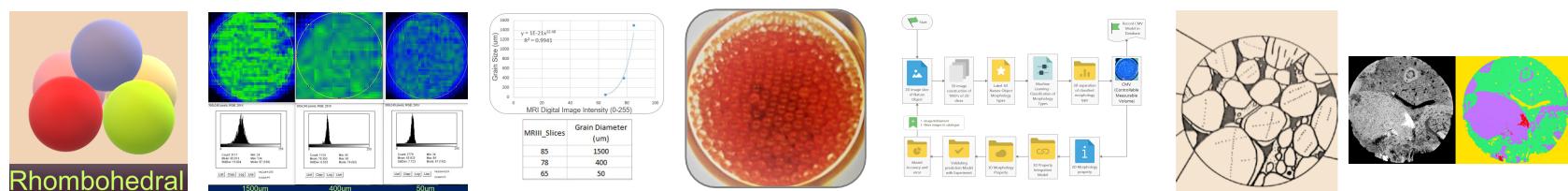
We rewrite Eq. 8 in terms of grain surface area, as shown in Eq. 9 below:

$$PorTS_{rhombohedral3DEffective} = A_{surface_{grain}} = 0.02731\pi r_g^2 \quad (9)$$

Permeability is a resultant of both grain size and grain configuration to form a proportional relation between permeability and grain surface area (58) “ this physical aspect of permeability has been used to create empirical equations for prediction of permeability,” as described below in Eq. 10:

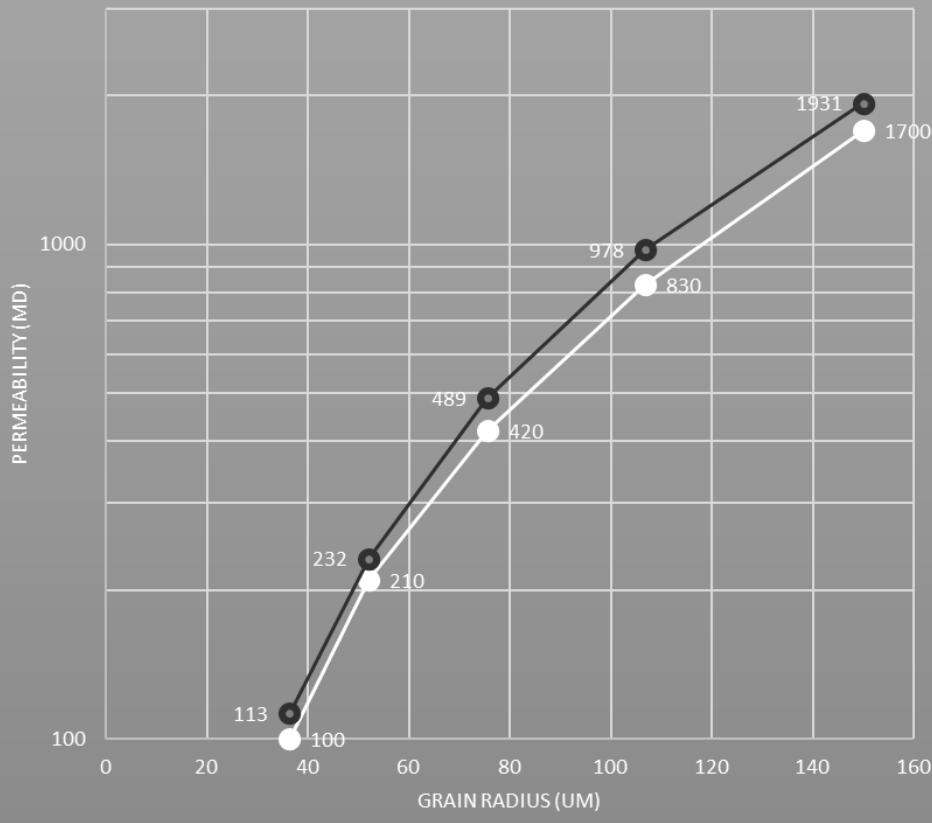
$$\text{Permeability (mD)} = A_{surface_{grain}} (\mu\text{m}^2) \quad (10)$$

$$k_{3Drhombohedral} = PorTS_{rhombohedral3DEffective} = 0.0858r_g^2 \quad (11)$$

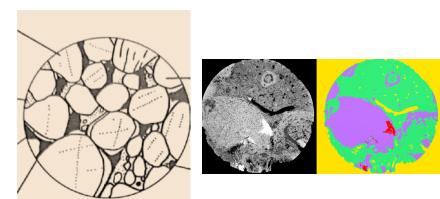
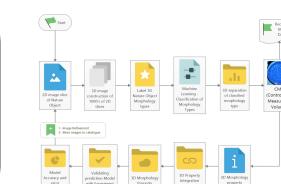
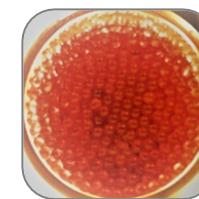
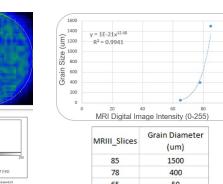
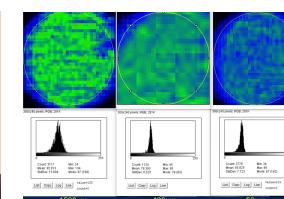


Permeability Equation Validation

Permeability: Experimental vs. Geometrical



- Permeability (mD) (Bread and Wely - 1973) various Grain sizes Experiments
- Permeability (mD) $k_{3D\text{rhombohedral}}$ (this research) Geometrical and Analytical Approaches

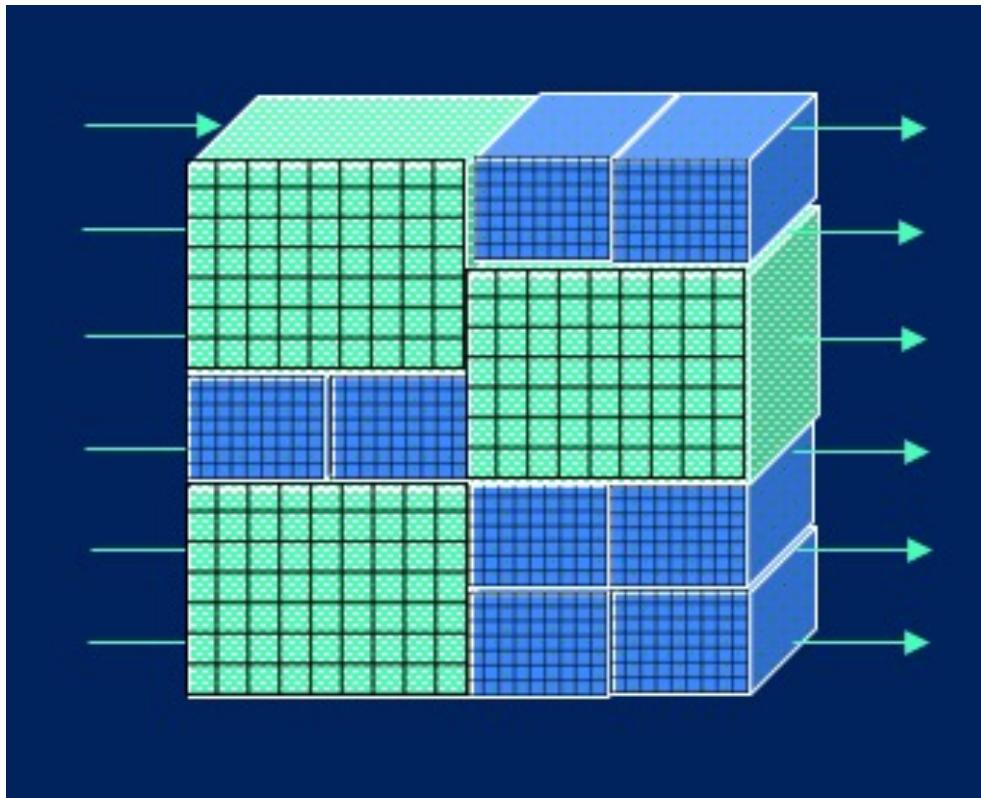


Beard, D. C., & Weyl, P. K. (1973). Influence of texture on porosity and permeability of unconsolidated sand. AAPG bulletin, 57(2), 349-369.

3D Permeability Equations

$$k_{avg_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \quad (4.5)$$

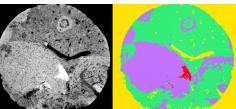
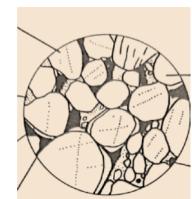
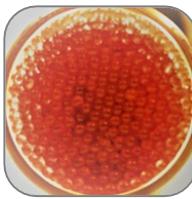
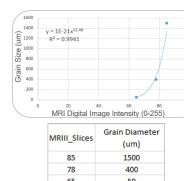
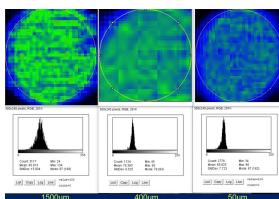
$$k_{avg_Parallel} = \frac{h_1 * k_1 + h_2 * K_2}{h_1 + h_2} \quad (4.6)$$



Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education. P-304.



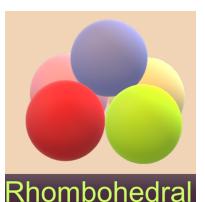
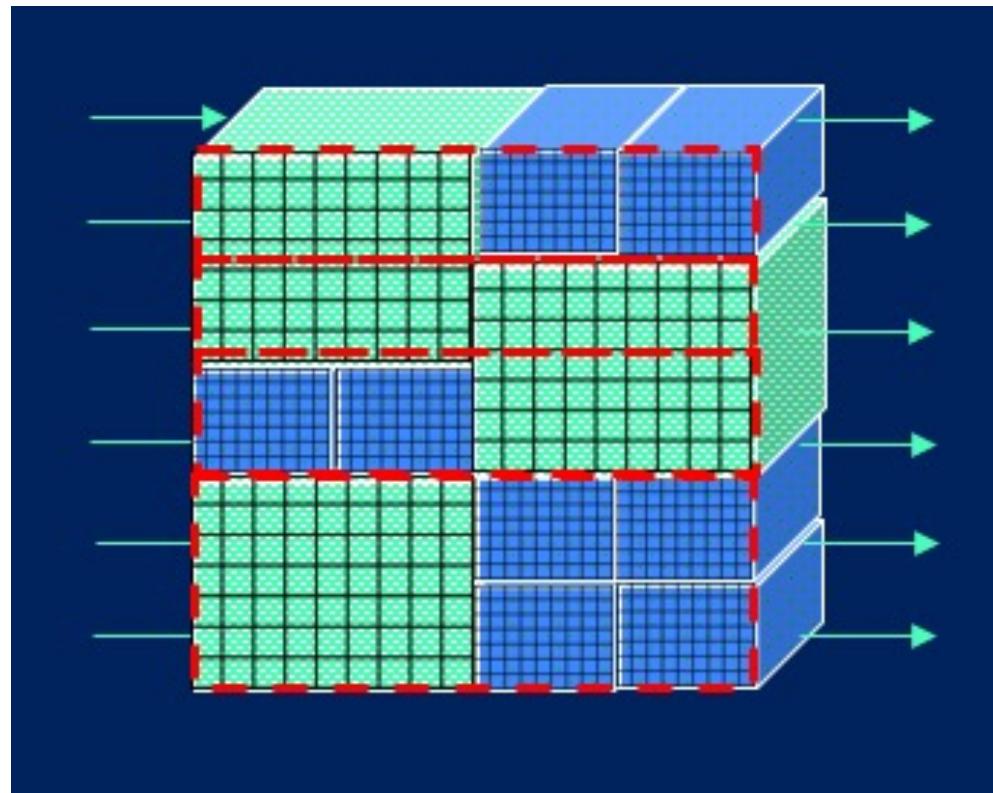
Rhombohedral



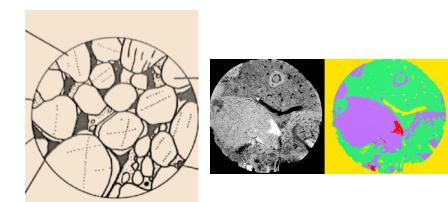
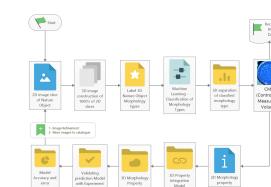
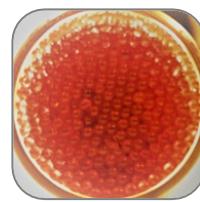
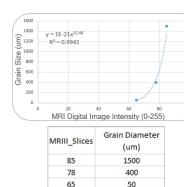
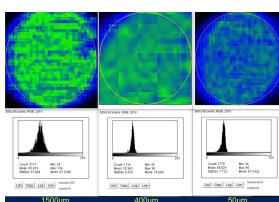
3D Permeability Equations for Heterogeneous Fabric

$$k_{avg_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \quad (4.5)$$

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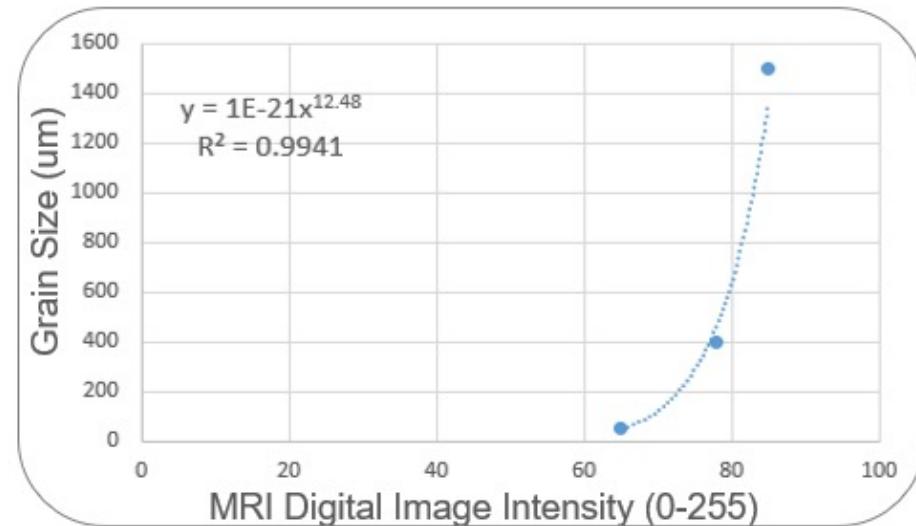
Rhombohedral



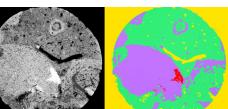
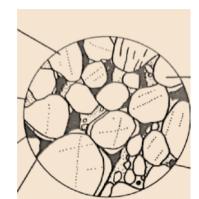
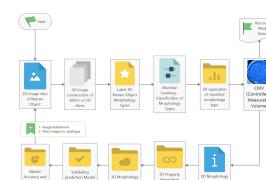
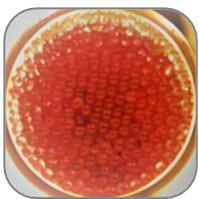
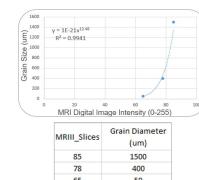
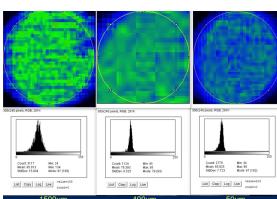
3D Permeability Equations and MRIII Model Validation

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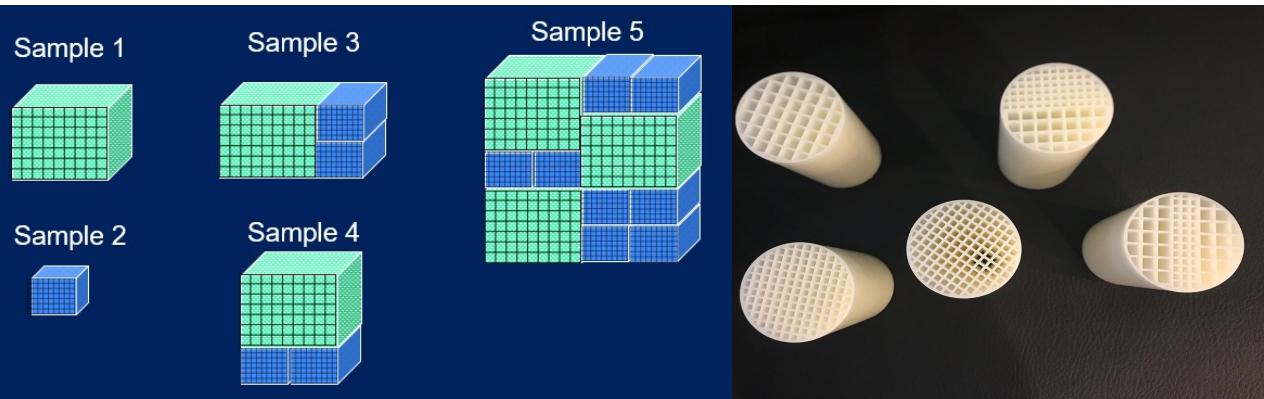
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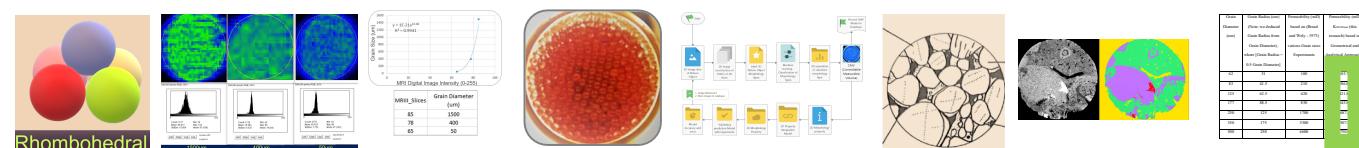
3D Permeability Equations



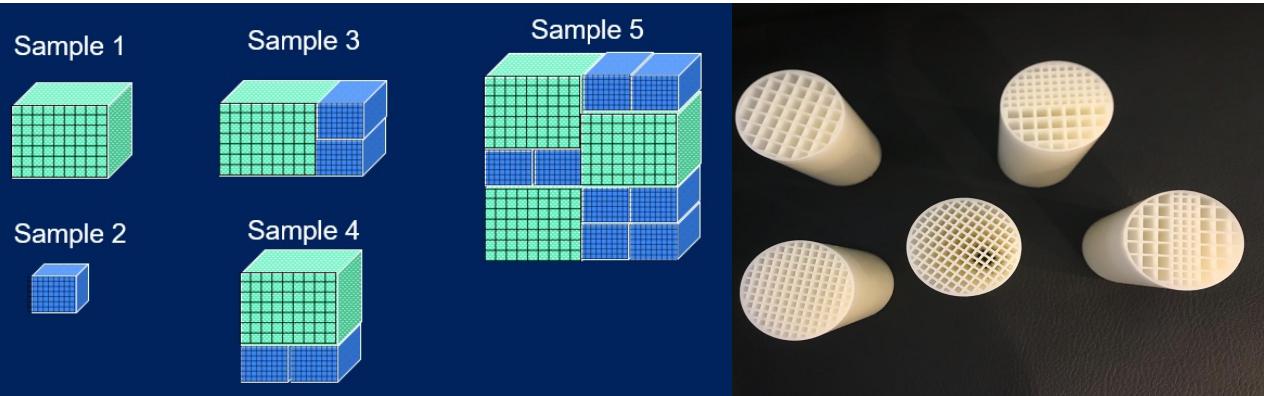
Designed five 3D models and 3D printed them

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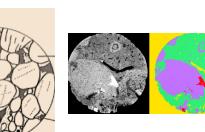
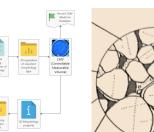
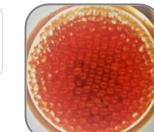
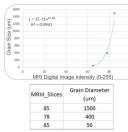
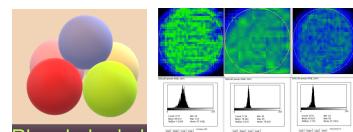
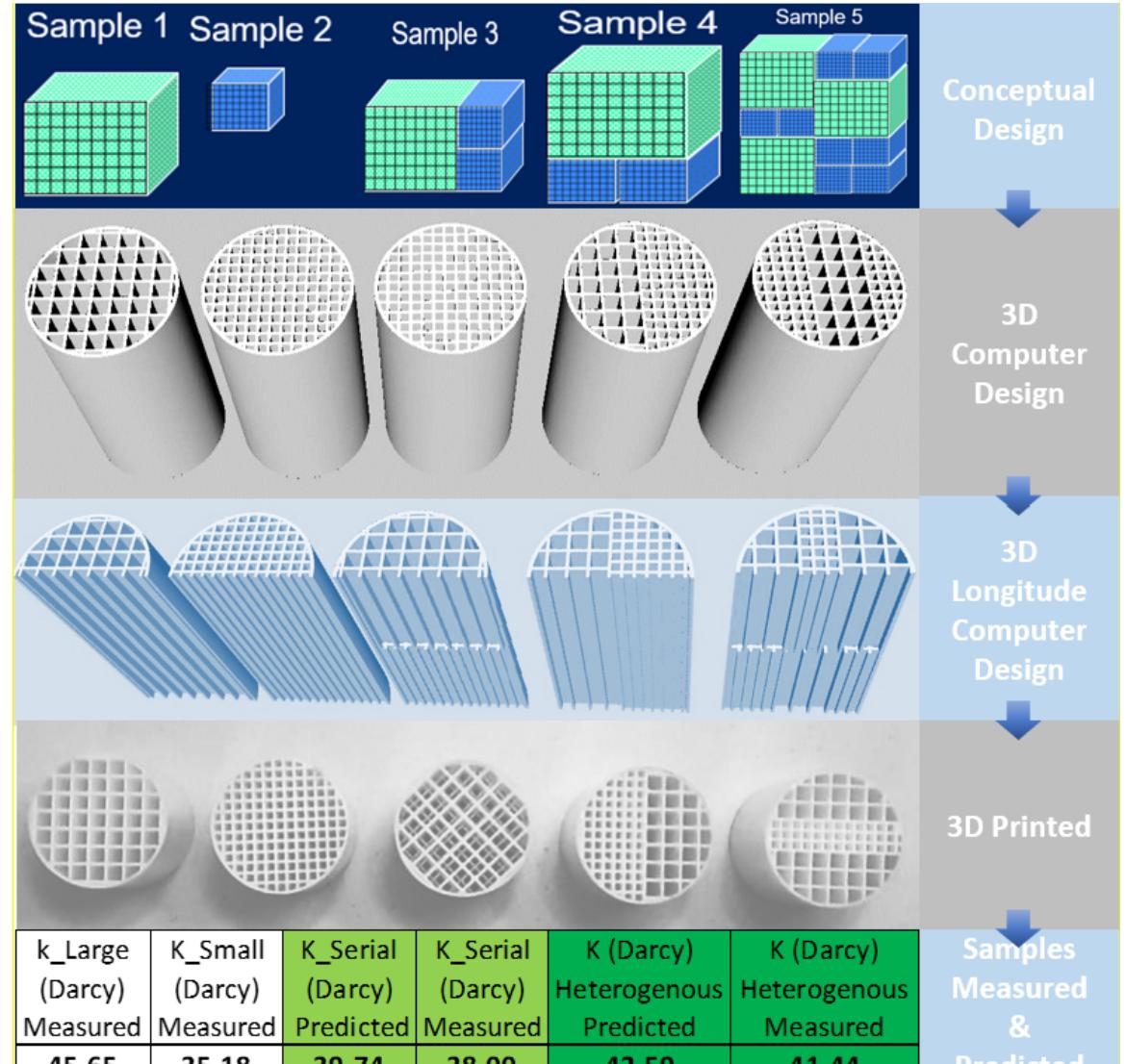
3D Permeability Equations



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$$k_{avg_Parallel} = \frac{h_1 * k_1 + h_2 * K_2}{h_1 + h_2} \quad (4.6)$$



Dataset	Grain Size (mm)	Grain Diameter (μm)	Porosity (%)	Permeability (Darcy)	Porosity (%)	Permeability (Darcy)
1	0.1	100	10	10	10	10
2	0.2	200	15	20	15	20
3	0.3	300	20	30	20	30
4	0.4	400	25	40	25	40
5	0.5	500	30	50	30	50
6	0.6	600	35	60	35	60
7	0.7	700	40	70	40	70
8	0.8	800	45	80	45	80
9	0.9	900	50	90	50	90
10	1.0	1000	55	100	55	100

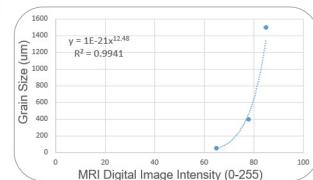
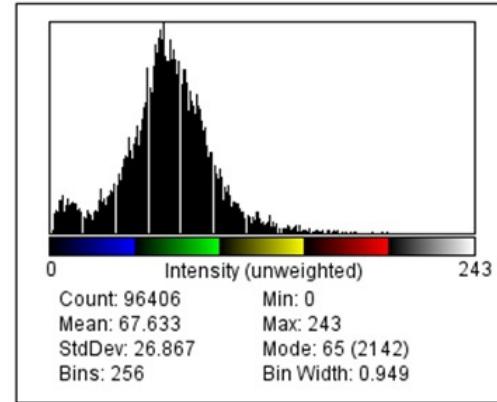
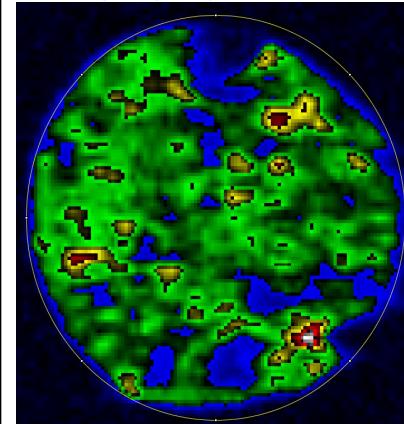
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O. Al-Farisi^{1,2,3*}, A. Raza¹, H. Zhang¹, H. Li¹, D. Ozzane^{4,5}, M. Sassi¹, T. Zhang¹, (2019) Decoding heterogeneity by 3D-vision machine learning reveals Cretaceous permeability.

MRIII Model Validation

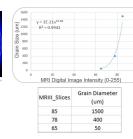
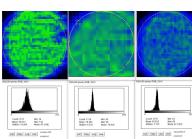
Histogram of MRI_plug9_Saturated_3500um_20190122150337.tif

300x240 pixels; RGB; 281K



MRIII_Slices	Grain Diameter (um)
85	1500
78	400
65	50

List | Copy | Log | **Live** | RGB | value=9.492
count=356



Distance (um)	Count (raw)	Count (binned)	Count (raw)	Count (binned)	Count (raw)	Count (binned)
0-10	12	12	12	12	12	12
10-20	12	12	12	12	12	12
20-30	12	12	12	12	12	12
30-40	12	12	12	12	12	12
40-50	12	12	12	12	12	12
50-60	12	12	12	12	12	12
60-70	12	12	12	12	12	12
70-80	12	12	12	12	12	12
80-90	12	12	12	12	12	12
90-100	12	12	12	12	12	12
100-110	12	12	12	12	12	12
110-120	12	12	12	12	12	12
120-130	12	12	12	12	12	12
130-140	12	12	12	12	12	12
140-150	12	12	12	12	12	12
150-160	12	12	12	12	12	12
160-170	12	12	12	12	12	12
170-180	12	12	12	12	12	12
180-190	12	12	12	12	12	12
190-200	12	12	12	12	12	12
200-210	12	12	12	12	12	12
210-220	12	12	12	12	12	12
220-230	12	12	12	12	12	12
230-240	12	12	12	12	12	12
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360-370	12	12	12	12	12	12
370-380	12	12	12	12	12	12
380-390	12	12	12	12	12	12
390-400	12	12	12	12	12	12
400-410	12	12	12	12	12	12
410-420	12	12	12	12	12	12
420-430	12	12	12	12	12	12
430-440	12	12	12	12	12	12
440-450	12	12	12	12	12	12
450-460	12	12	12	12	12	12
460-470	12	12	12	12	12	12
470-480	12	12	12	12	12	12
480-490	12	12	12	12	12	12
490-500	12	12	12	12	12	12
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510-520	12	12	12	12	12	12
520-530	12	12	12	12	12	12
530-540	12	12	12	12	12	12
540-550	12	12	12	12	12	12
550-560	12	12	12	12	12	12
560-570	12	12	12	12	12	12
570-580	12	12	12	12	12	12
580-590	12	12	12	12	12	12
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630-640	12	12	12	12	12	12
640-650	12	12	12	12	12	12
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660-670	12	12	12	12	12	12
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690-700	12	12	12	12	12	12
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710-720	12	12	12	12	12	12
720-730	12	12	12	12	12	12
730-740	12	12	12	12	12	12
740-750	12	12	12	12	12	12
750-760	12	12	12	12	12	12
760-770	12	12	12	12	12	12
770-780	12	12	12	12	12	12
780-790	12	12	12	12	12	12
790-800	12	12	12	12	12	12
800-810	12	12	12	12	12	12
810-820	12	12	12	12	12	12
820-830	12	12	12	12	12	12
830-840	12	12	12	12	12	12
840-850	12	12	12	12	12	12
850-860	12	12	12	12	12	12
860-870	12	12	12	12	12	12
870-880	12	12	12	12	12	12
880-890	12	12	12	12	12	12
890-900	12	12	12	12	12	12
900-910	12	12	12	12	12	12
910-920	12	12	12	12	12	12
920-930	12	12	12	12	12	12
930-940	12	12	12	12	12	12
940-950	12	12	12	12	12	12
950-960	12	12	12	12	12	12
960-970	12	12	12	12	12	12
970-980	12	12	12	12	12	12
980-990	12	12	12	12	12	12
990-1000	12	12	12	12	12	12

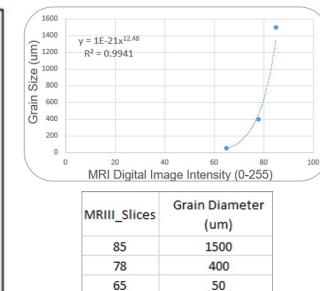
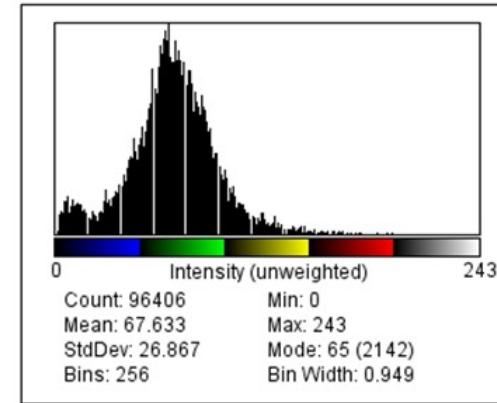
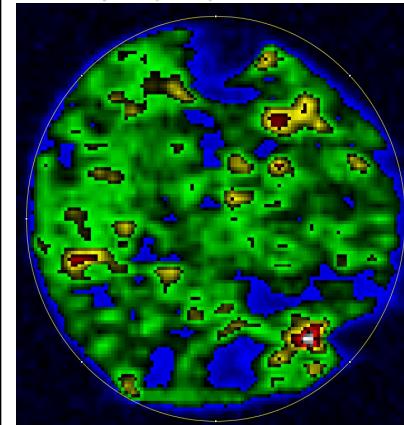
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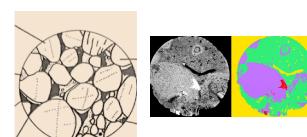
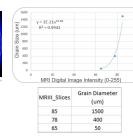
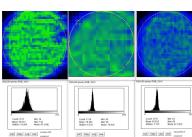
3D Permeability Equations and MRIII Model Validation

Histogram of MRI_plug9_Saturated_3500um_20190122150337.tif

300x240 pixels; RGB; 281K



MRII_Slice from plug 9	Drain Diameter calculated from Chart	Permeability (mD) from K_Omar2019	Core Permeability
67.6	68.82	129.07	126

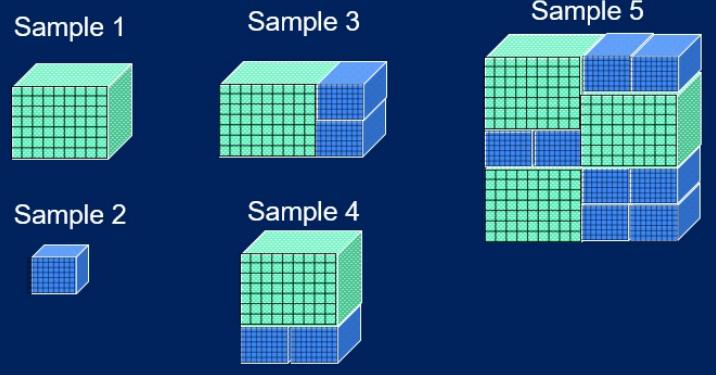


Dataset	Core Permeability	Grain Radius (μm)	Grain Radius (μm) and Water Saturation (%)	Grain Radius (μm) and Water Saturation (%) and Depth (m)	Grain Radius (μm) and Water Saturation (%) and Depth (m) and Experimental Permeability (mD)
85	1500	1500	1500	1500	1500
78	400	400	400	400	400
65	50	50	50	50	50

Journal Paper due for submission:

O. Al-Farisi^{1,2,3*}, A. Raza¹, H. Zhang¹, H. Li¹, D. Ozzane^{4,5}, M. Sassi¹, T. Zhang¹, (2019) Decoding heterogeneity by 3D-vision machine learning reveals Cretaceous permeability.

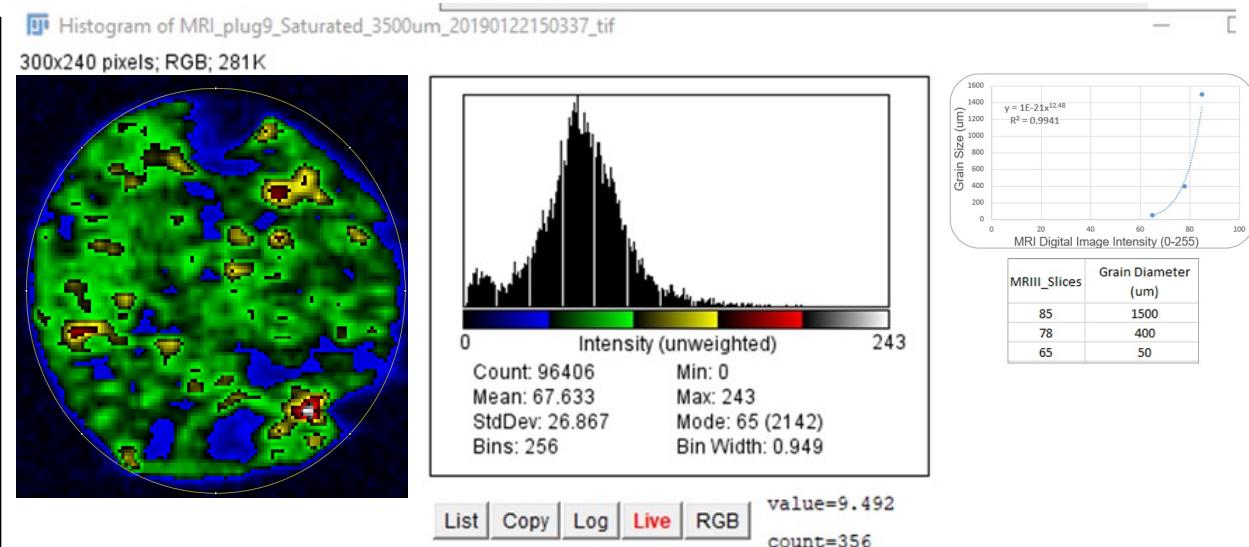
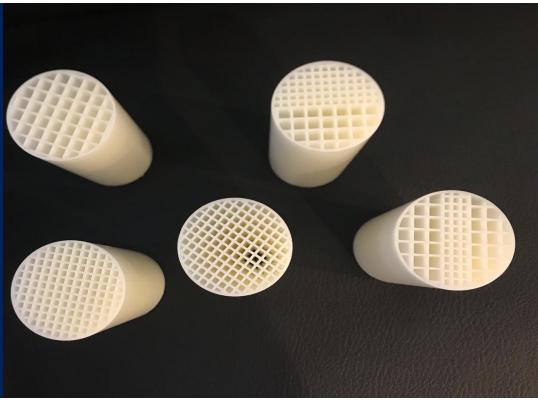
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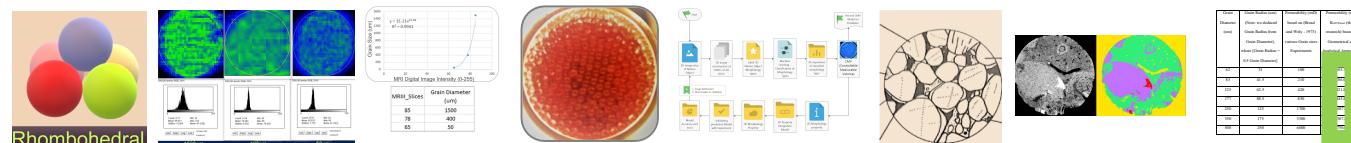
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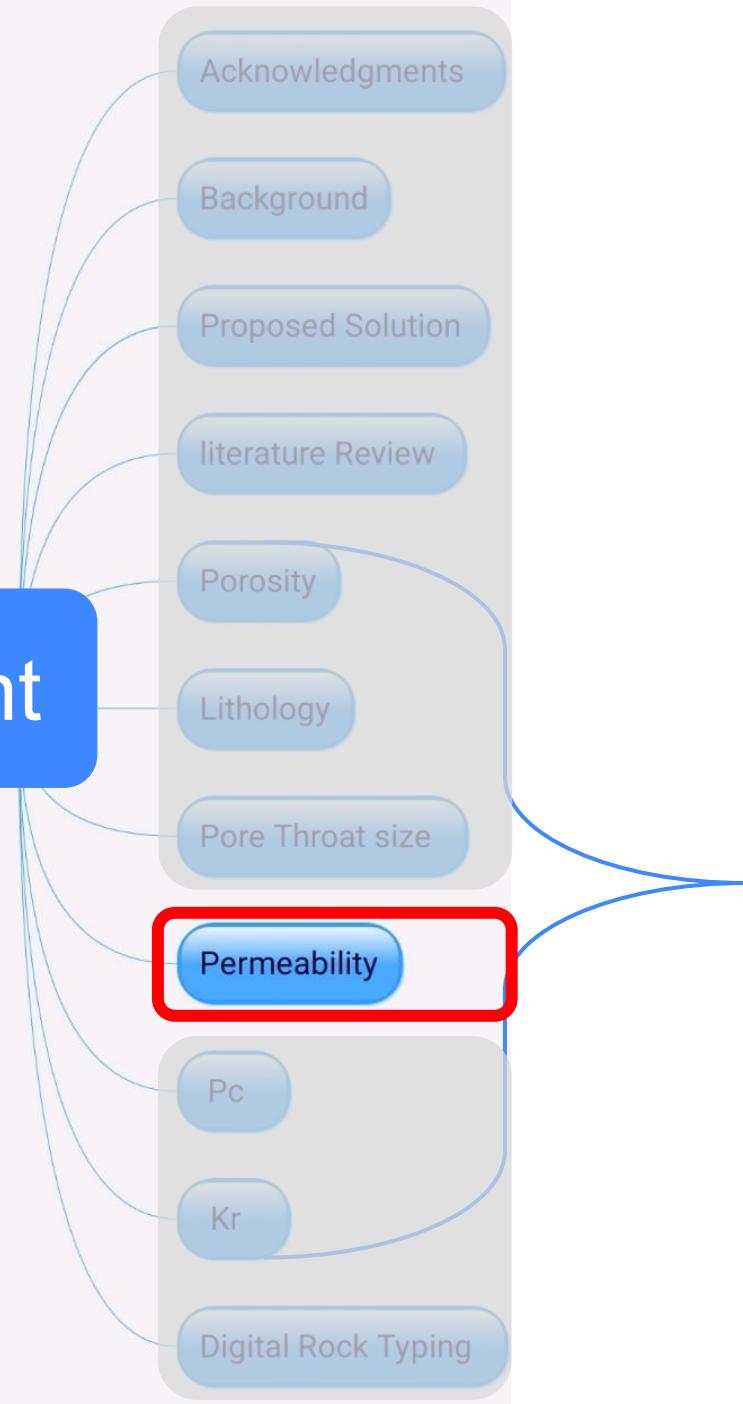


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Content



Machine
Learning
3D Image
Recognition



Content

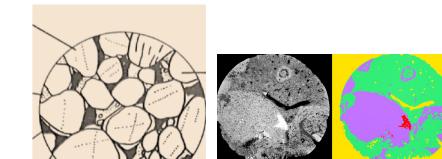
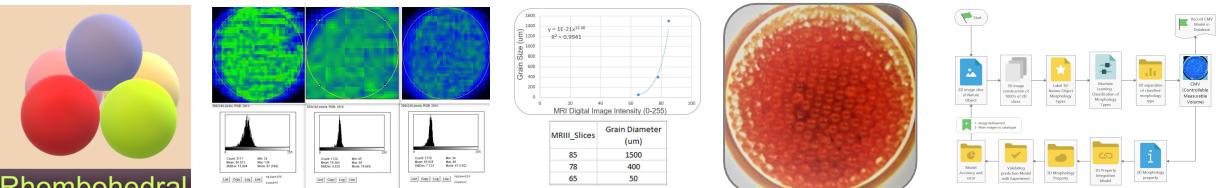
Acknowledgments
Background
Proposed Solution
literature Review
Porosity
Lithology
Pore Throat size
Permeability
Pc
Kr
Digital Rock Typing

**Machine
Learning
3D Image
Recognition**

Pc (Capillarity) - Machine Learning Heterogenous Morphology

$$P_c = \frac{2 \sigma \cos\theta}{r} \quad (1)$$

Where; r is the pore throat radius, which we also denote r_{PorTh} ,
 σ is Interfacial Tension,
 θ is the Contact Angle.



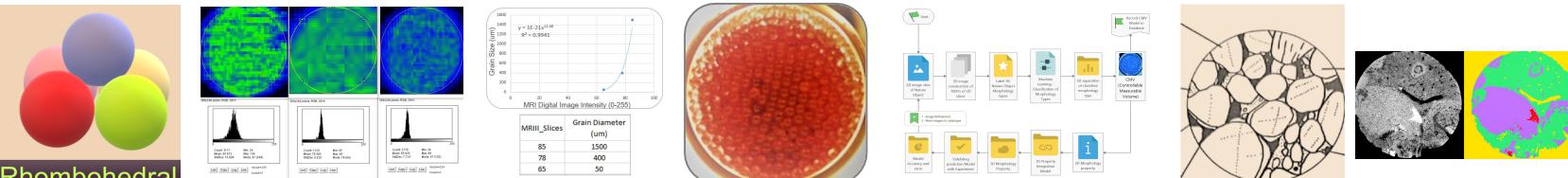
Alfarisi, O., Ouzzane, D., Sassi, M., & Zhang, T. (2021). The Understanding of Intertwined Physics: Discovering Capillary Pressure and Permeability Co-Determination. *arXiv preprint arXiv:2112.12784*.

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$$k_{3D_{rhombohedral}} = PorTS_{rhombohedral\ 3D\ Effective} = 0.0858r_g^2 \quad (2)$$



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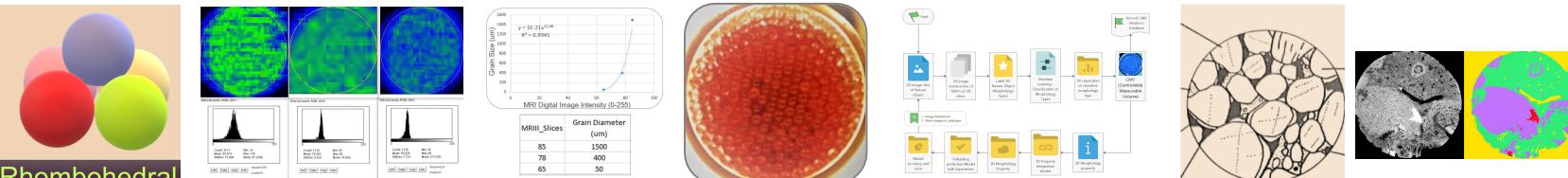
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$$k_{3D_{rhombohedral}} = PorTS_{rhombohedral}_{3D\ Effective} = 0.0858r_g^2 \quad (2)$$

$$k_{3D_{rhombohedral}} = 0.02731\pi r_g^2 \quad (3)$$



Alfarisi, O., Ouzzane, D., Sassi, M., & Zhang, T. (2021). The Understanding of Intertwined Physics: Discovering Capillary Pressure and Permeability Co-Determination. *arXiv preprint arXiv:2112.12784*.

Pc (Capillarity) - Machine Learning Heterogenous Morphology

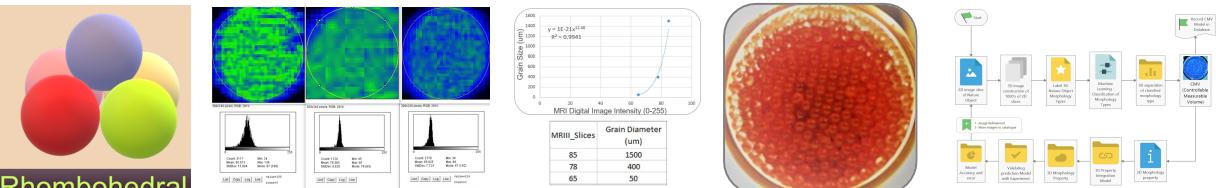
$$P_c = \frac{2 \sigma \cos\theta}{r} \quad (1)$$

Where; r is the pore throat radius, which we also denote r_{PorTh} ,
 σ is Interfacial Tension,
 θ is the Contact Angle.

$$k_{3D_{rhombohedral}} = PorTS_{rhombohedral3DEffective} = 0.0858r_g^2 \quad (2)$$

$$k_{3D_{rhombohedral}} = 0.02731\pi r_g^2 \quad (3)$$

$$\pi r_{PorTh}^2 = 0.027311\pi r_g^2 \quad (4)$$



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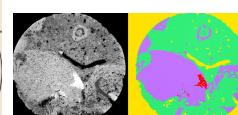
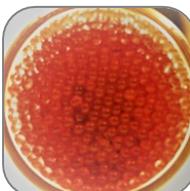
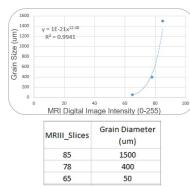
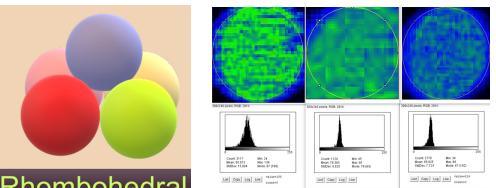
$$r_{PorTh} = 0.027311 r_g \quad (5)$$

Also,

$$r_{PorTh}^2 = 0.027311 r_g^2 = \left(\frac{1}{36.615283}\right) r_g^2 \quad (6)$$

Then by substituting Eq. 6 in Eq. 2, we get Eq. 7 below:

$$k_{3D_{rhombohedral}} = (0.0858) \cdot (36.615283) r_{PorTh}^2 = 3.14159 r_{PorTh}^2 \quad (7)$$



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Pc (Capillarity) - Machine Learning Heterogenous Morphology

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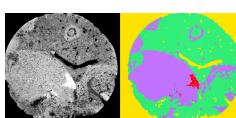
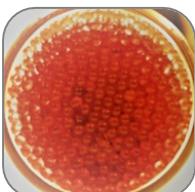
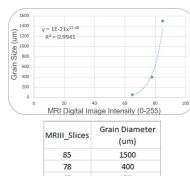
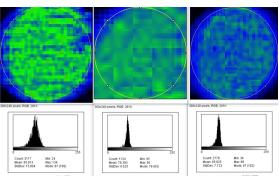
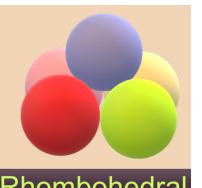
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$$k_{3D_{rhombohedral}} = \pi r_{PorTh}^2 \quad (8)$$

Also, we write Eq. 8 for r_{PorTh} to be as shown in Eq. 9:

$$r_{PorTh} = \sqrt{\frac{k_{3D_{rhombohedral}}}{\pi}} \quad (9)$$



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Pc (Capillarity) - Machine Learning Heterogenous Morphology

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$$(5)$$

We can now substitute the value 3.14159 in Eq. 7 with $\sim\pi$ to have the following equation:

$$k_{3D_{rhombohedral}} = \pi r_{PorTh}^2 \quad (8)$$

$$(5)$$

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Also,

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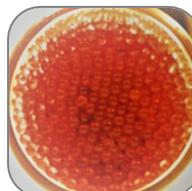
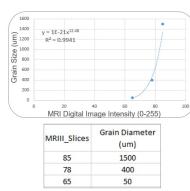
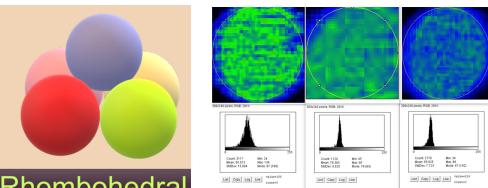
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Also, we write Eq. 8 for r_{PorTh} to be as shown in Eq. 9:

$$r_{PorTh} = \sqrt{\frac{k_{3D_{rhombohedral}}}{\pi}} \quad (9)$$

$$P_{cd} = 2 \frac{\sigma \cos(\theta)}{\sqrt{\frac{k_{3D_{rhombohedral}}}{\pi}}} \quad (P\text{-Function or 10})$$



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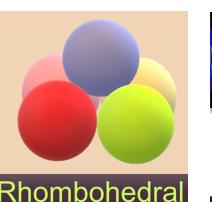
Pc (Capillarity) - Machine Learning Heterogenous Morphology

Reference r_Grain (um) Experiment	Derived r_PorTh (um) using r_PorThN-MorphologyDecoder	Reference Experimental Permeability (mD)	K_3DRhombohedral (mD) using r_Grain	K_3DRhombohedral (mD)_using r_PorTh	pc_P-Function (psi) for Hg/air	Reference Pc (psi) for Hg/air
31	5.77	100.00	103.79	104.75	9.69	
41.5	7.73	210.00	186.00	187.73	7.24	
62.5	11.64	420.00	421.88	425.78	4.80	
88.5	16.48	830.00	845.88	853.72	3.39	
125	23.28	1700.00	1687.50	1703.13	2.40	
175	32.60	3300.00	3307.50	3338.13	1.72	
250	46.57	6600.00	6750.00	6812.51	1.20	
			1000	3.14		
			500	4.43		
			400	4.96		
			396	4.98	5.01	
			250	6.27		
			200	7.01		
			150	8.10		
			100	9.91		
			80	11.08		
			60	12.80		
			55	13.37	12.52	
			40	15.68		
			30	18.10		
			20	22.17		
			11.6	29.11	30.85	
			10	31.35		
			8	35.05		
			5	44.34		
			3	57.24		
			1.4	83.79	87.04	
			1	99.15		
			0.5	140.21		
			0.1	313.53		

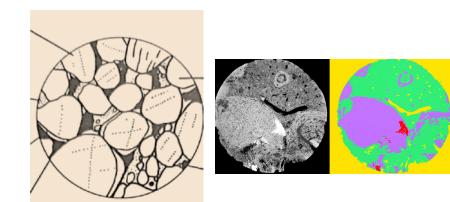
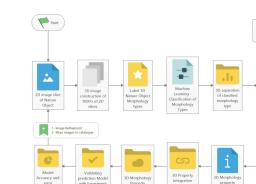
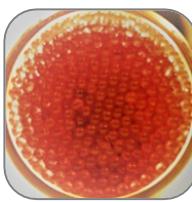
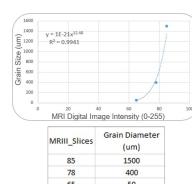
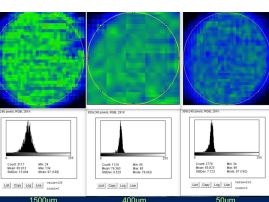
(P-Function or 10)

Legend		
Given Reference Parameter		
Our Research Derived equations and Calculation		
Establishing Catalog data		
Experimental Reference		
Converted to Reservoir Condition Field application		

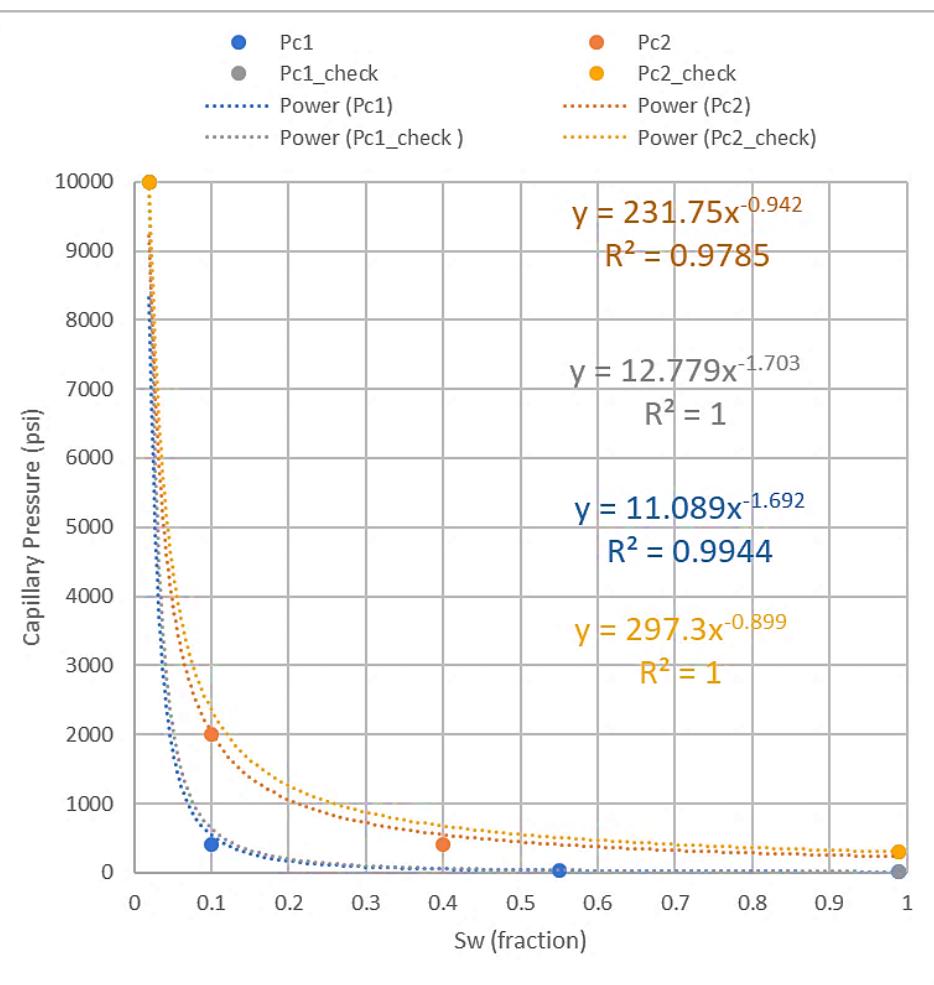
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Rhombohedral



Pc (Capillarity) - Machine Learning Heterogenous Morphology



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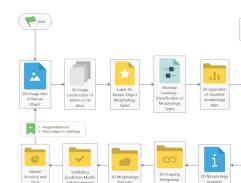
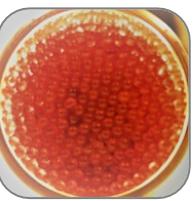
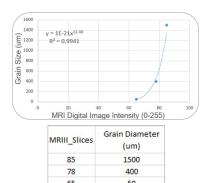
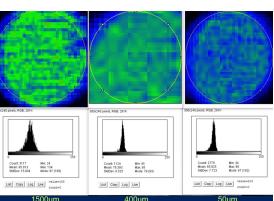
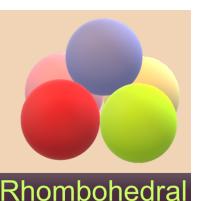
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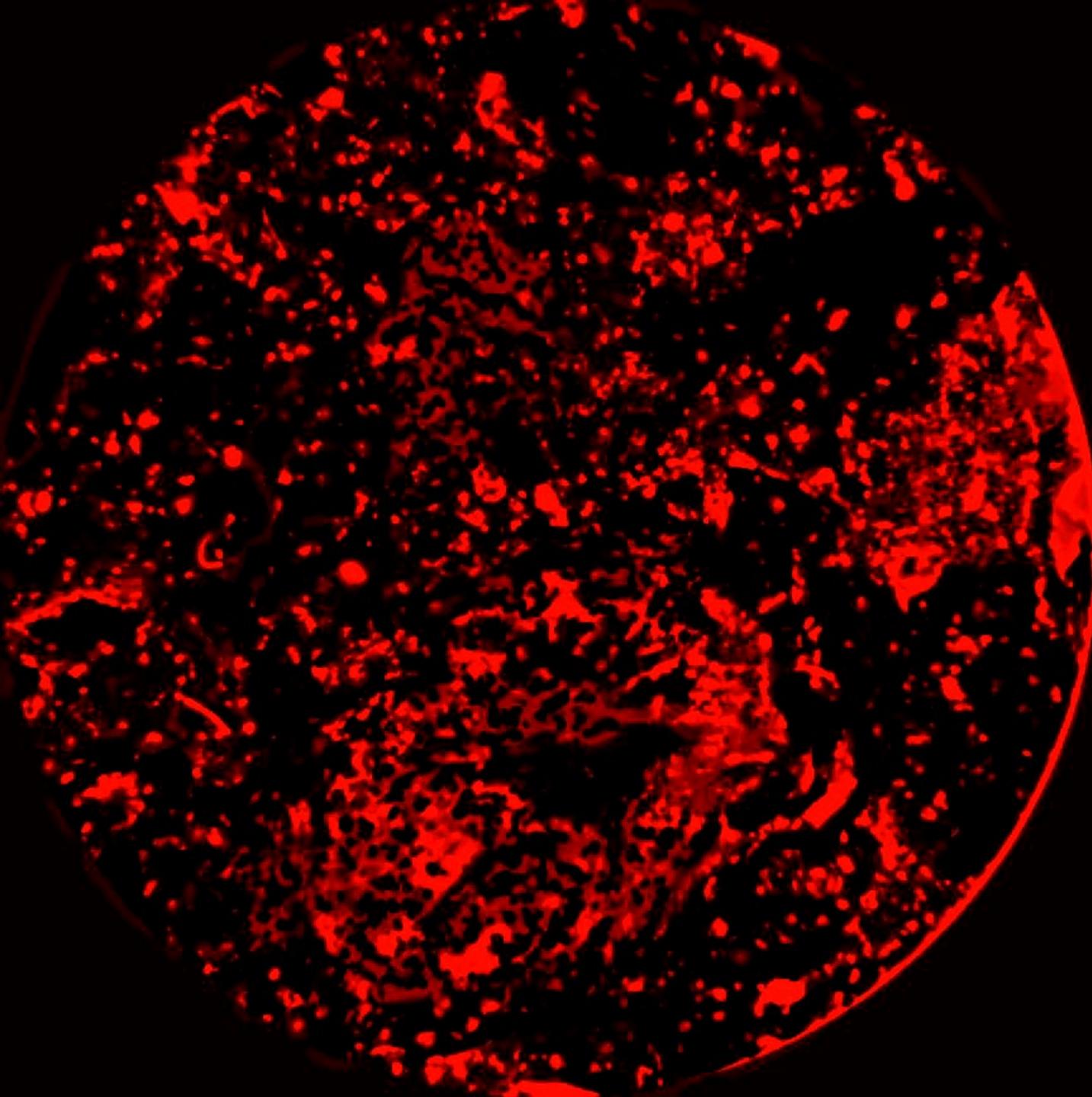
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(P-Function or 10)

Legend	
Given Reference Parameter	
Our Research Derived equations and Calculation	
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Thank you



Applying Machine Learning Image Recognition with on
Carbonate Rock uCT Image