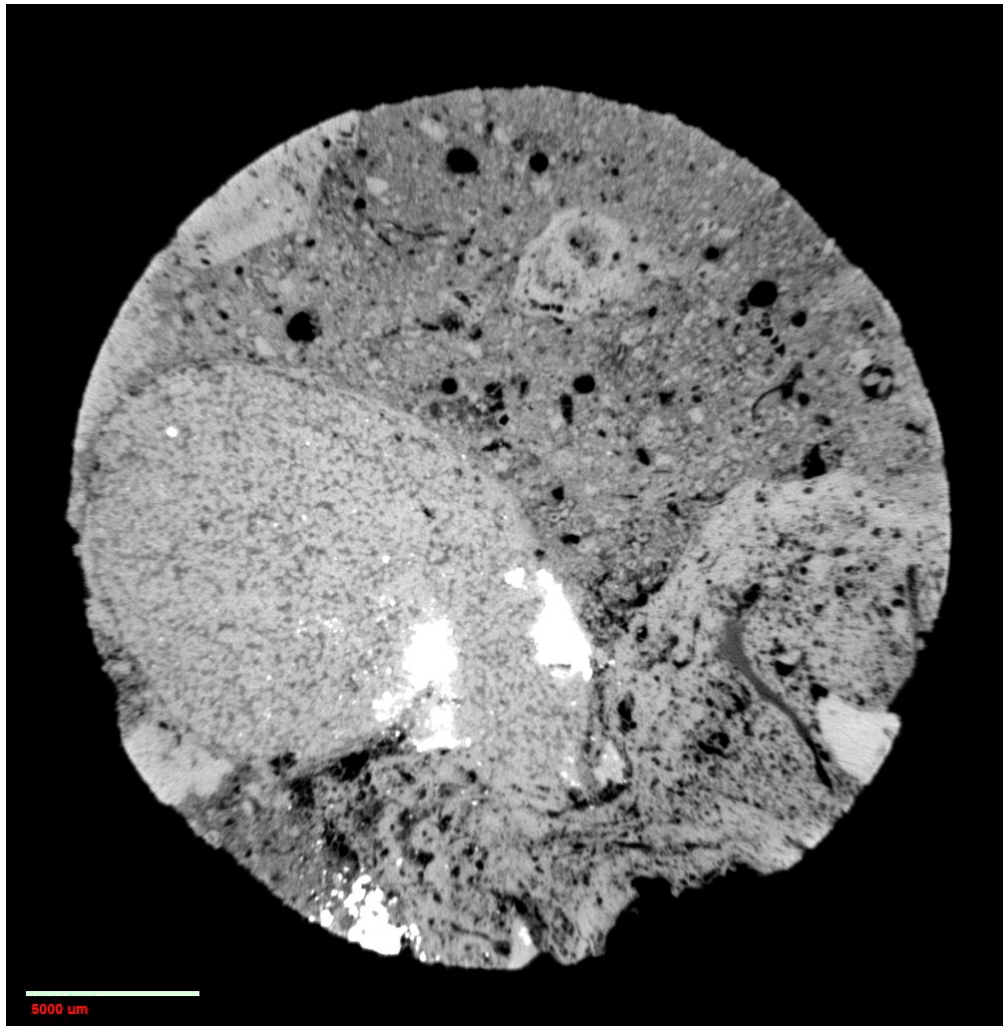


InterPore2022 Hybrid

Khalifa University

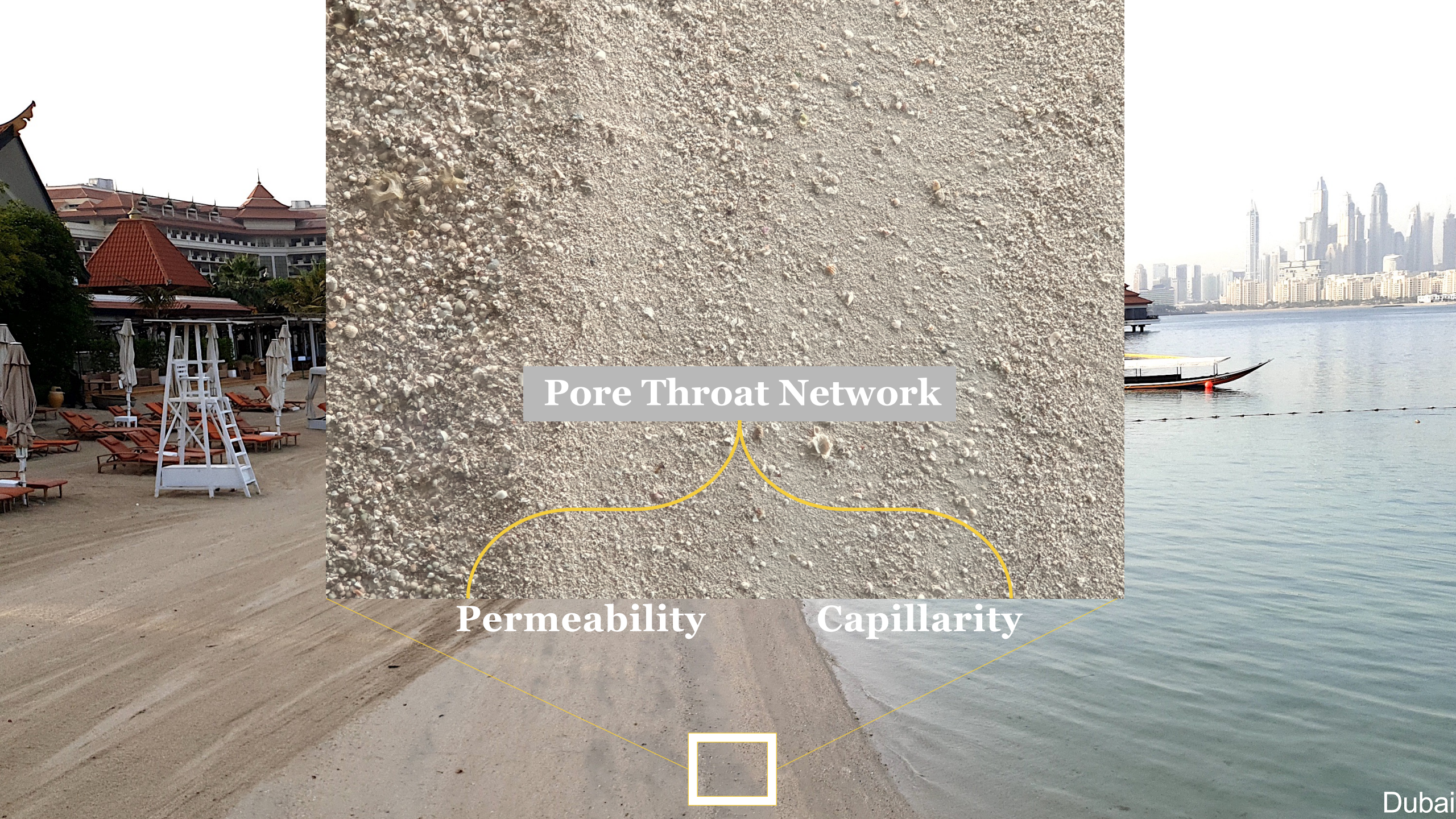
Morphology Decoder: Untangling Heterogeneous Porous Media Texture and Quantifying Permeability and Capillary Pressure by Semantic Segmentation

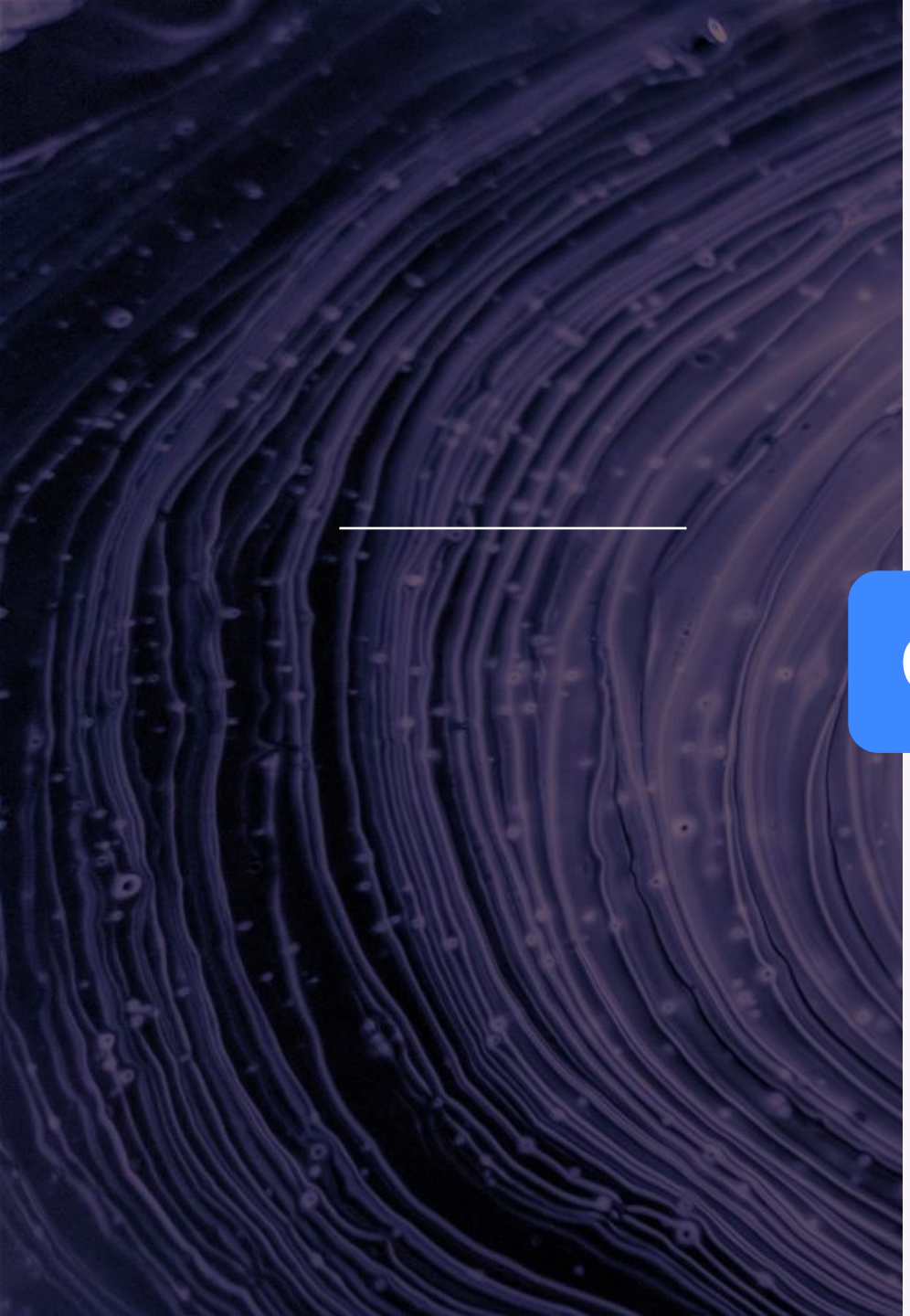
Dr. Omar Alfarisi

| 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 sandor or without water,
otherwise it would become **desert** or **sea**.
Dubai

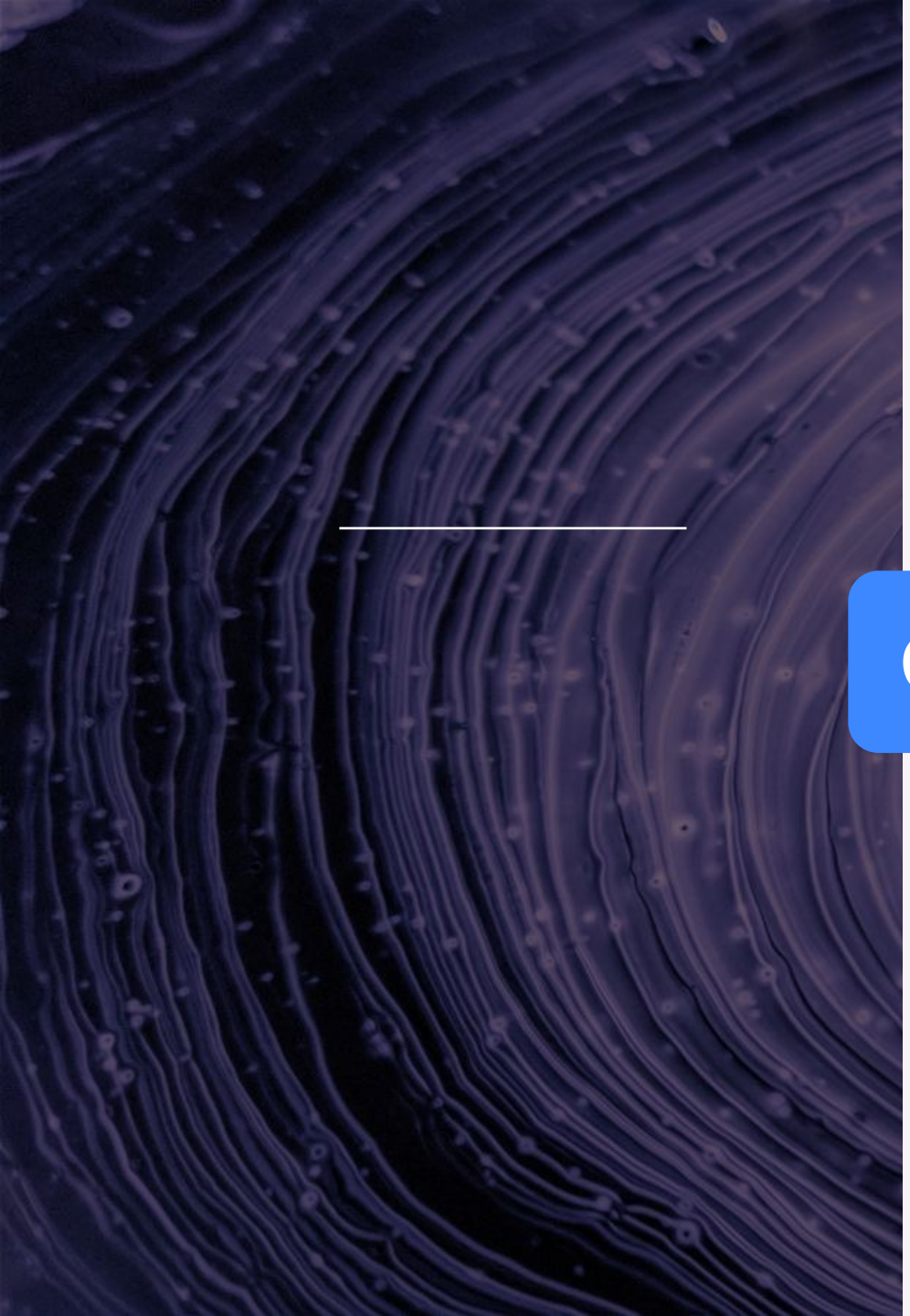

Permeability
Capillarity
Dubai


Pore Throat Network
Permeability
Capillarity
Dubai



Content

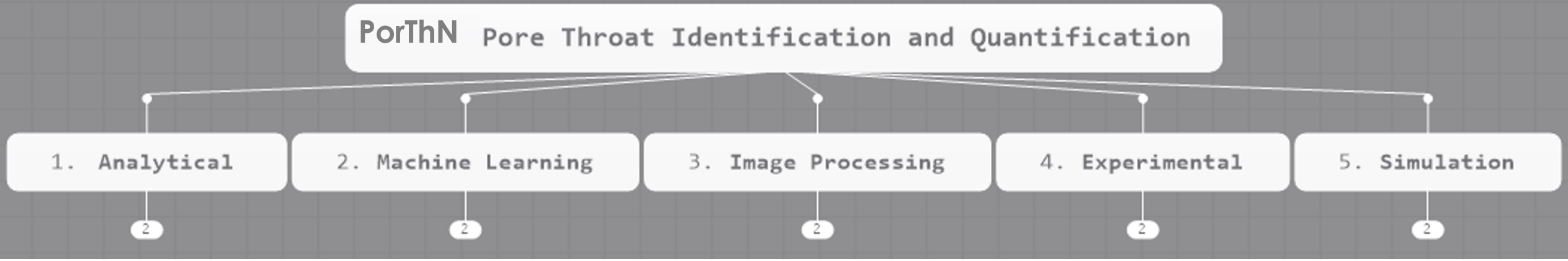
Machine Learning 3D Image Recognition



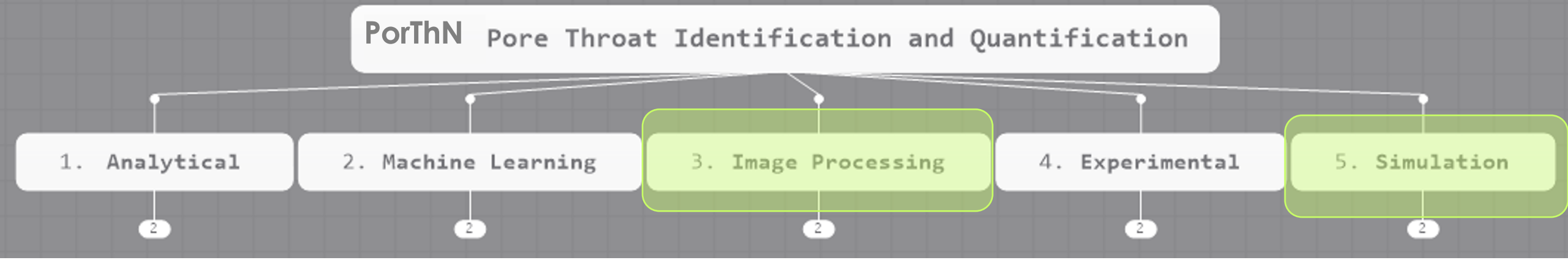
Content

Machine Learning 3D Image Recognition

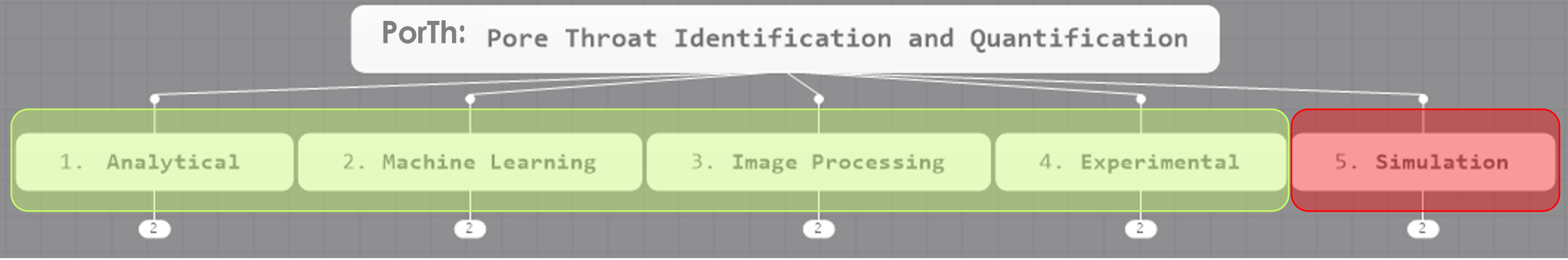
Research Options



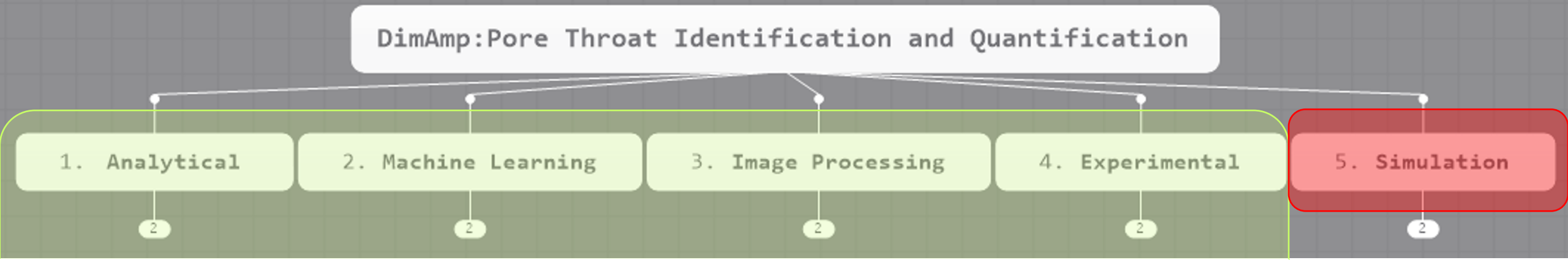
The Conventional Research Approach

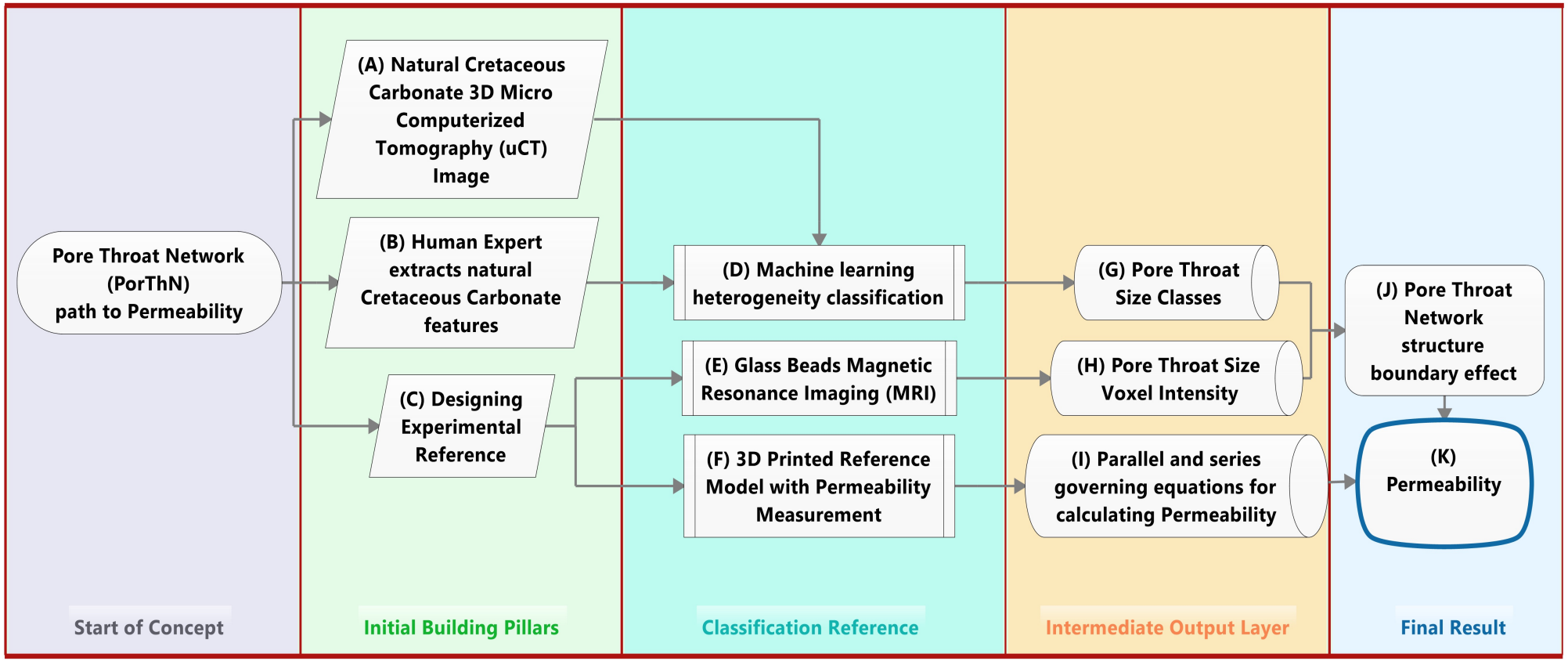


Novel - Morphology Decoder

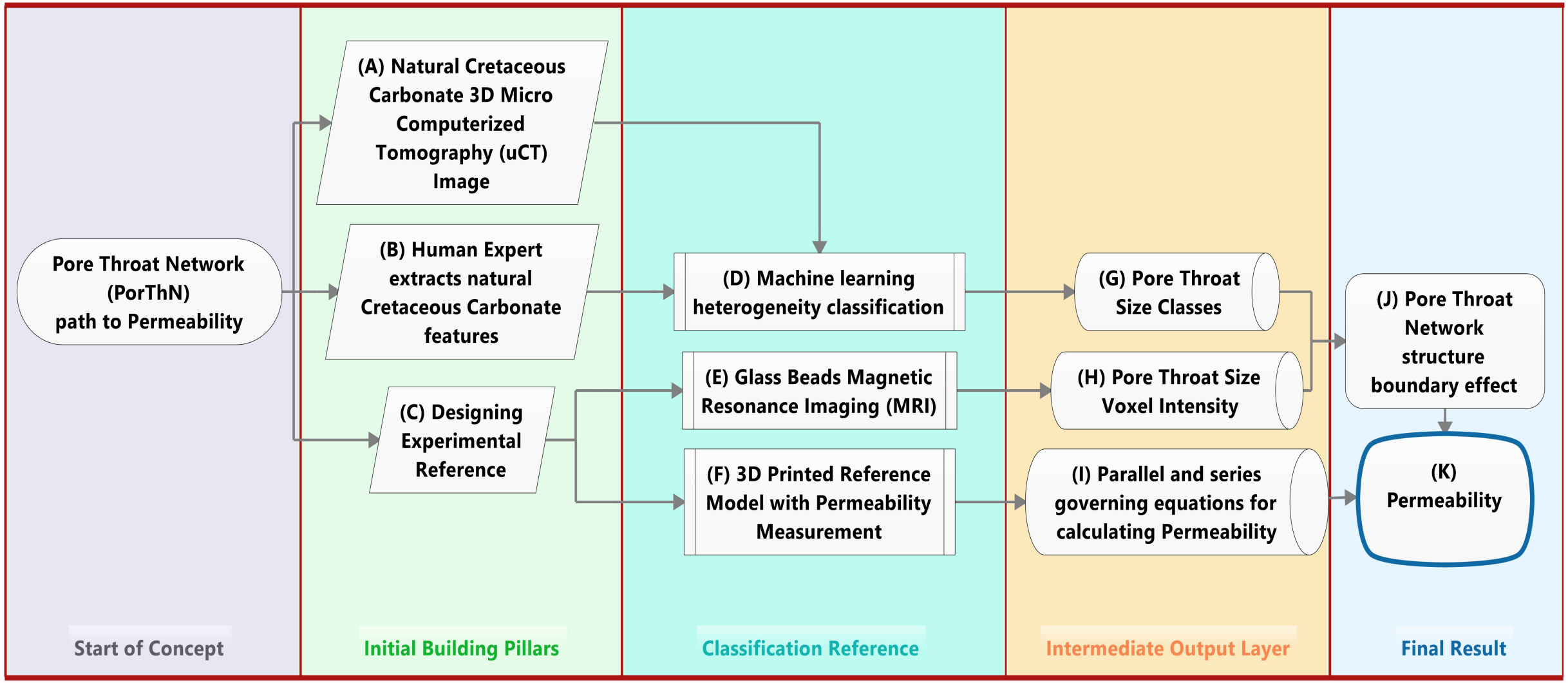


Research Options



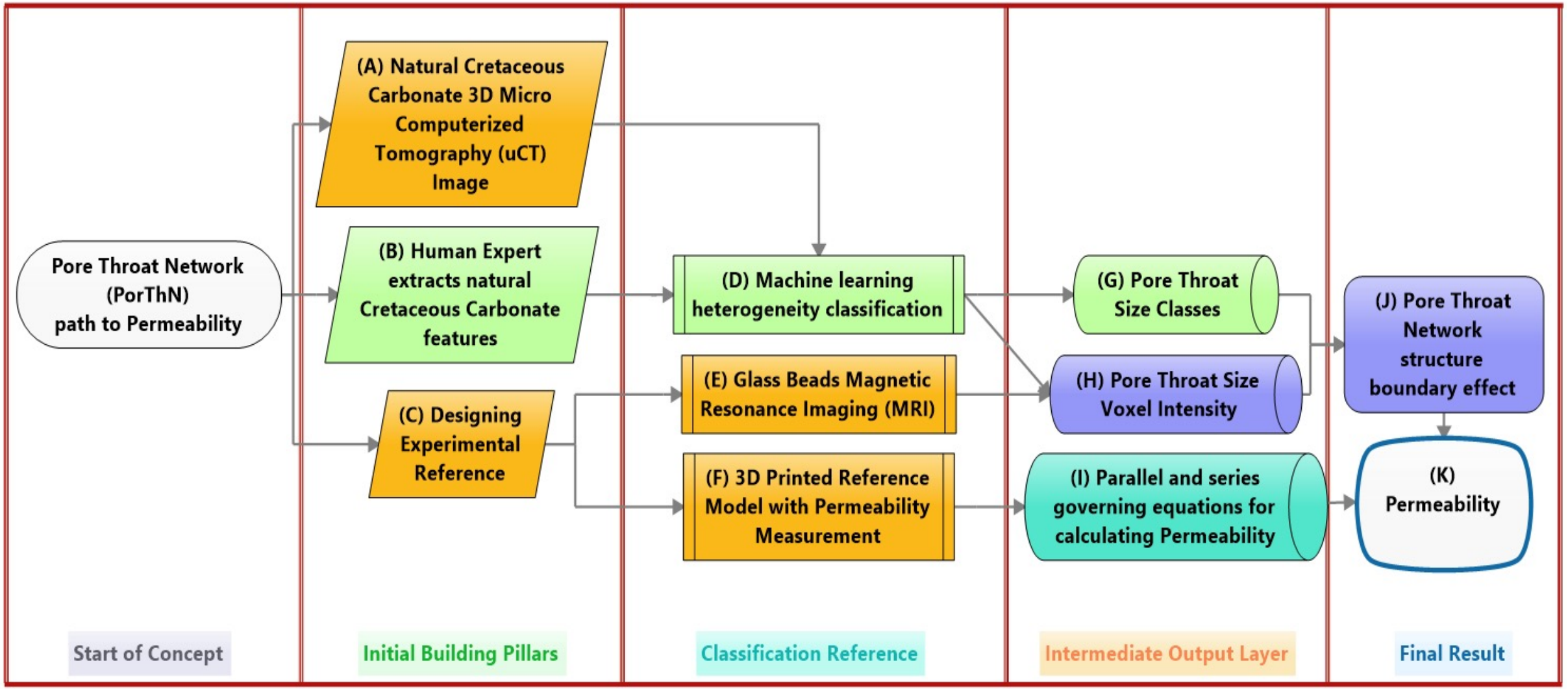


Pore Throat Network (PorThN) path to Permeability determination flow chart



Alfarisi, O., Raza, A., Ouzzane, D., Li, H., Sassi, M., & Zhang, T. (2021). Morphology Decoder: A Machine Learning Guided 3D Vision Quantifying Heterogenous Rock Permeability for Planetary Surveillance and Robotic Functions. *arXiv preprint arXiv:2111.13460*.

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



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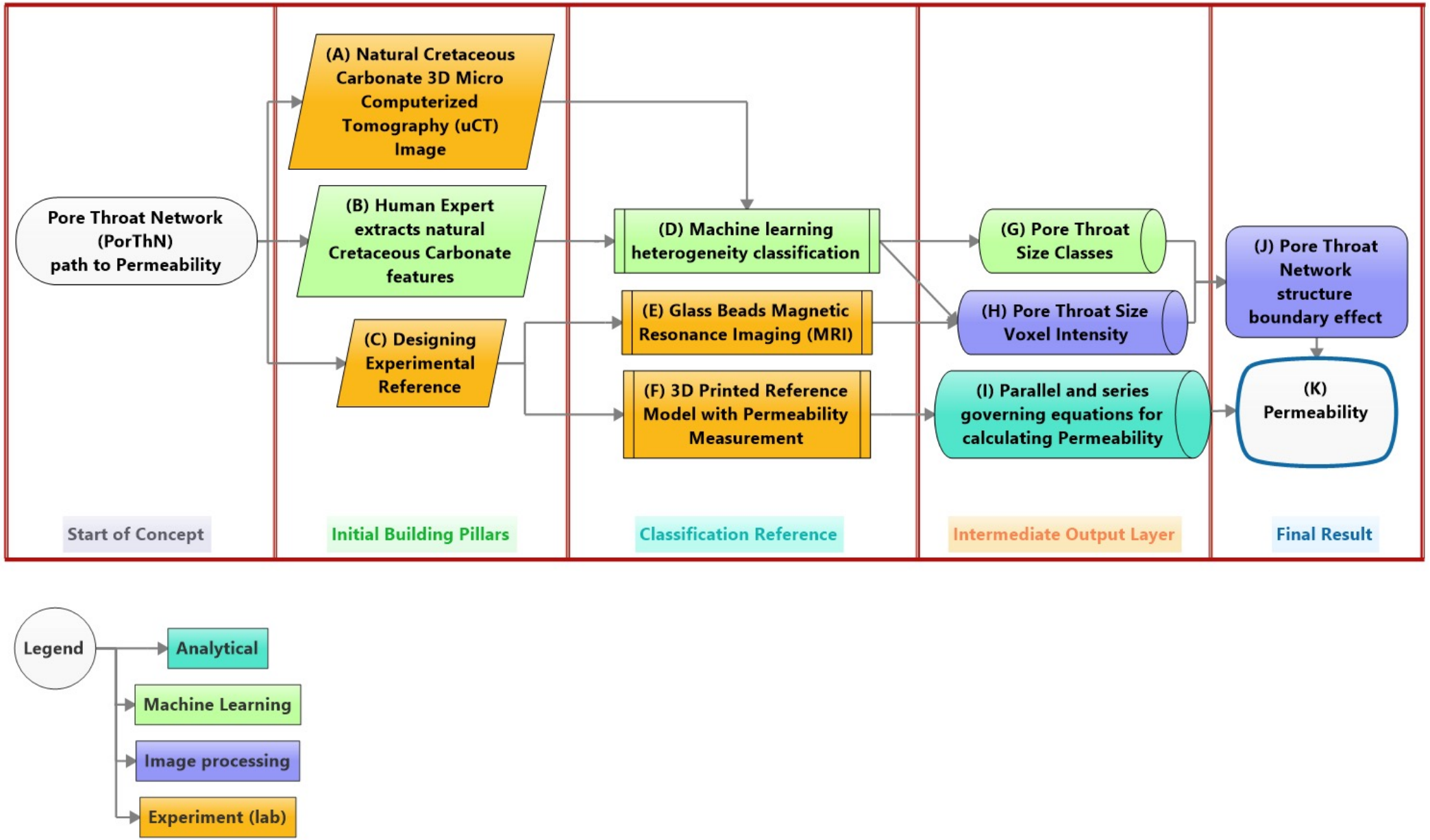
Pore Throat Network (PorThN) path to Permeability determination flow chart



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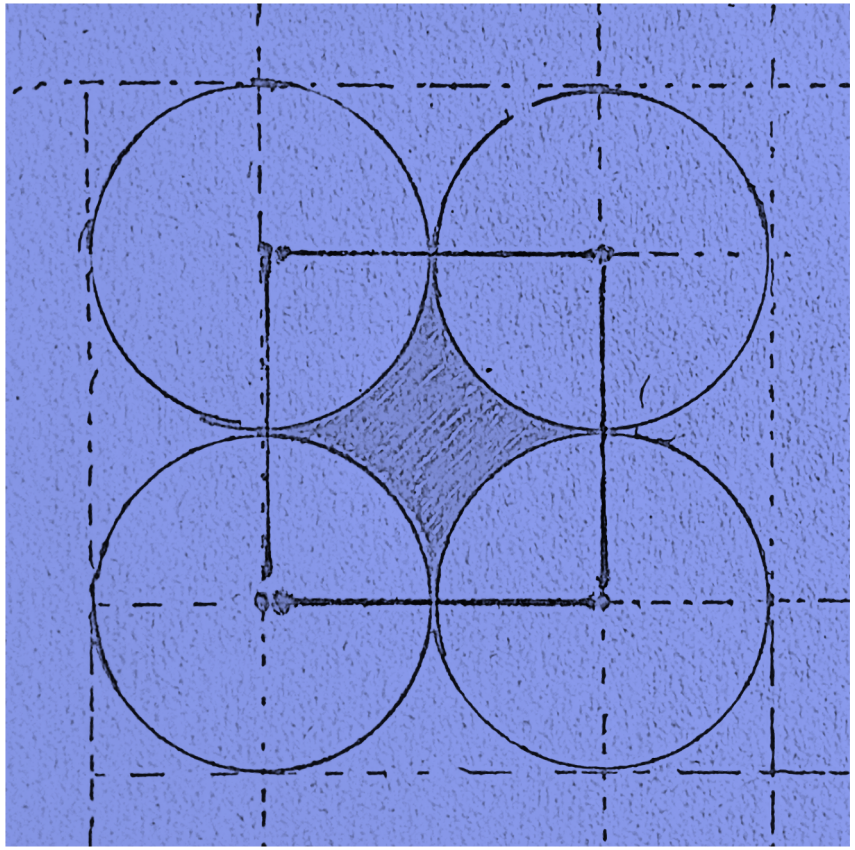
Geometrical Analysis



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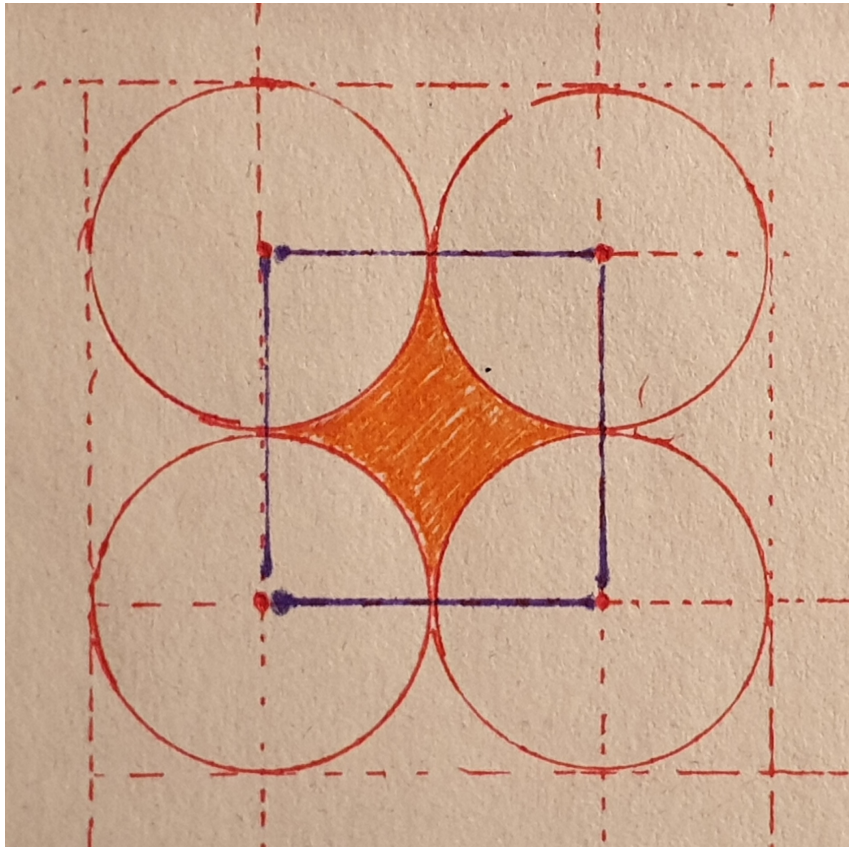
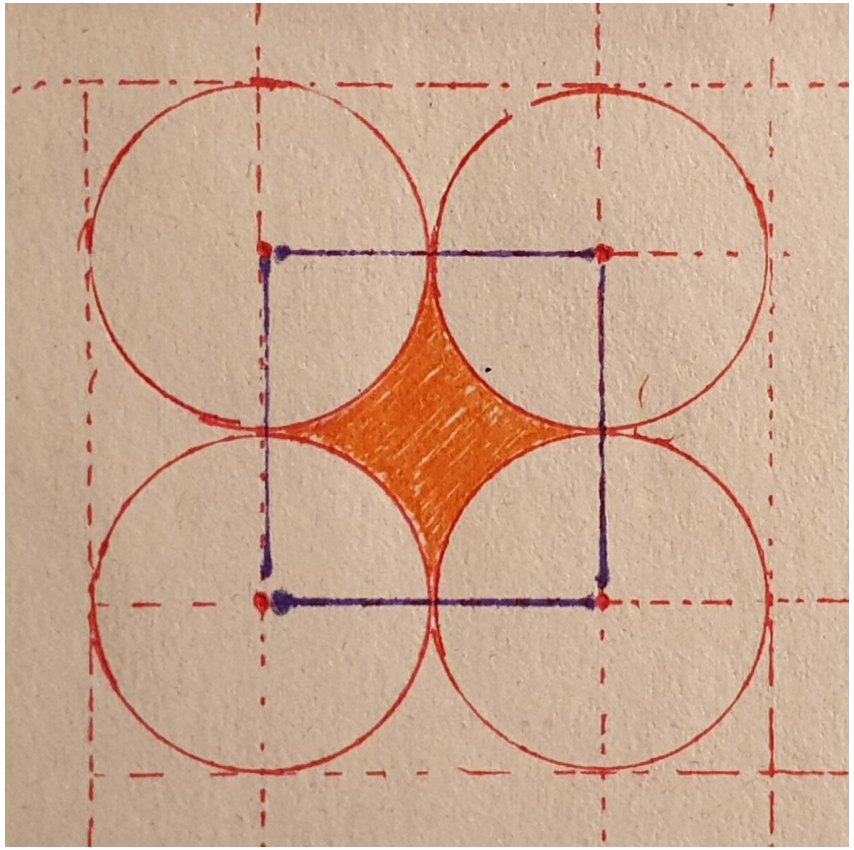
Geometrical Analysis



Geometrical Analysis

Axiom 0: Pore Throat has enclosure from all directions.



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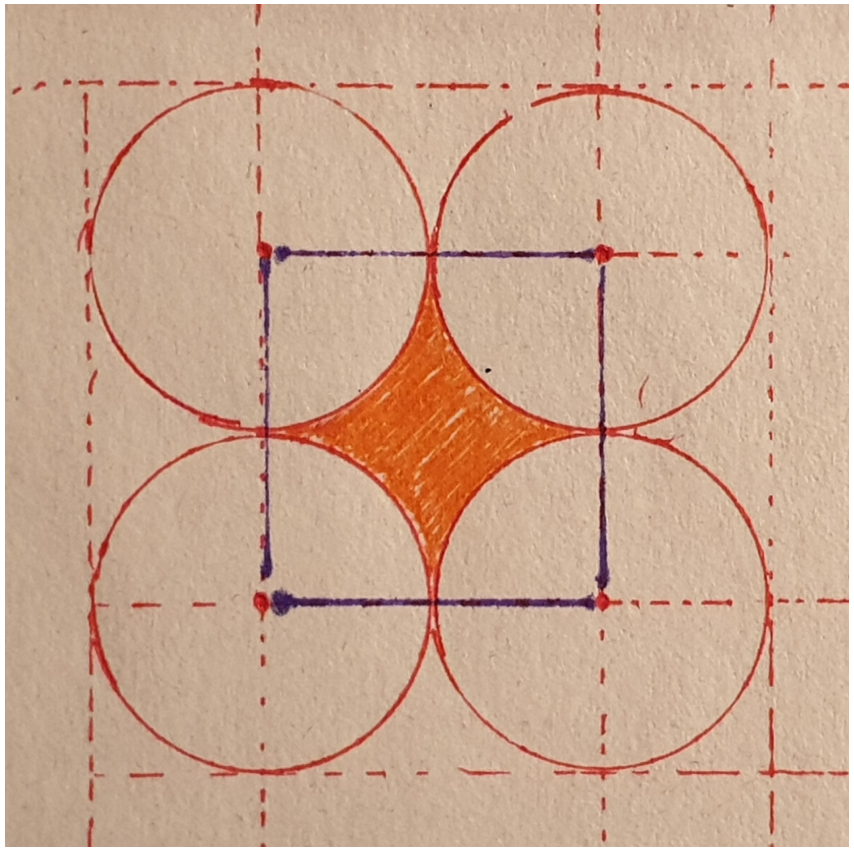
Geometrical Analysis

Axiom 0: Pore Throat has enclosure from all directions.

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

where r is the grain size



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Geometrical Analysis

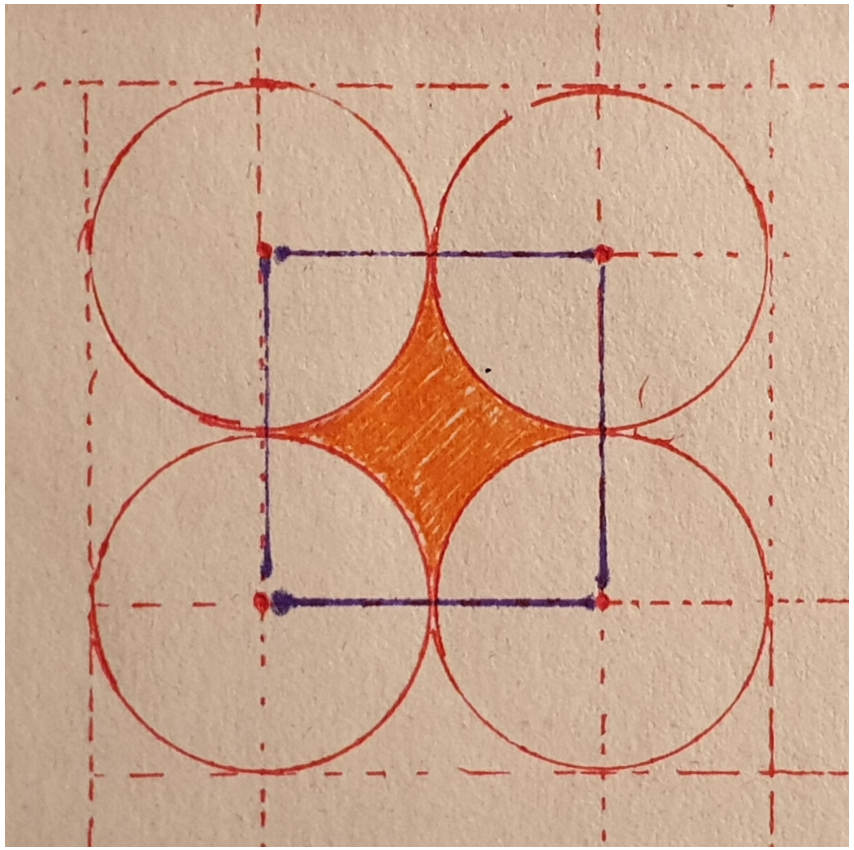
Axiom 0: Pore Throat has enclosure from all directions.

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

$$\text{Pore Throat Size} = \text{Small Square Area} - \text{Circle Area}$$

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

where r is the grain size



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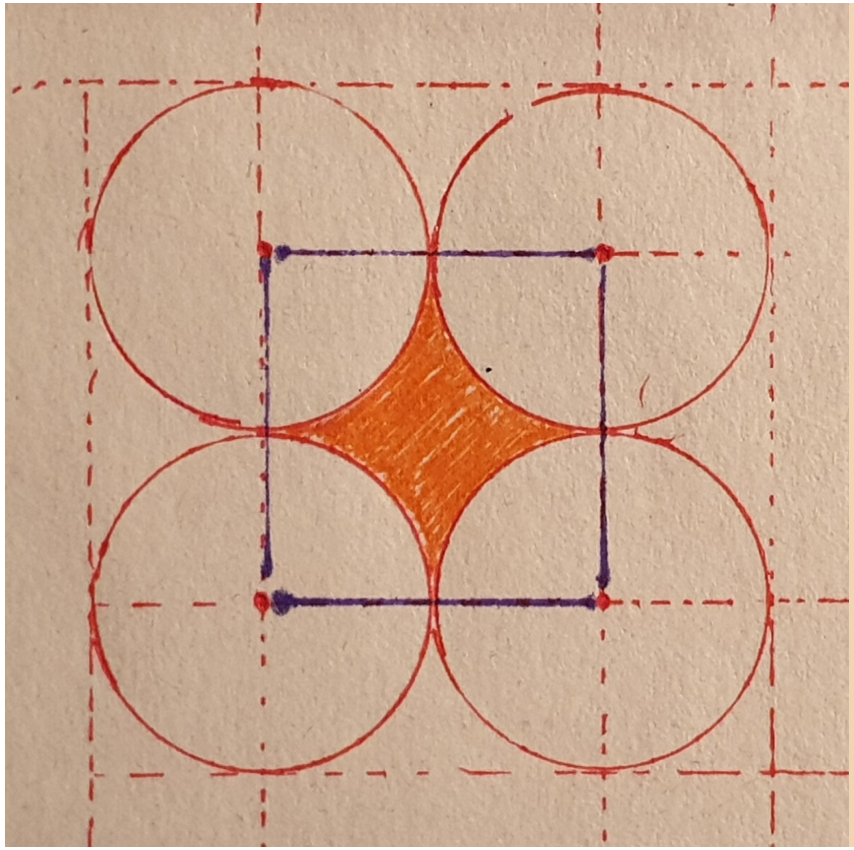
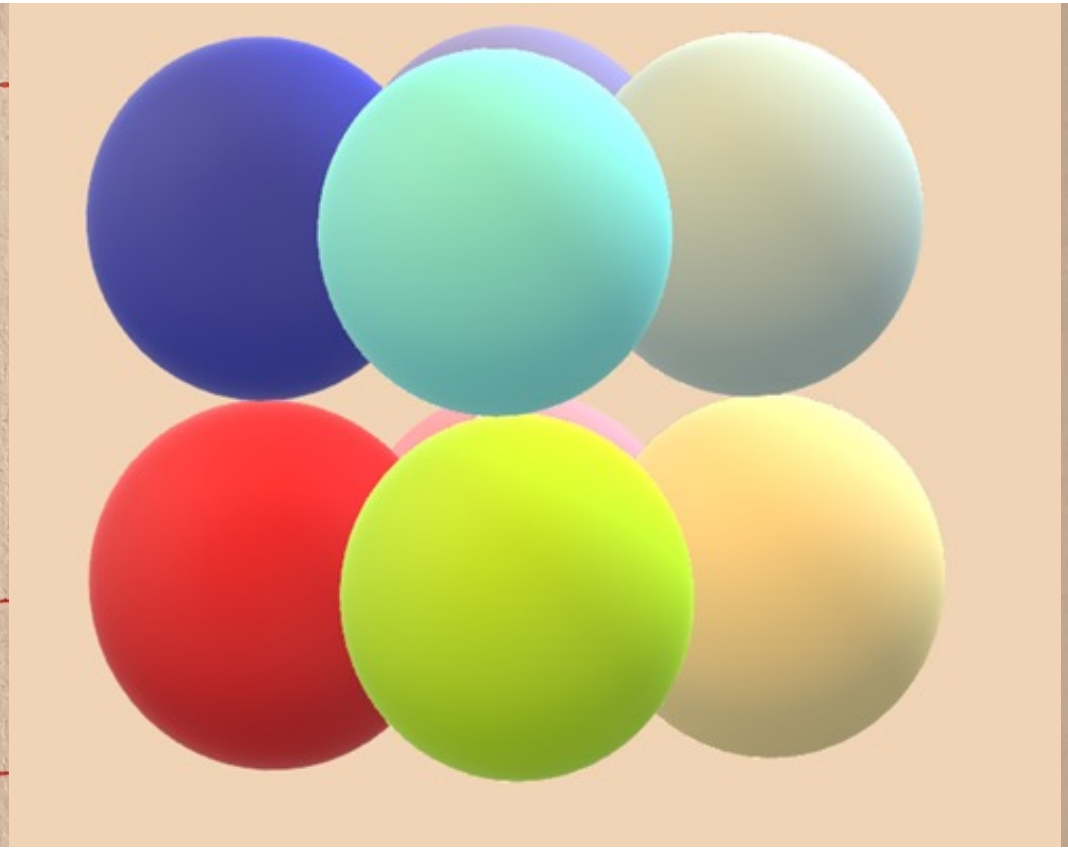
Geometrical Analysis

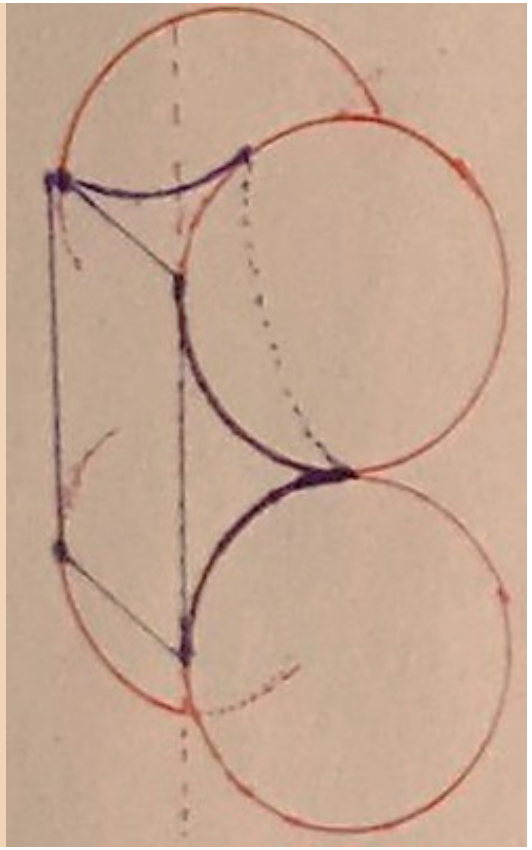
2D



3D Full pore



3D Half pore



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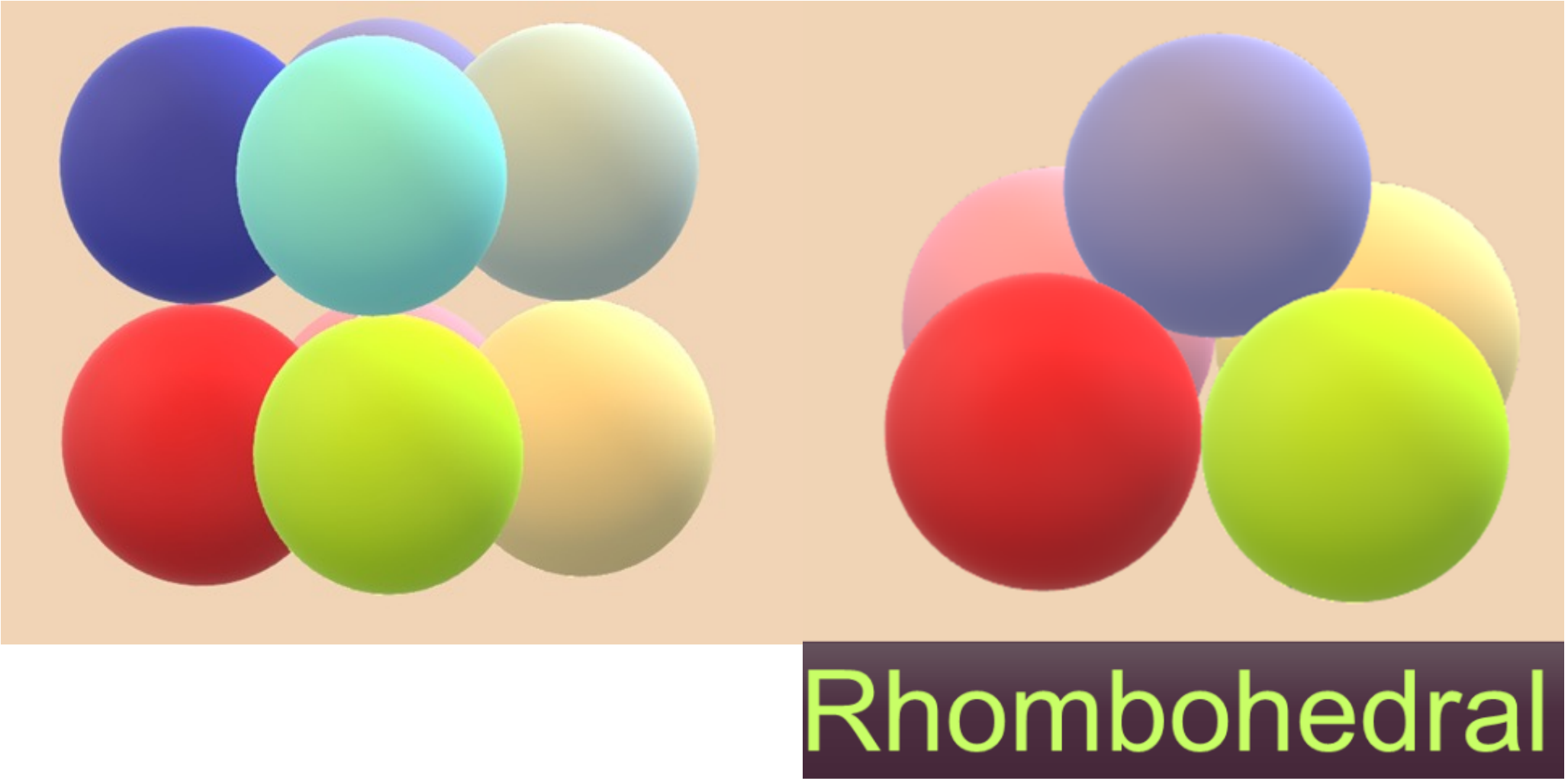
Geometrical Analysis

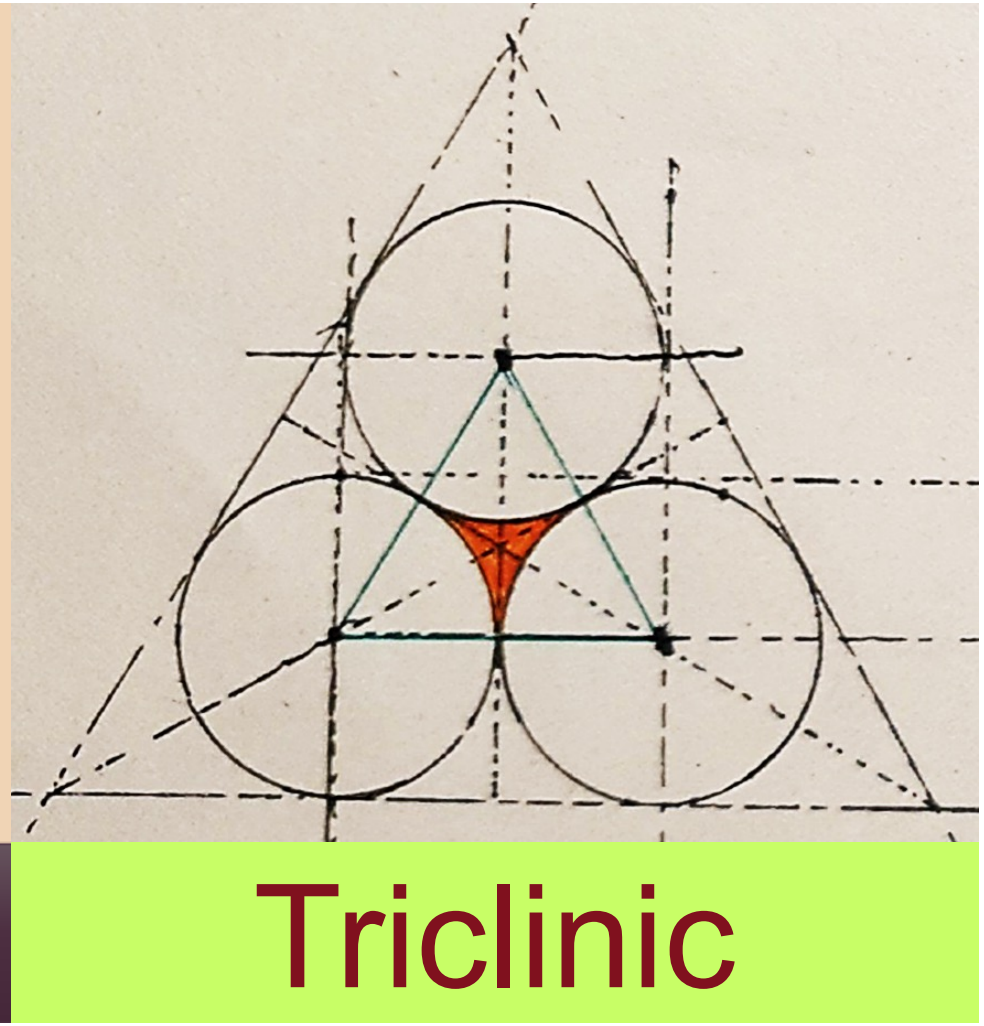
Natural Rock will be a form of below:



Serra, O. (1985). Sedimentary Environments from Wireline Logs, Schlumberger Technical Services Publication No. M-081030/SMP-7008.

Geometrical Analysis

We started with easier Configuration:



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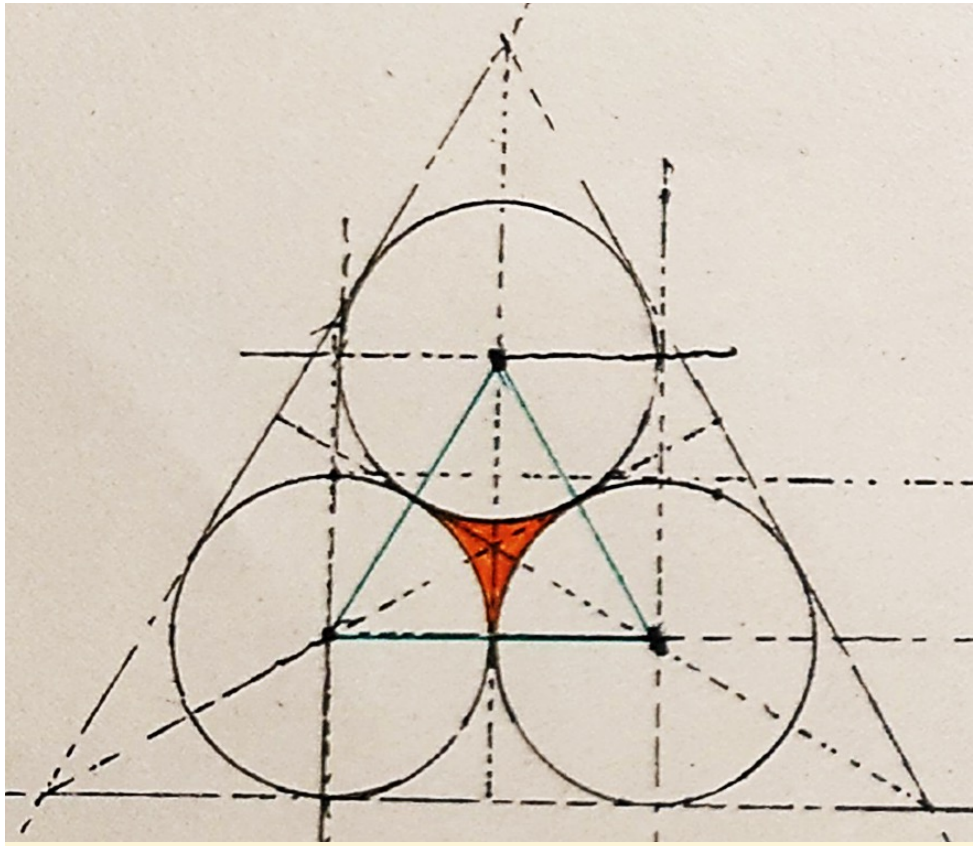
Geometrical Analysis

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

where r is the grain size

We started with easier Configuration:

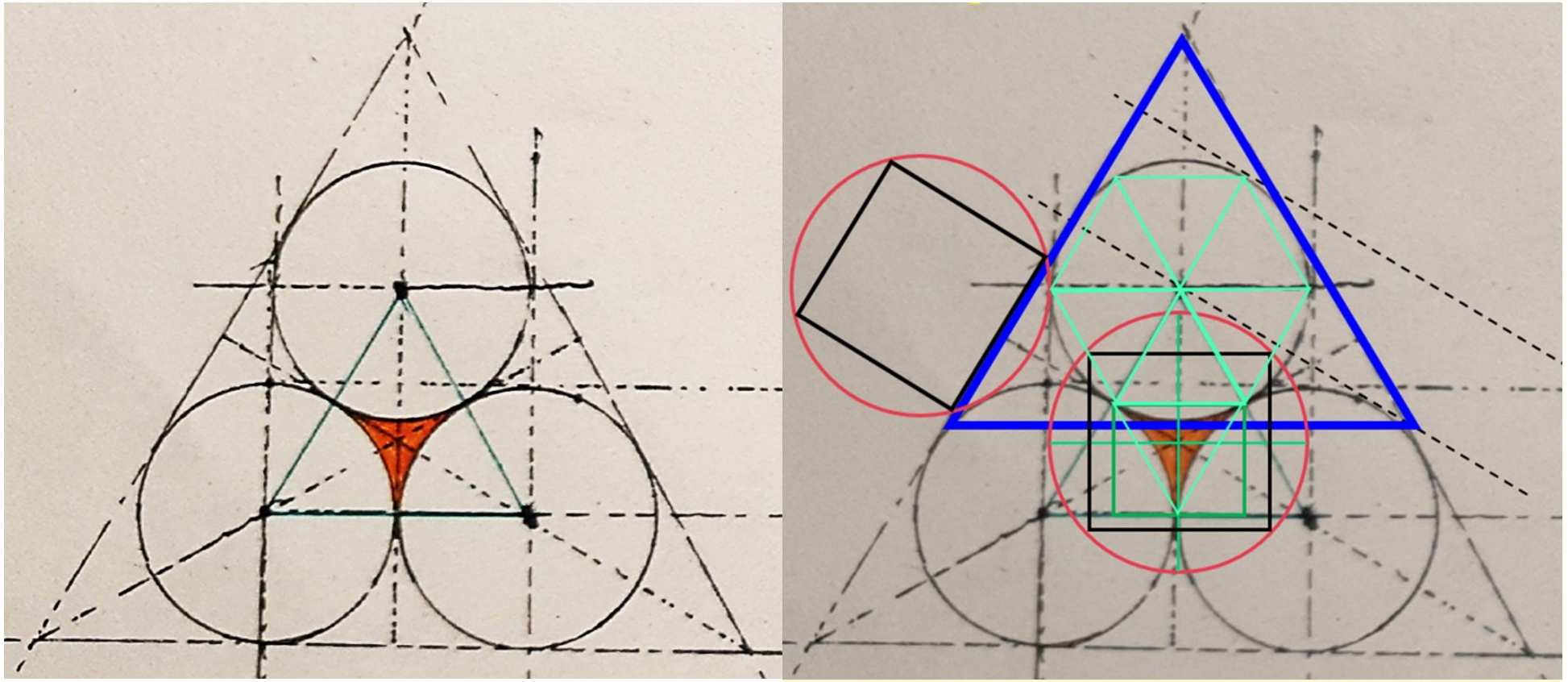


Triclinic

Alfarisi, O., Raza, A., Ouzzane, D., Li, H., Sassi, M., & Zhang, T. (2021). Morphology Decoder: A Machine Learning Guided 3D Vision Quantifying Heterogenous Rock Permeability for Planetary Surveillance and Robotic Functions. *arXiv preprint arXiv:2111.13460*.

Geometrical Analysis

Found Pore throat size geometrically



Triclinic

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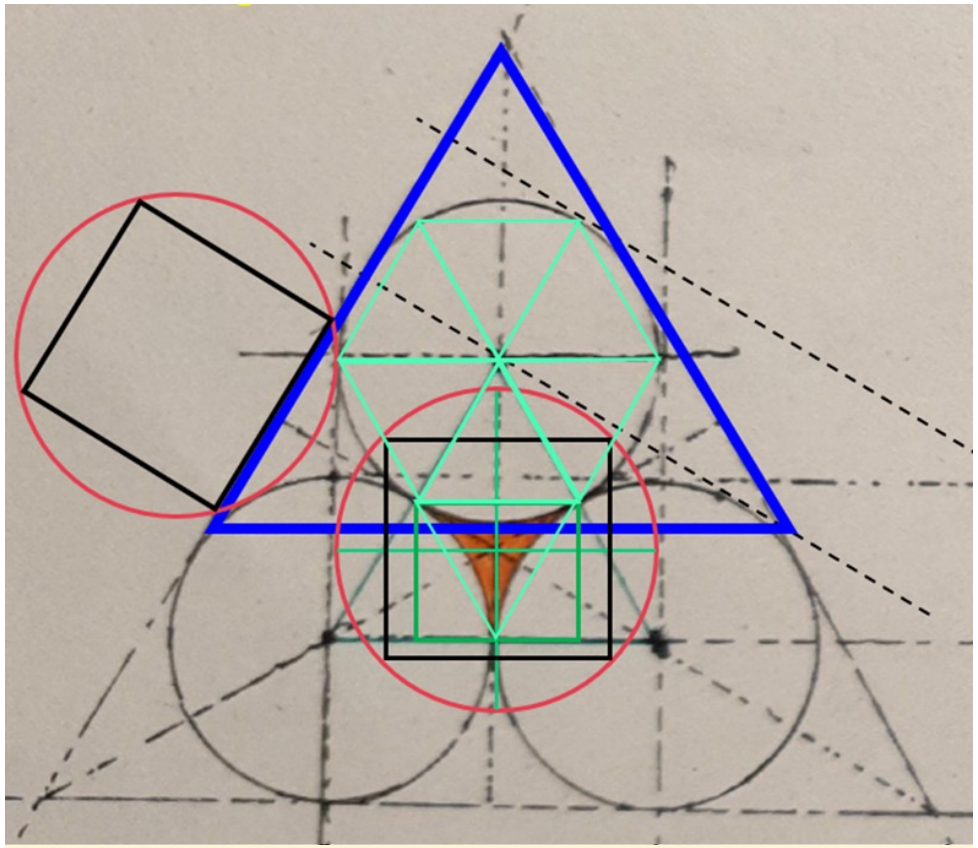
Geometrical Analysis

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

$$PorTS_{Triclinic} = \sqrt{3}\ r^2 - \frac{\pi}{2}\ r^2 = (\sqrt{3} - \frac{\pi}{2})\ r^2 = 0.162\ r^2 \qquad (3.6)$$

where r is the grain size

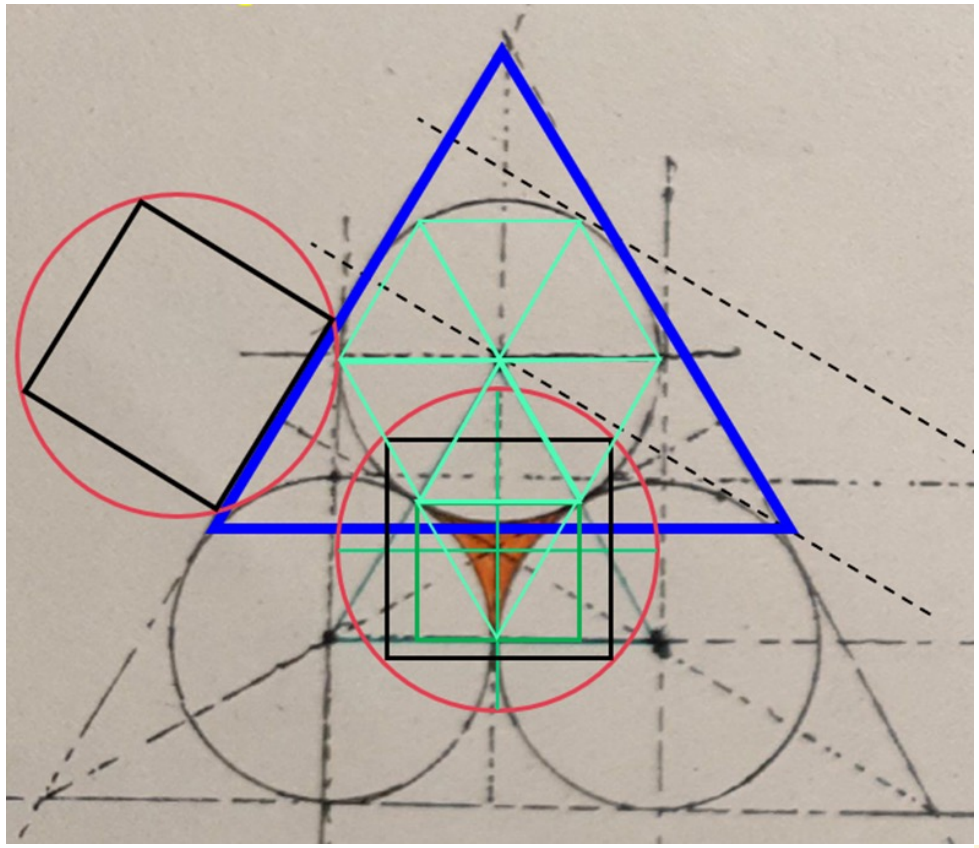
Found Pore throat size geometrically



Triclinic

Alfarisi, O., Raza, A., Ouzzane, D., Li, H., Sassi, M., & Zhang, T. (2021). Morphology Decoder: A Machine Learning Guided 3D Vision Quantifying Heterogenous Rock Permeability for Planetary Surveillance and Robotic Functions. *arXiv preprint arXiv:2111.13460*.

Geometrical Analysis



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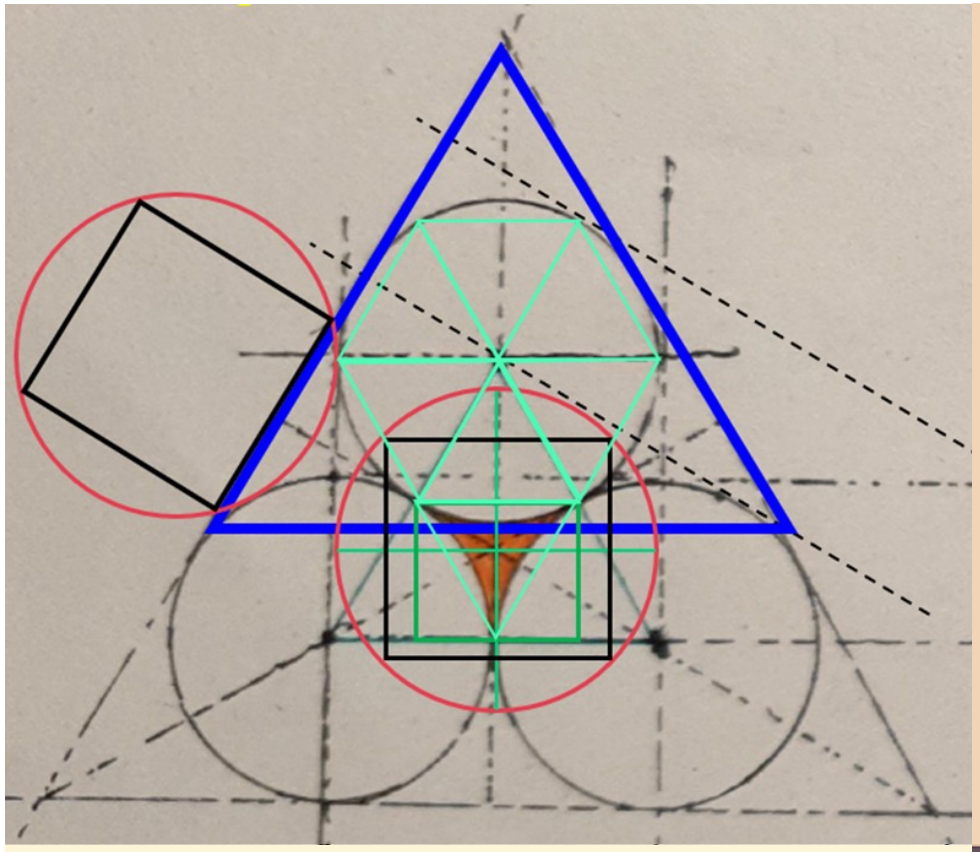
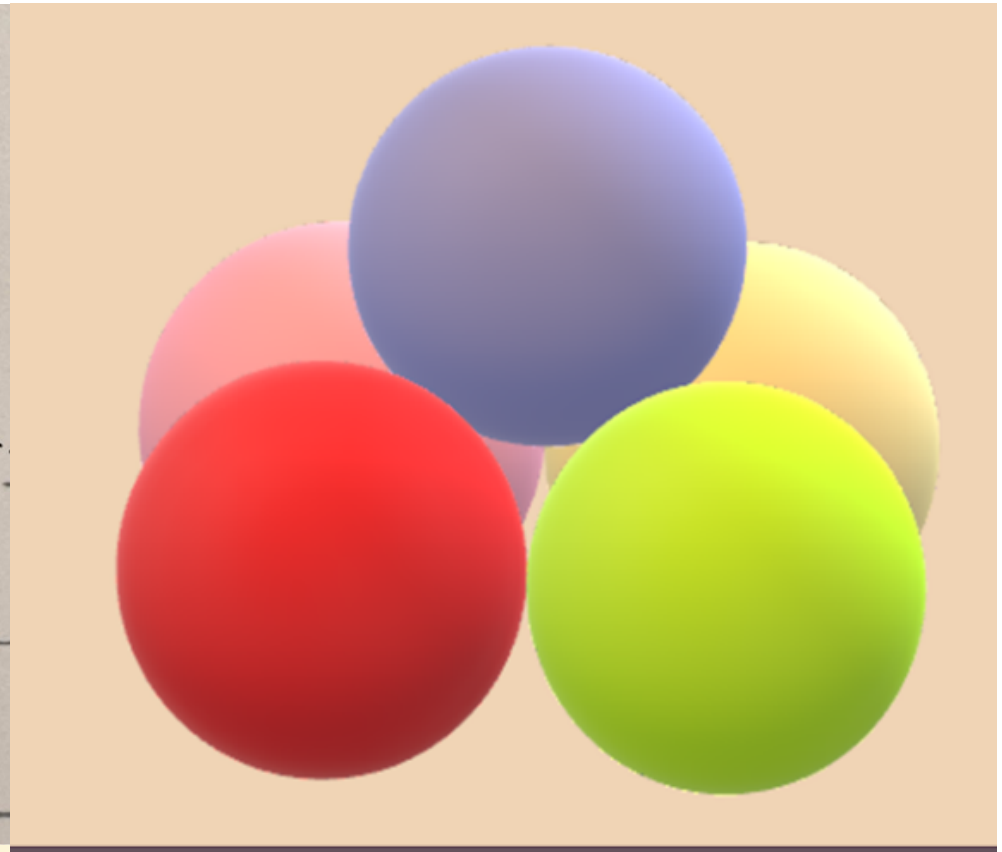
Geometrical Analysis

We need to upgrade Triclinic Equation to Rhombohedral



Triclinic

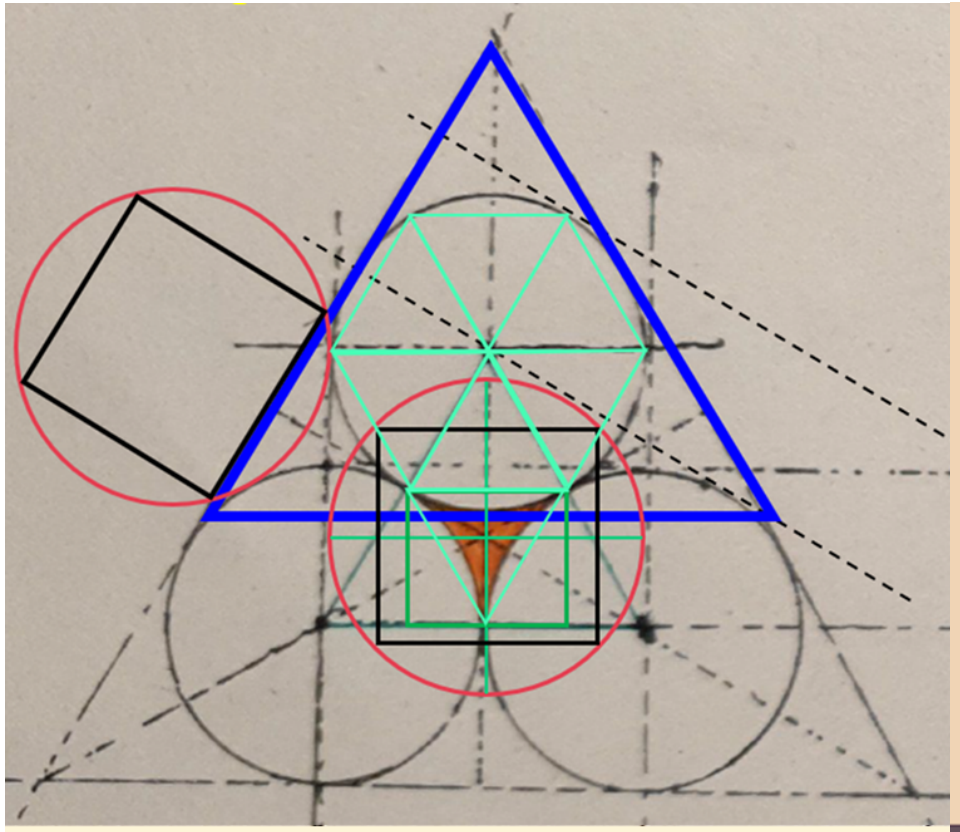


Rhombohedral

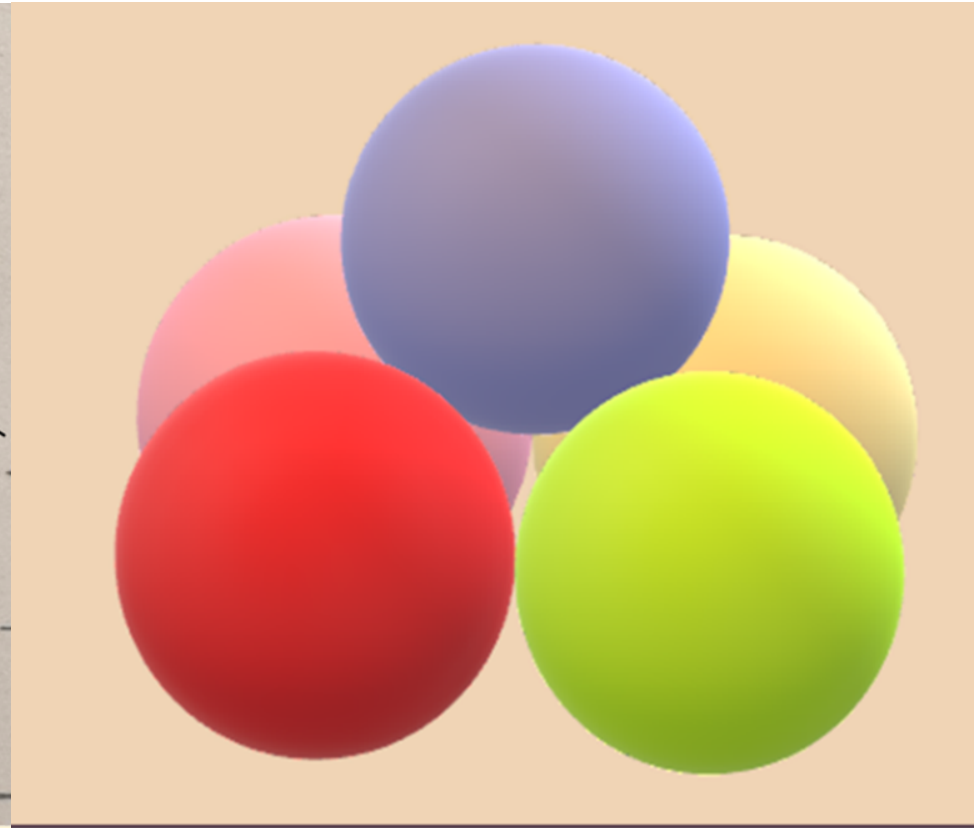
Alfarisi, O., Raza, A., Ouzzane, D., Li, H., Sassi, M., & Zhang, T. (2021). Morphology Decoder: A Machine Learning Guided 3D Vision Quantifying Heterogenous Rock Permeability for Planetary Surveillance and Robotic Functions. *arXiv preprint arXiv:2111.13460*.

Geometrical Analysis

Ratio



Triclinic



Rhombohedral

Alfarisi, O., Raza, A., Ouzzane, D., Li, H., Sassi, M., & Zhang, T. (2021). Morphology Decoder: A Machine Learning Guided 3D Vision Quantifying Heterogenous Rock Permeability for Planetary Surveillance and Robotic Functions. *arXiv preprint arXiv:2111.13460*.

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 $5.148{r_g}^2$.

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

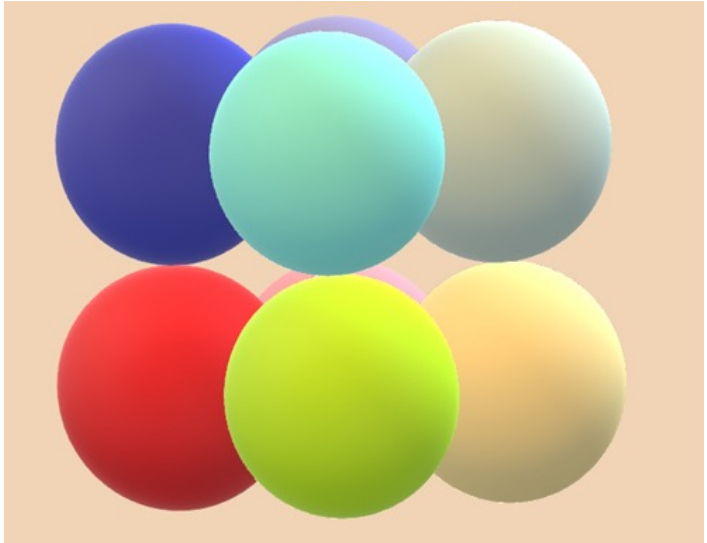
$$PorTS_{cubic_{3D_{Effective}}} = \frac{A_{cubic_{PorT}}}{N_{PorT} \cdot N_{C_{\forall inets}}} r_g^2 = \frac{5.148}{6 * 2} r_g^2 = 0.429 r_g^2$$

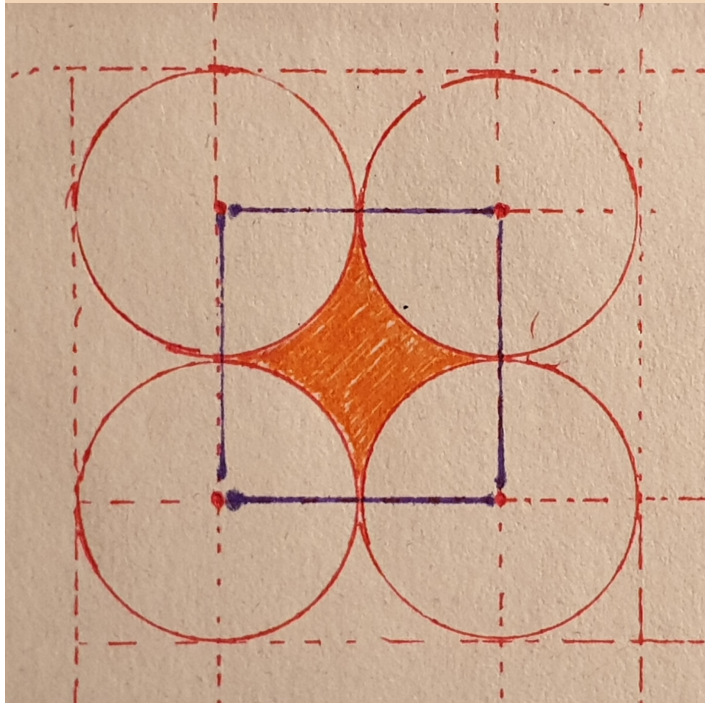
where,

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

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

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





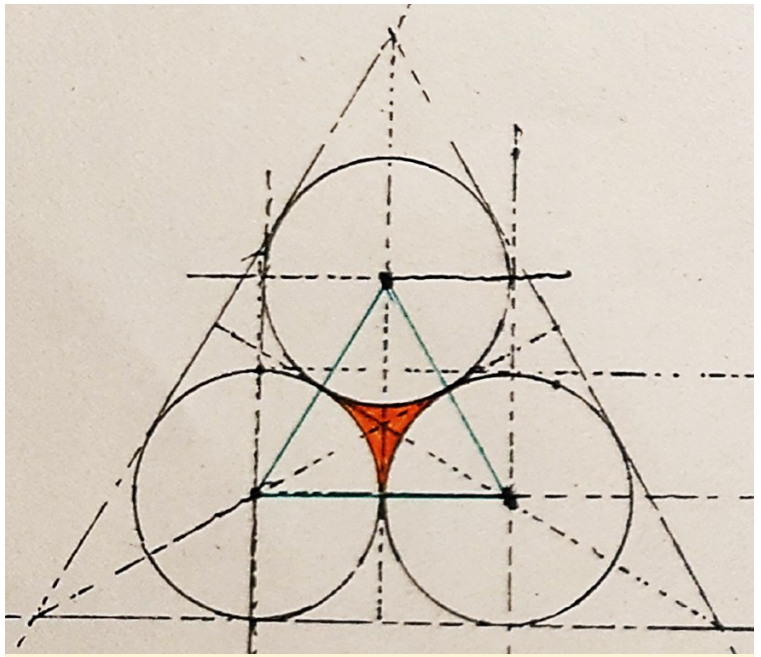
Experimental and Analytical (Triclinic)

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 $4.08{r_g}^2$. Then we calculate the Effective 3D Pore Throat Size of triclinic configuration ($PorTS_{triclinic_{3D_{Effective}}}$) as shown in Eq. 7, below:

$$PorTS_{triclinic_{3D_{Effective}}} = \frac{A_{triclinic_{PorT}}}{N_{PorT} \cdot N_{C\forall_{inets}}} r_g^2 = \frac{4.08}{8 * 2} r_g^2 = 0.255 r_g^2$$

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 $1.716{r_g}^2$.

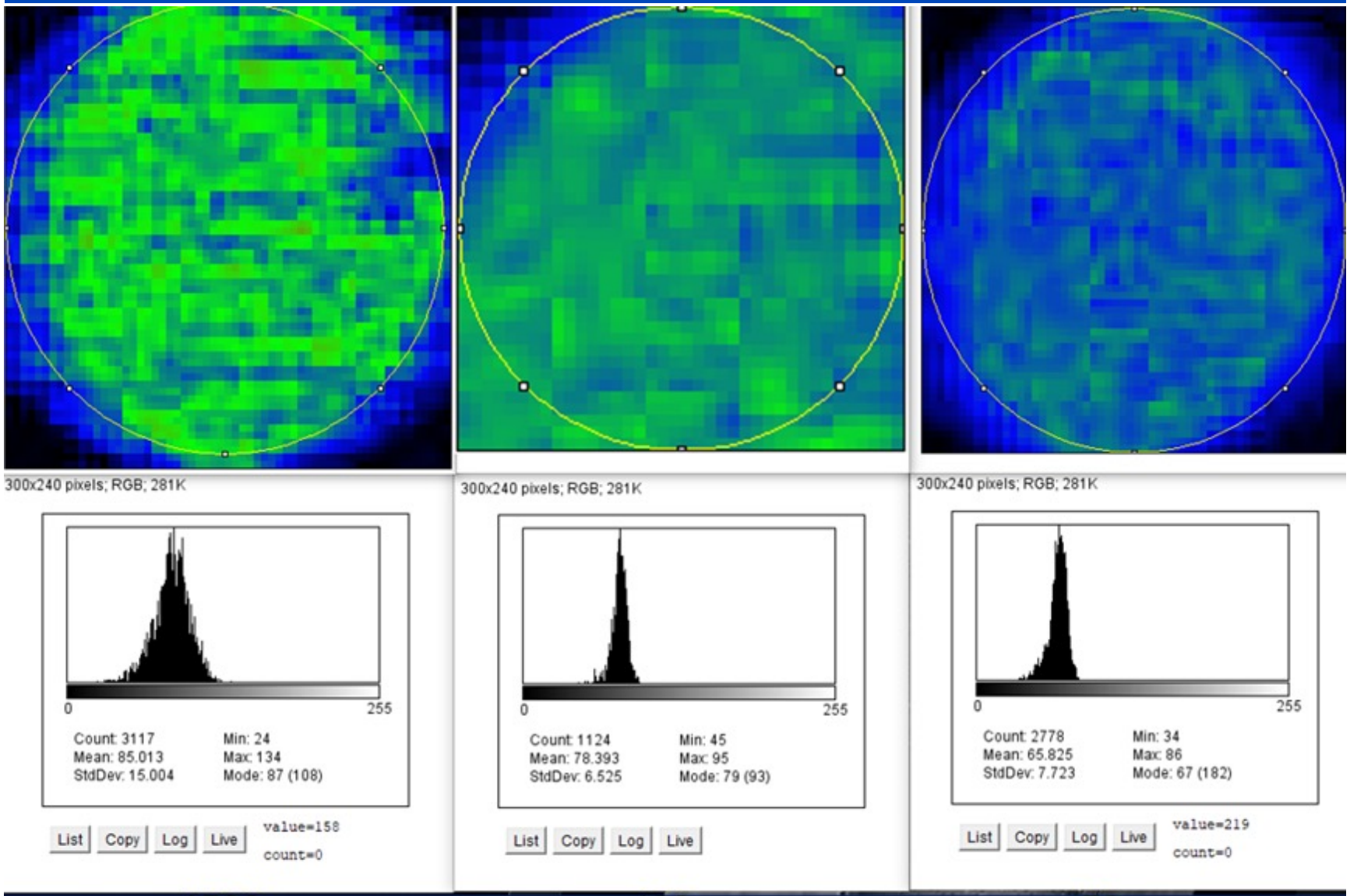
Then we calculate the Effective 3D Pore Throat Size of rhombohedral configuration ($PorTS_{rhombohedral_{3D_{Effective}}}$) as shown in Eq. 8 below:

$$PorTS_{rhombohedral_{3D_{Effective}}} = \frac{A_{rhombohedral_{PorT}}}{N_{PorT} \cdot N_{C_{\forall inets}}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \qquad (8)$$

where,

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

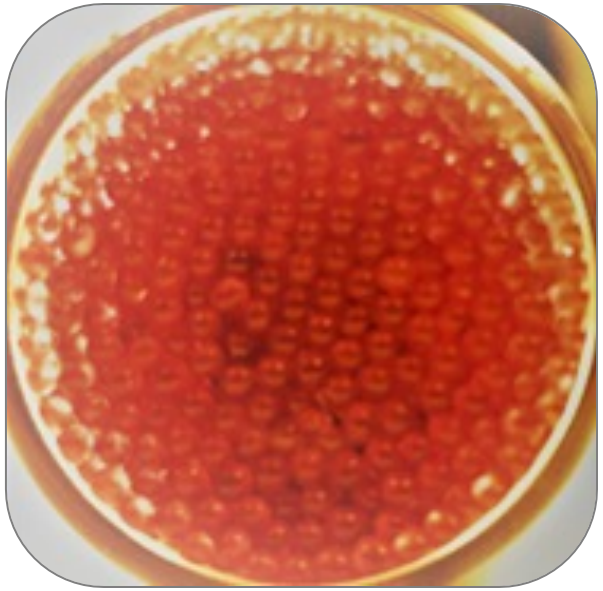
Experimental (MRI) – Different sizes of Glass Beads



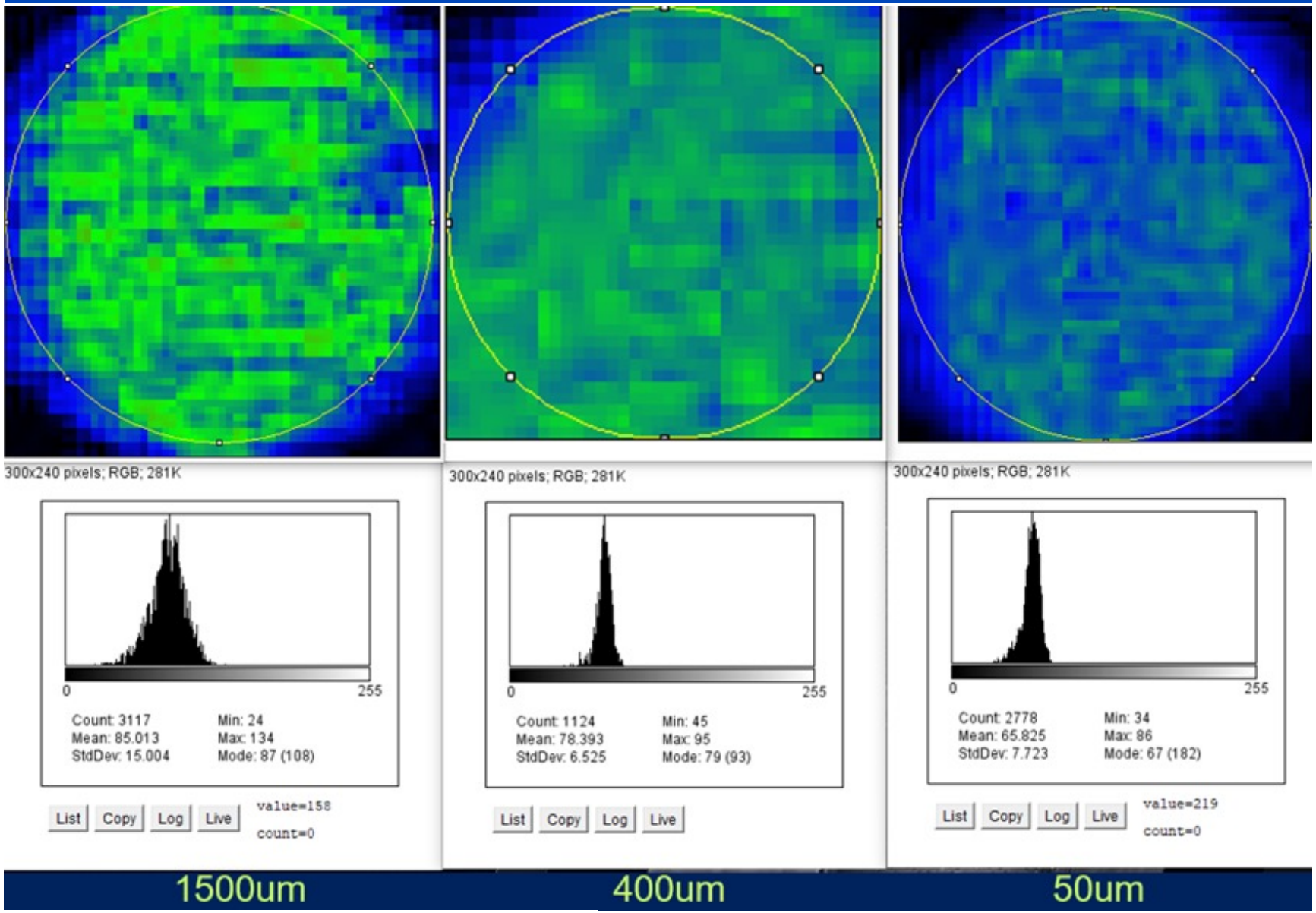
1500um 400um 50um

$$PorTS_{rhombohedral_{3D_{Effective}}} = \frac{A_{rhombohedral_{PorT}}}{N_{PorT} \cdot N_{C_{\forall inets}}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \qquad (8)$$

Experimental (MRI) – Different sizes of Glass Beads

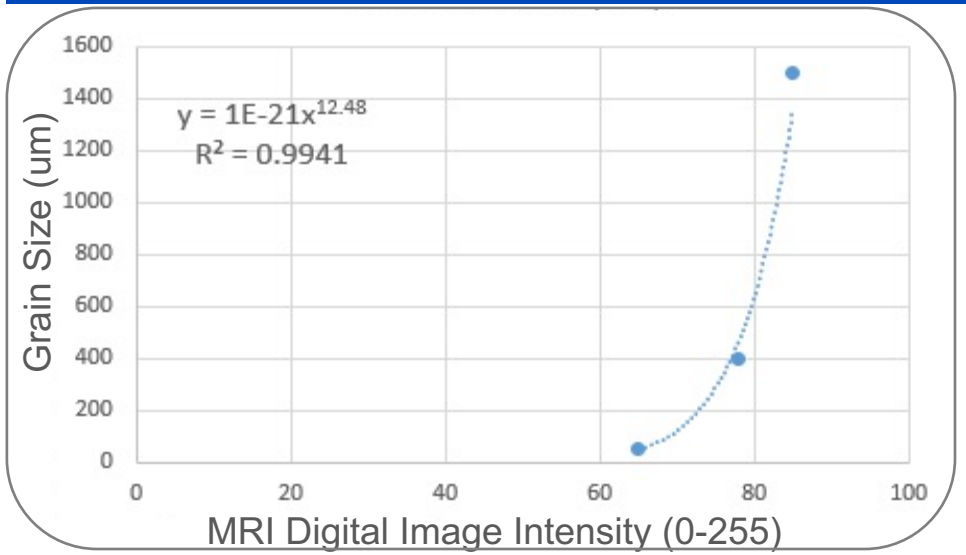


Glass Beads

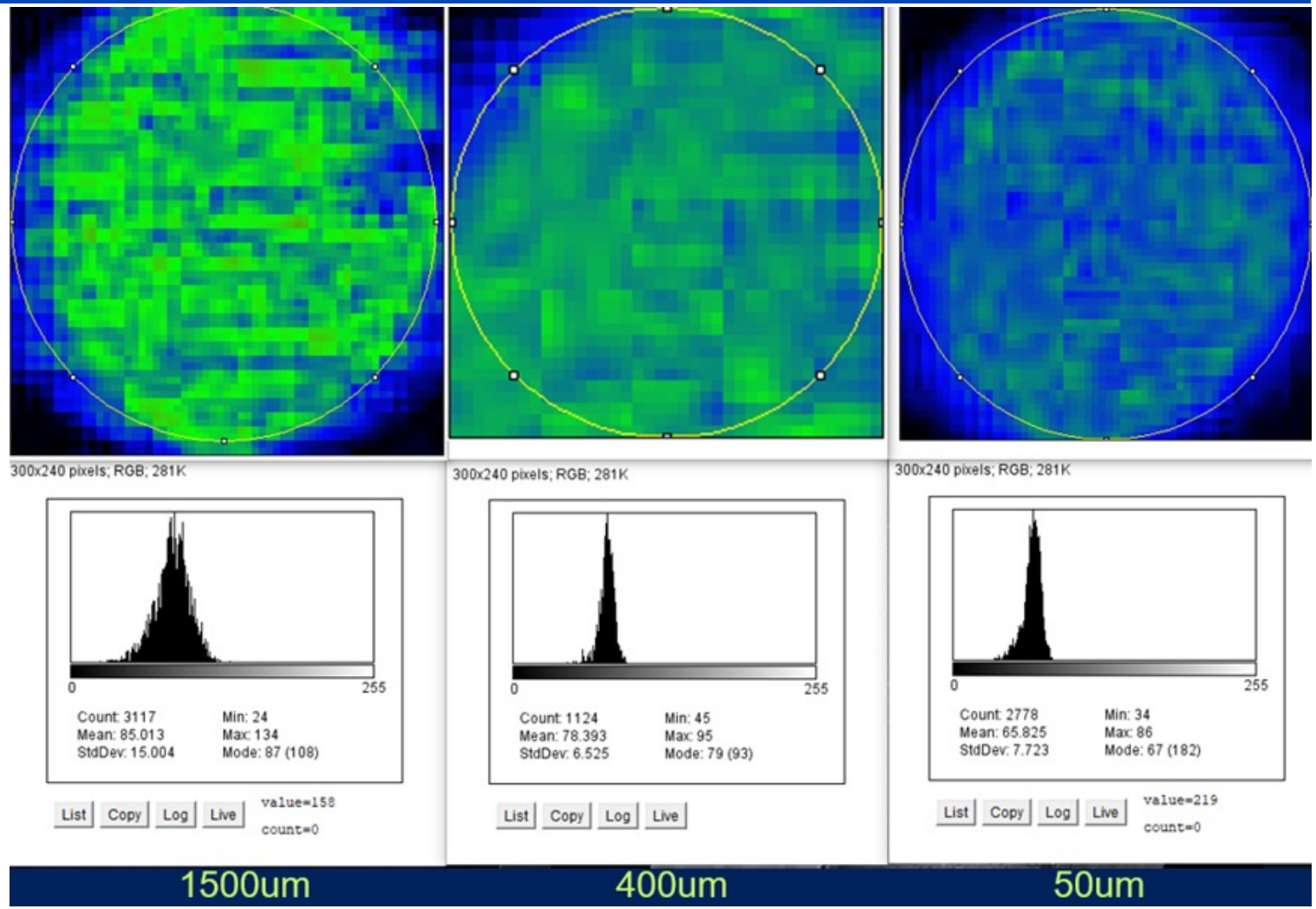


$$PorTS_{rhombohedral\,3D\,Effective} = \frac{A_{rhombohedral\,PorT}}{N_{PorT} \cdot N_{C\forall inets}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \qquad (8)$$

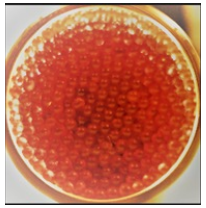
Experimental (MRI) – Different sizes of Glass Beads

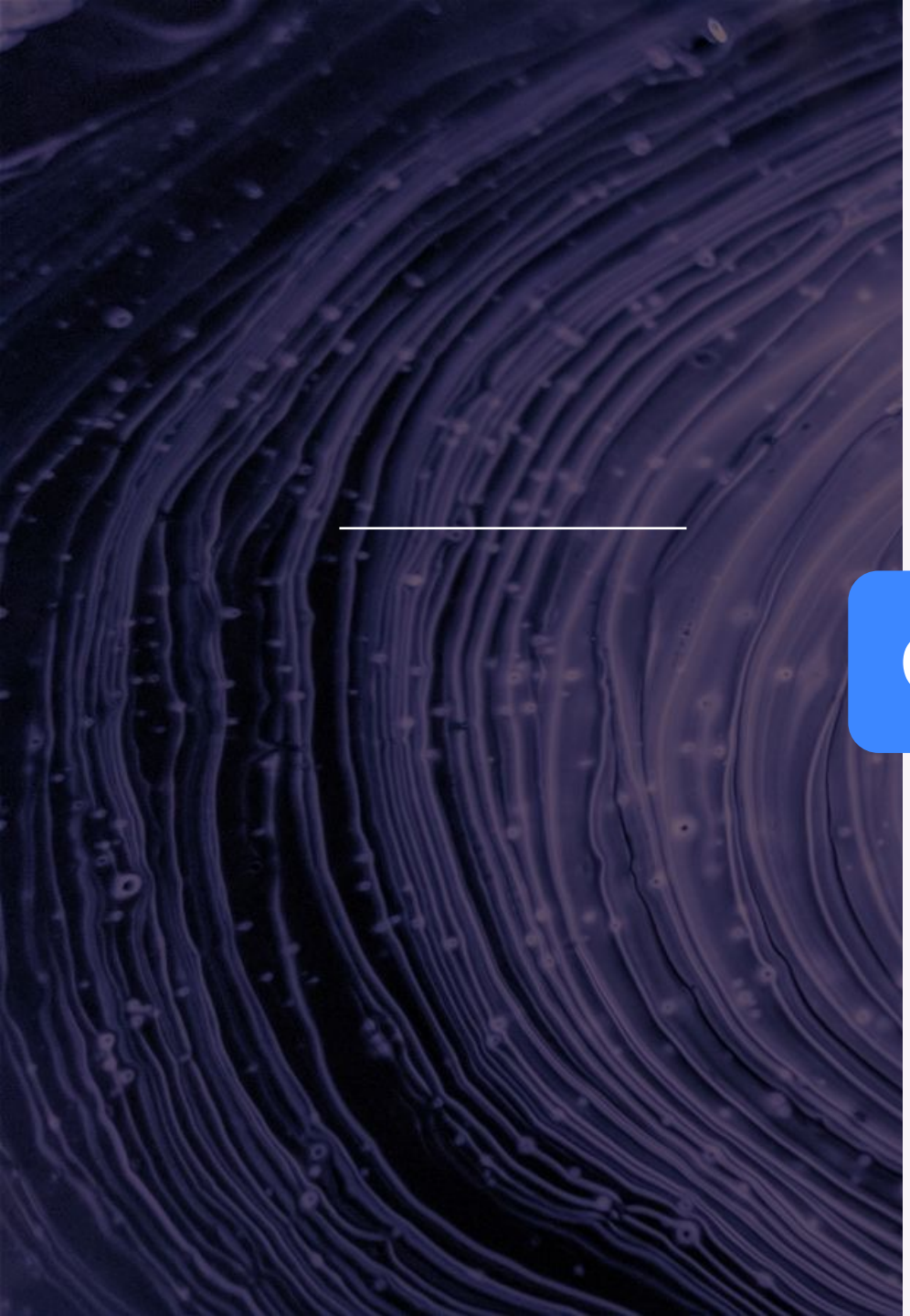


MRIII_Slices	Grain Diameter (um)
85	1500
78	400
65	50



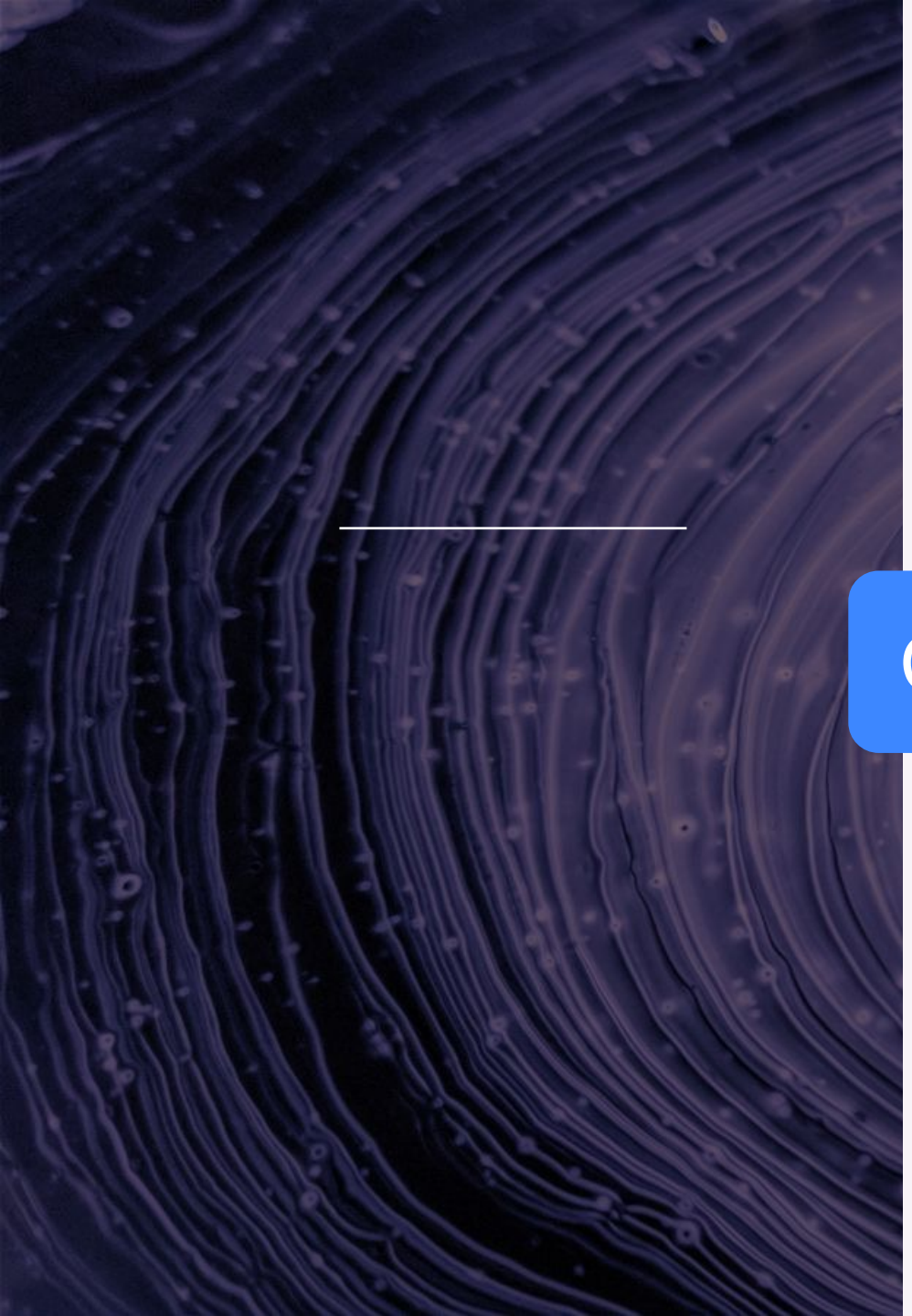
$$PorTS_{rhombohedral\,3D\,Effective} = \frac{A_{rhombohedral\,PorT}}{N_{PorT} \cdot N_{C\forall inets}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \qquad (8)$$





Content

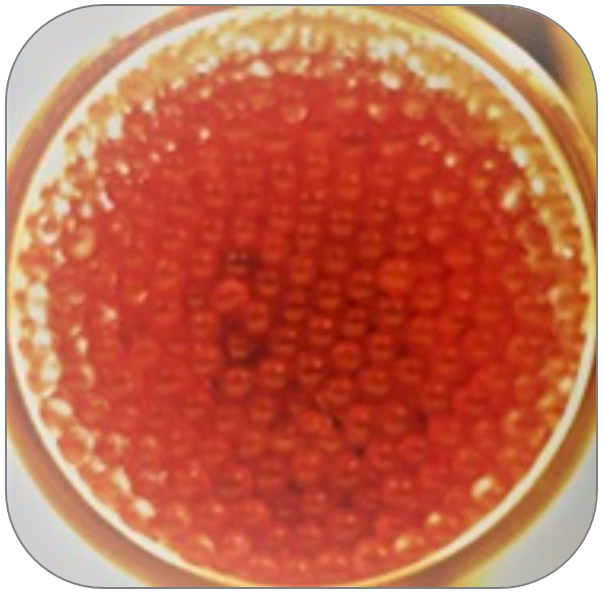
Machine Learning 3D Image Recognition



Content

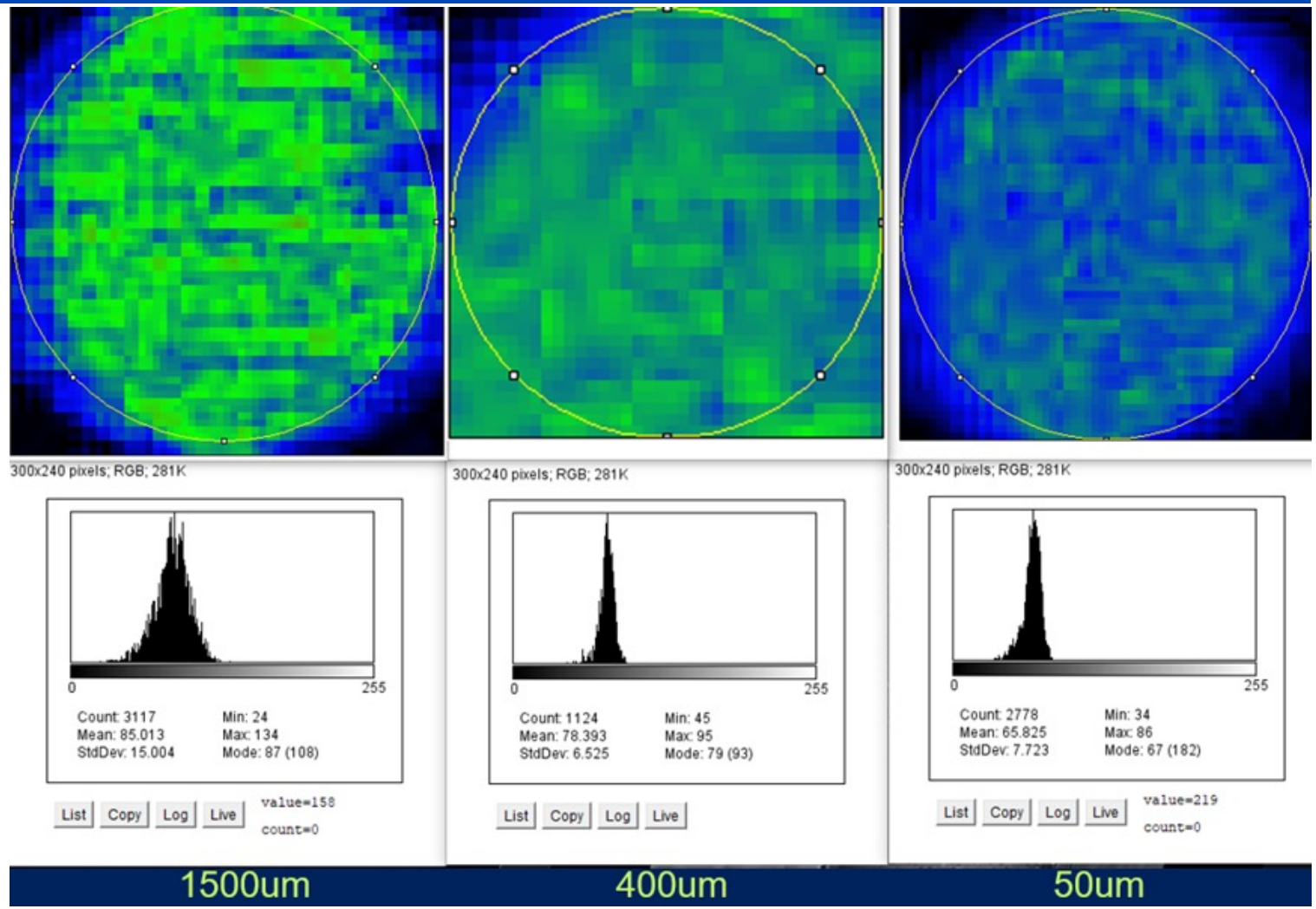
Machine Learning 3D Image Recognition

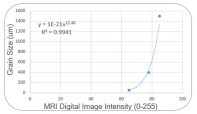
Experimental (MRI) – Different sizes of Glass Beads



Glass Beads

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





MRIII_Slices	Grain Diameter (um)
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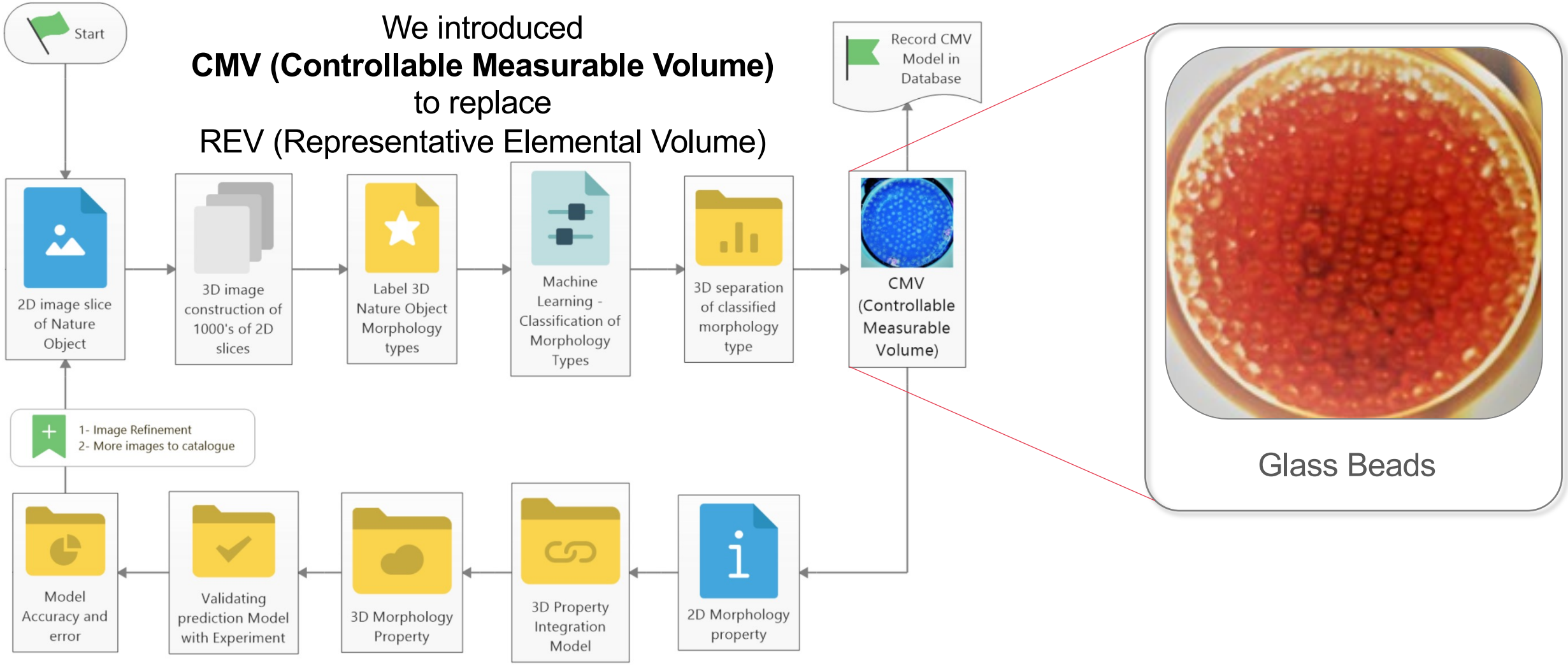
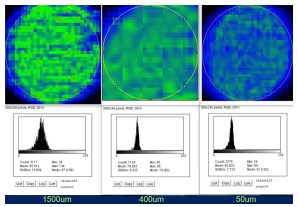
65	50

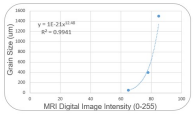
$$PorTS_{rhombohedral\,3D\,Effective} = \frac{A_{rhombohedral\,PorT}}{N_{PorT} \cdot N_{C\forall inets}} r_g^2 = \frac{1.716}{10 * 2} r_g^2 = 0.0858 r_g^2 \qquad (8)$$

CMV– Controllable Measurable Volume

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







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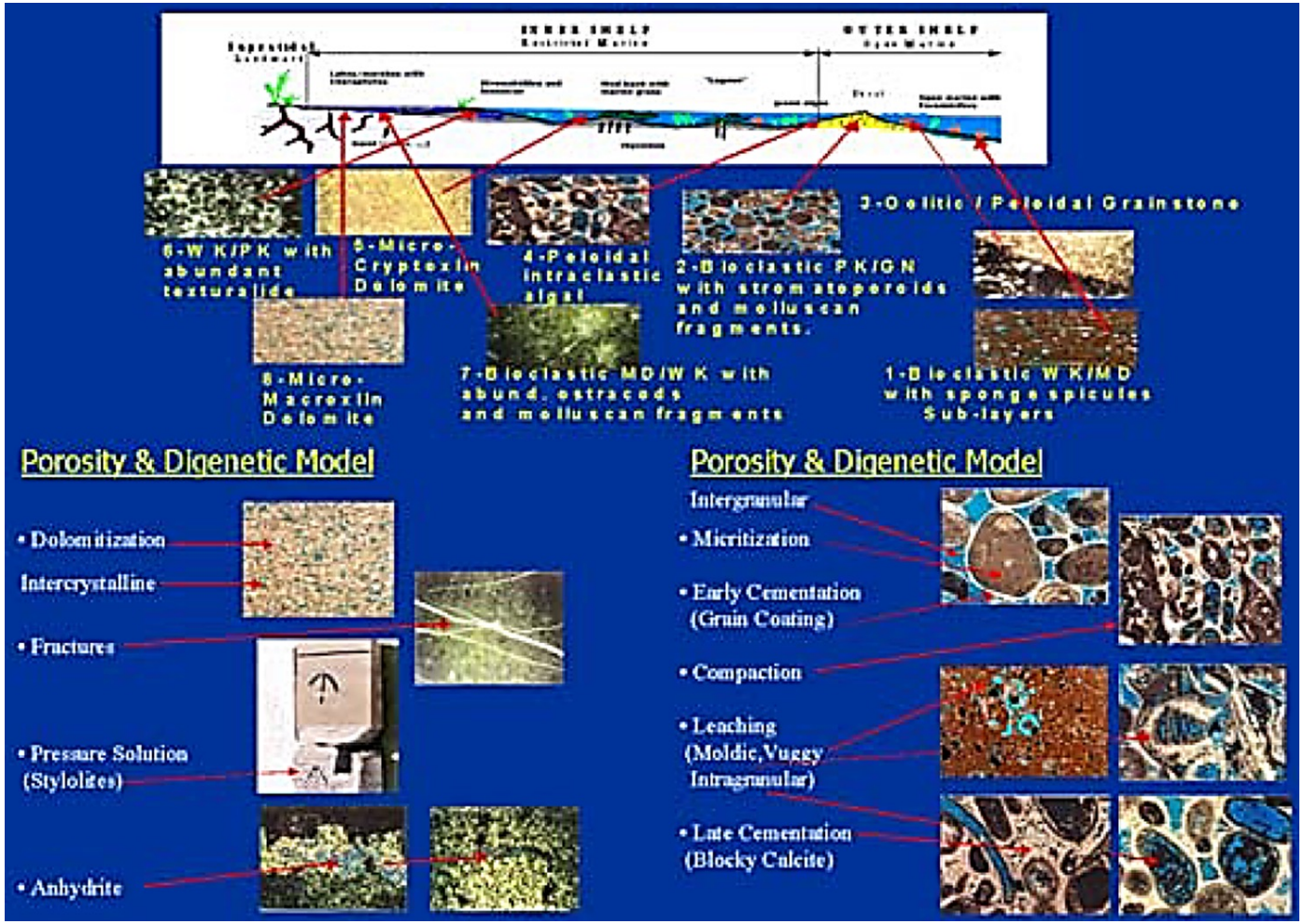
CMV– Controllable Measurable Volume

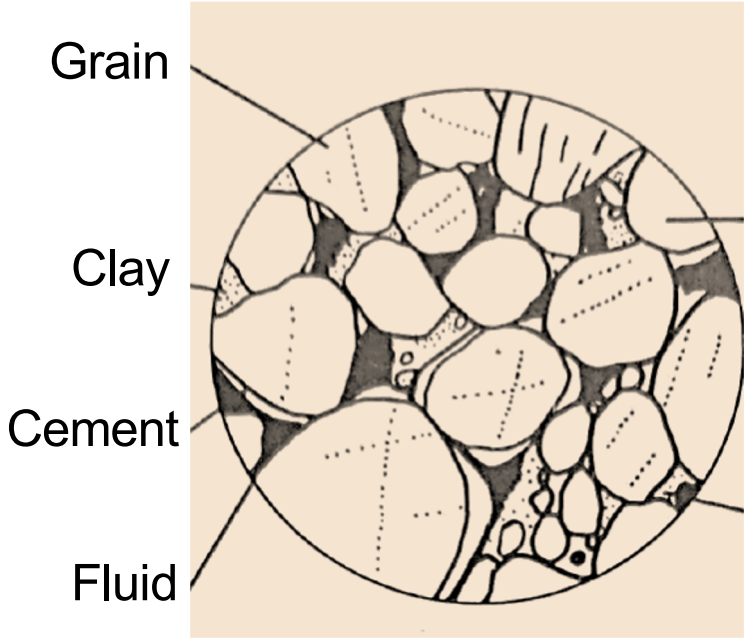


Al-Farisi, O., Belgaied, A., Elhami, M., Kadada, T., Aljefri, G., & Barkawi, A. N. (2004, January). Electrical Resistivity and Gamma-Ray Logs: Two Physics for Two Permeability Estimation Approaches in Abu Dhabi Carbonates. In Abu Dhabi International Conference and Exhibition. Society of Petroleum Engineers.

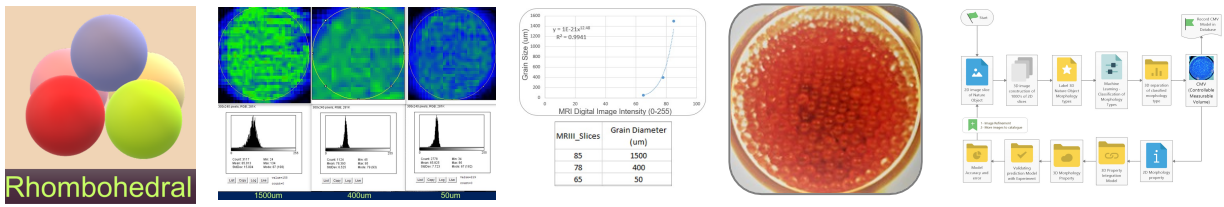
CMV (Controllable Measurable Volume)

provides

heterogenous rock morphology segmentation



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



CMV– Controllable Measurable Volume

Porosity & Diagenetic Model

- **Intergranular**

- **Intragranular**

Al-Farisi, O., Belgaied, 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.

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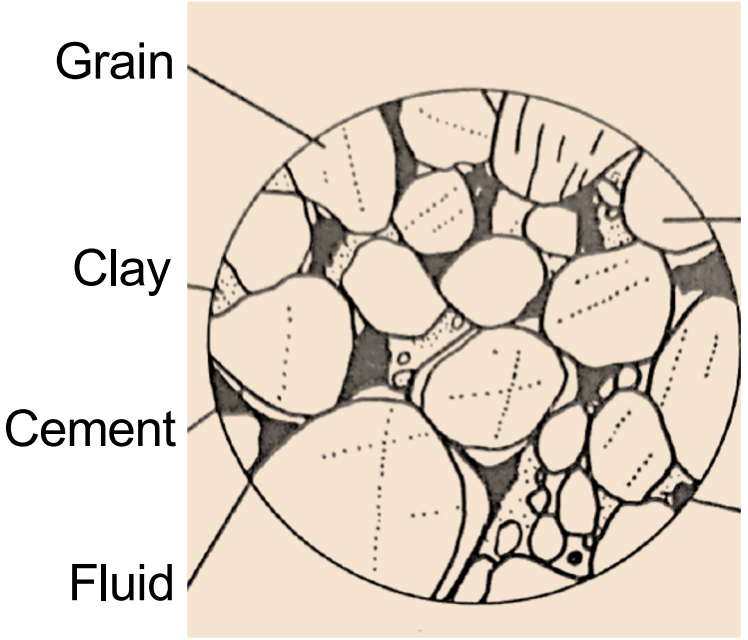

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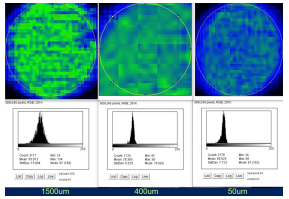

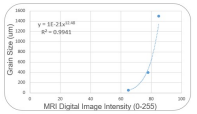

MRIII_Slices	Grain Diameter (um)
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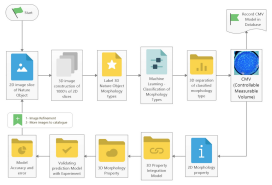
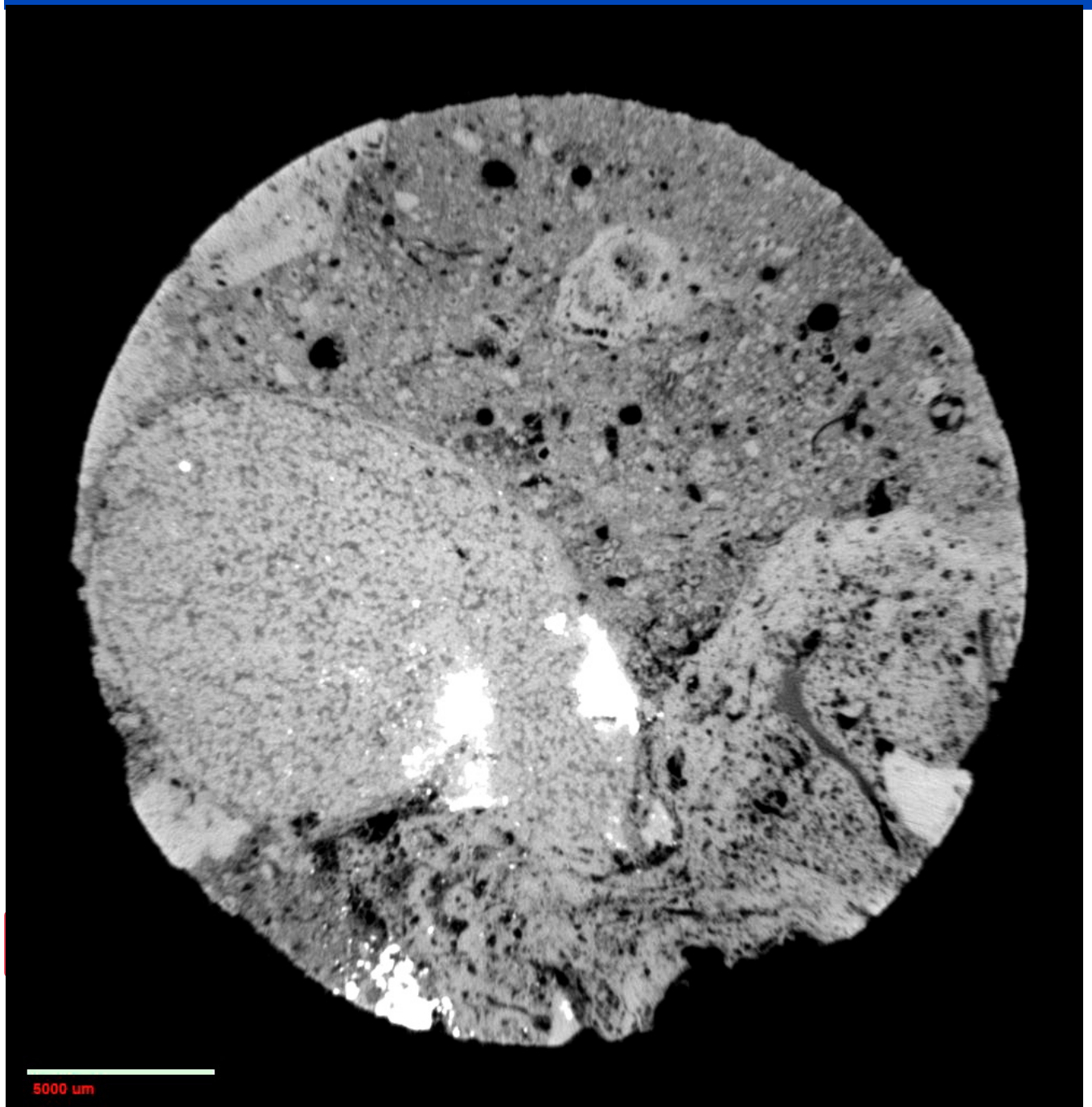
78	400
65	50

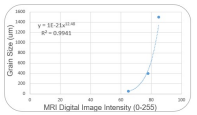


CMV– Controllable Measurable Volume



CMV (Controllable Measurable Volume)
provides
heterogenous rock morphology segmentation

Do we have Intragranular and Intergranular?



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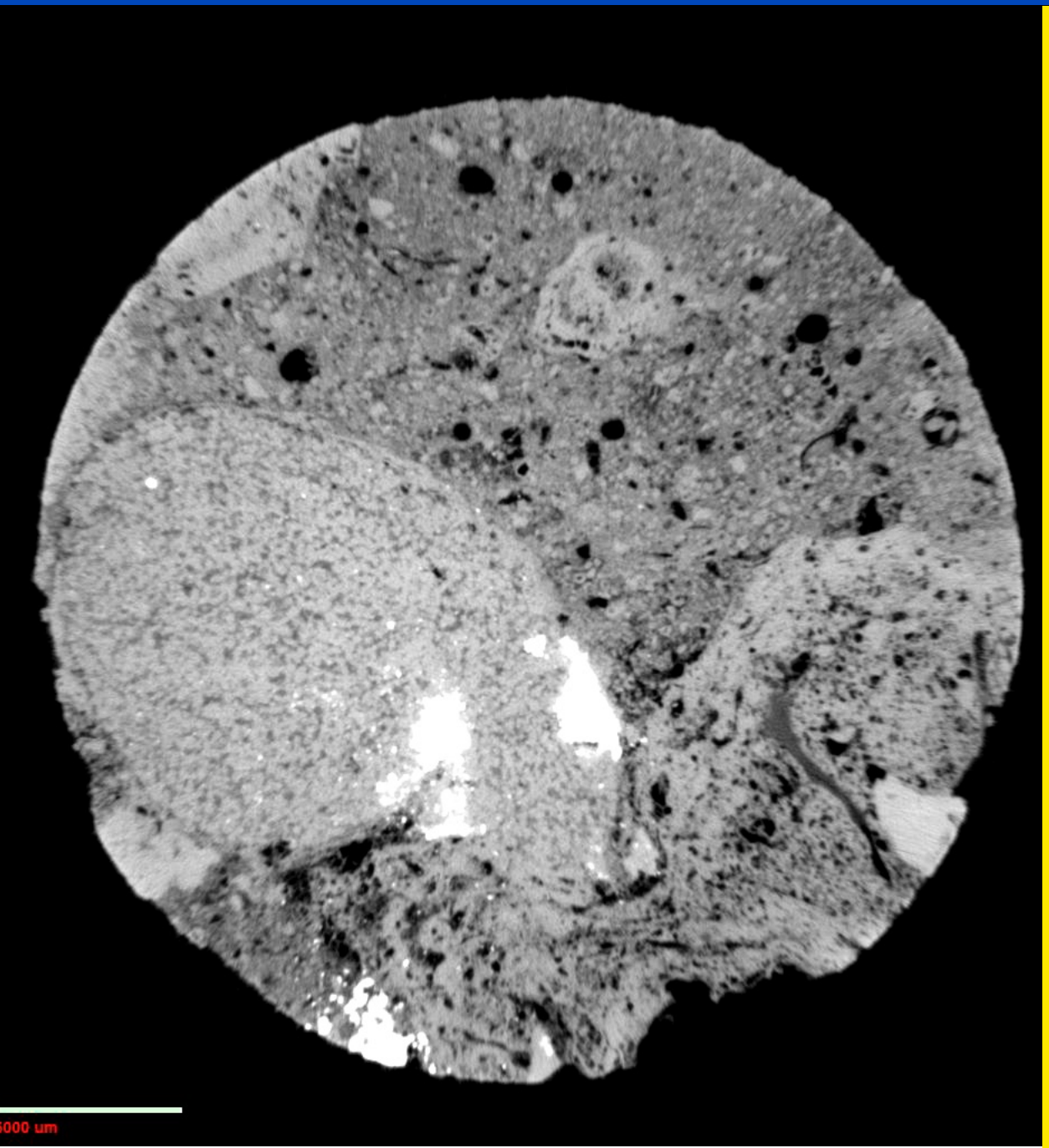
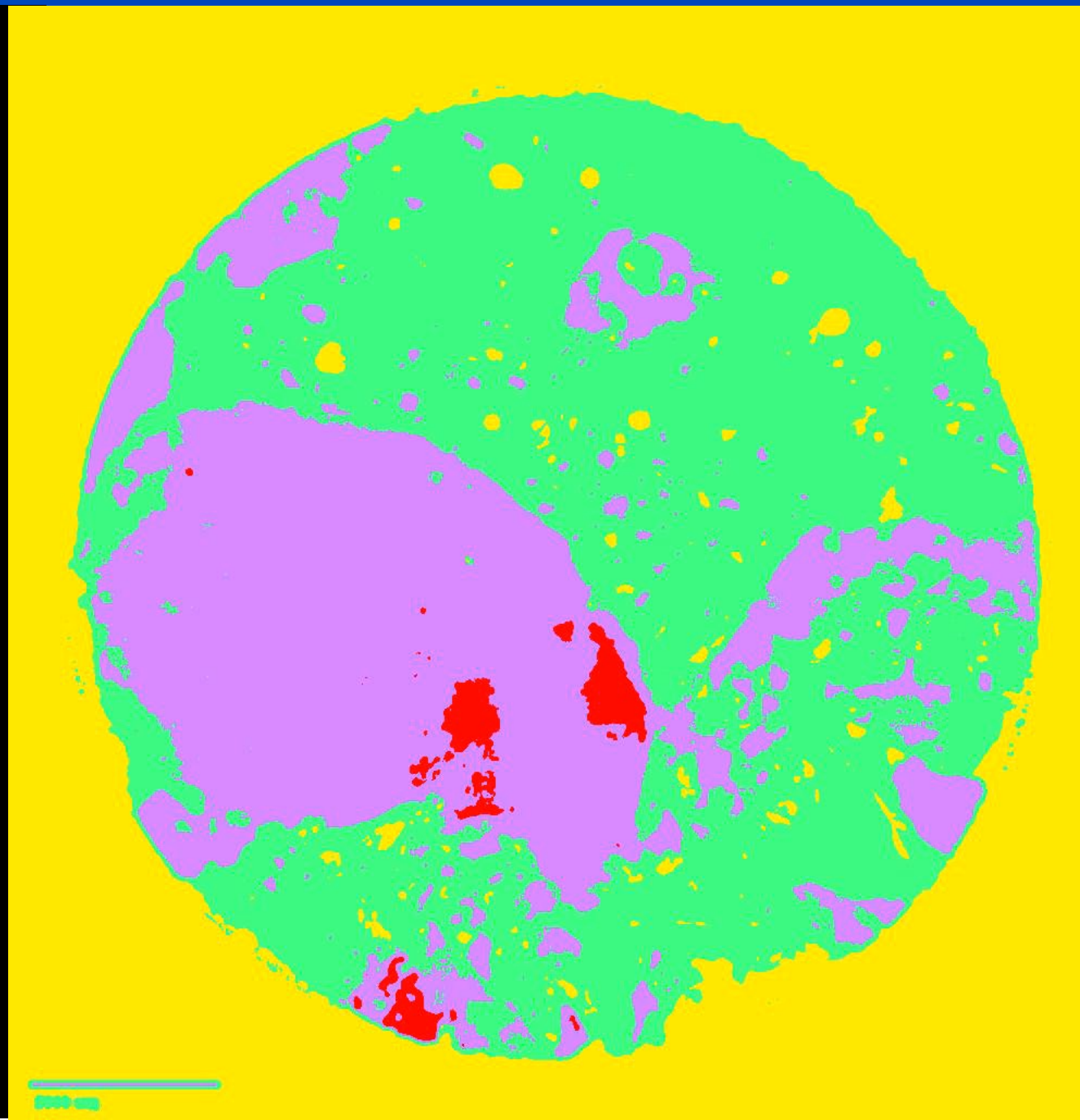
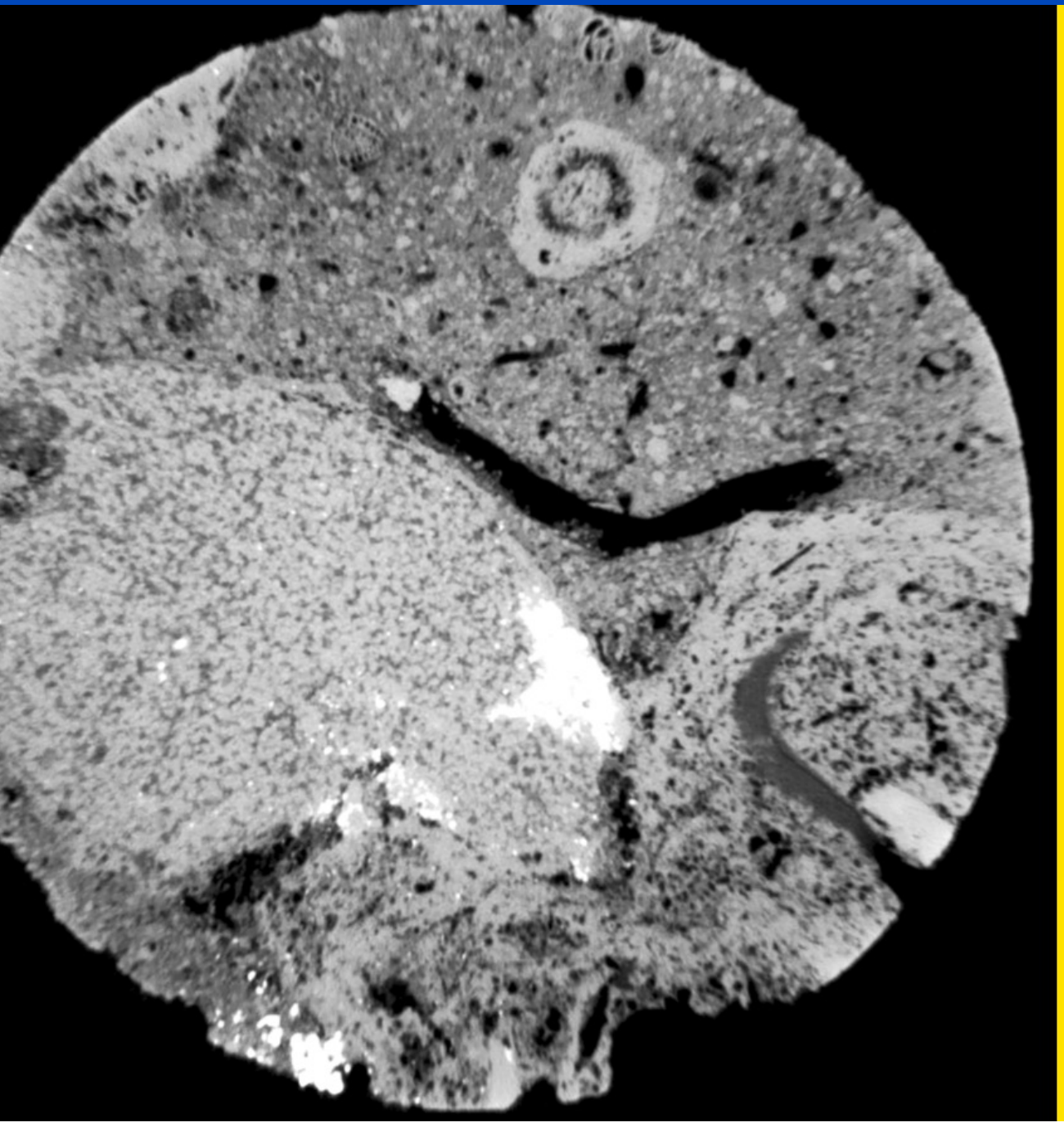
Machine Learning Heterogenous Morphology Segmentation





Machine Learning Heterogenous Morphology Segmentation



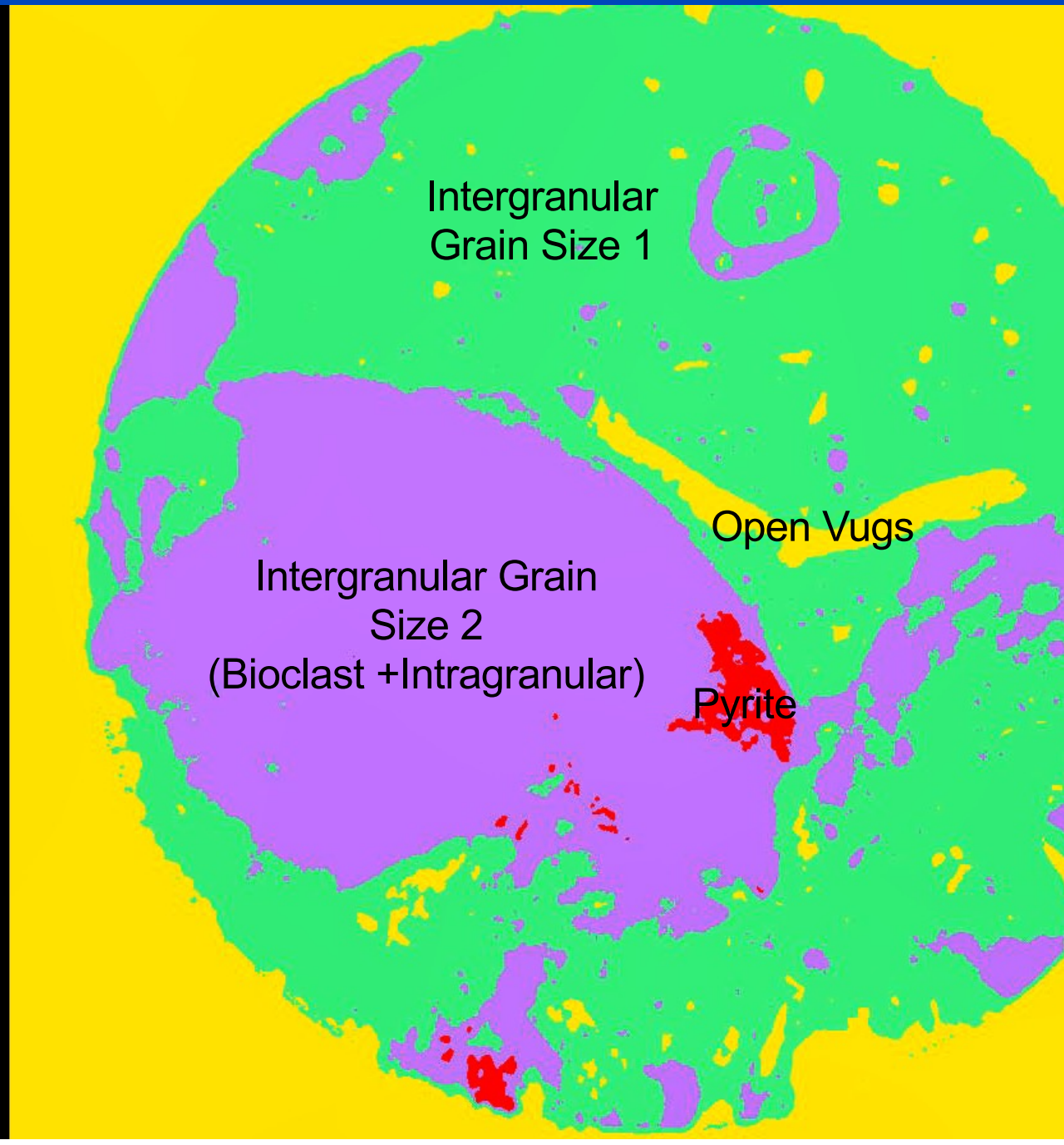
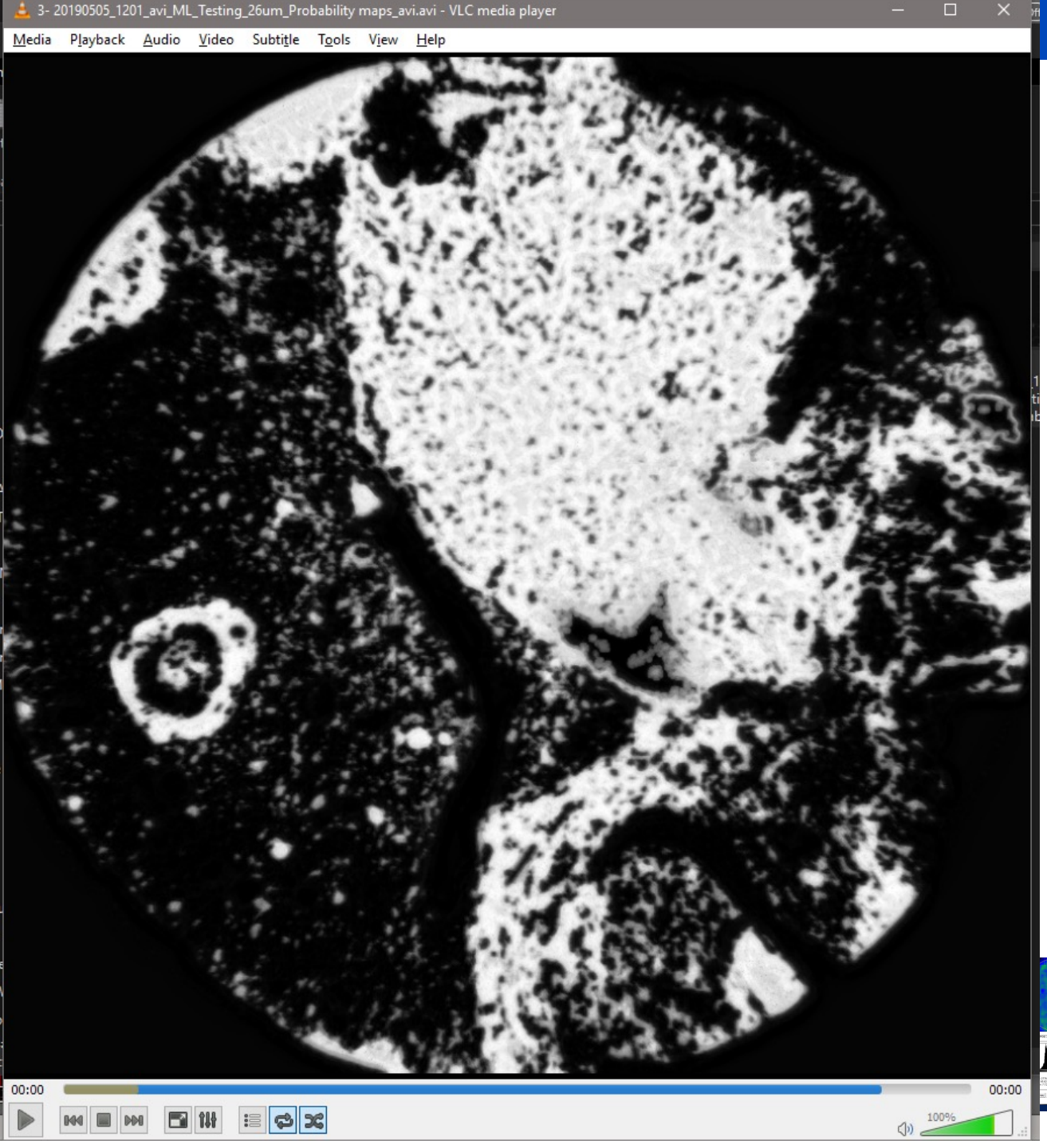
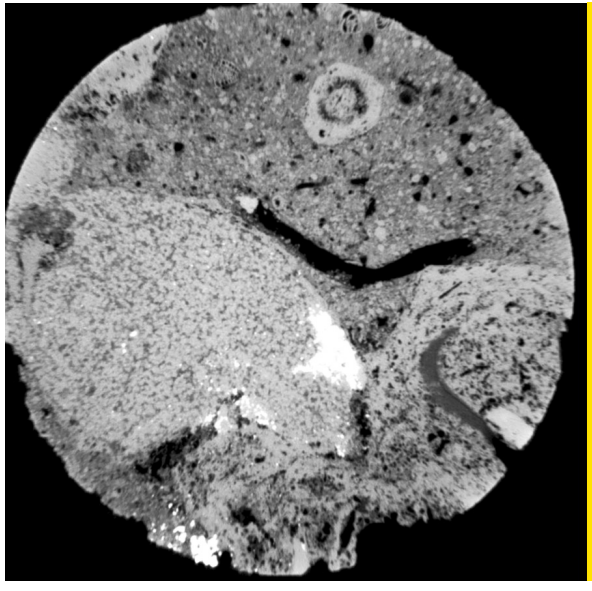
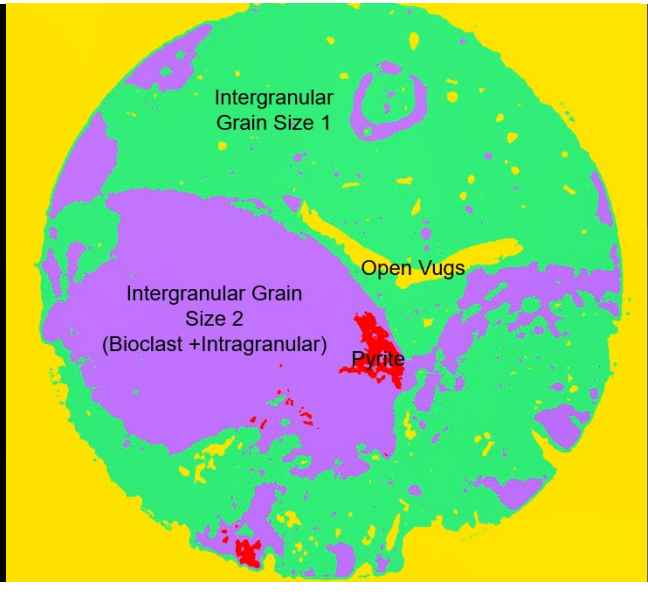
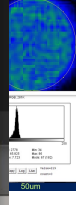


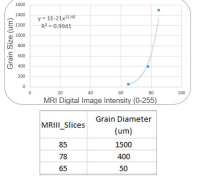
Image Processing Segregation of Morphology

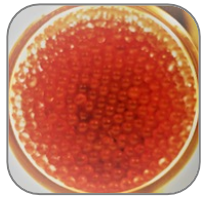












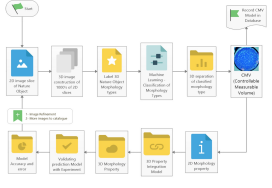
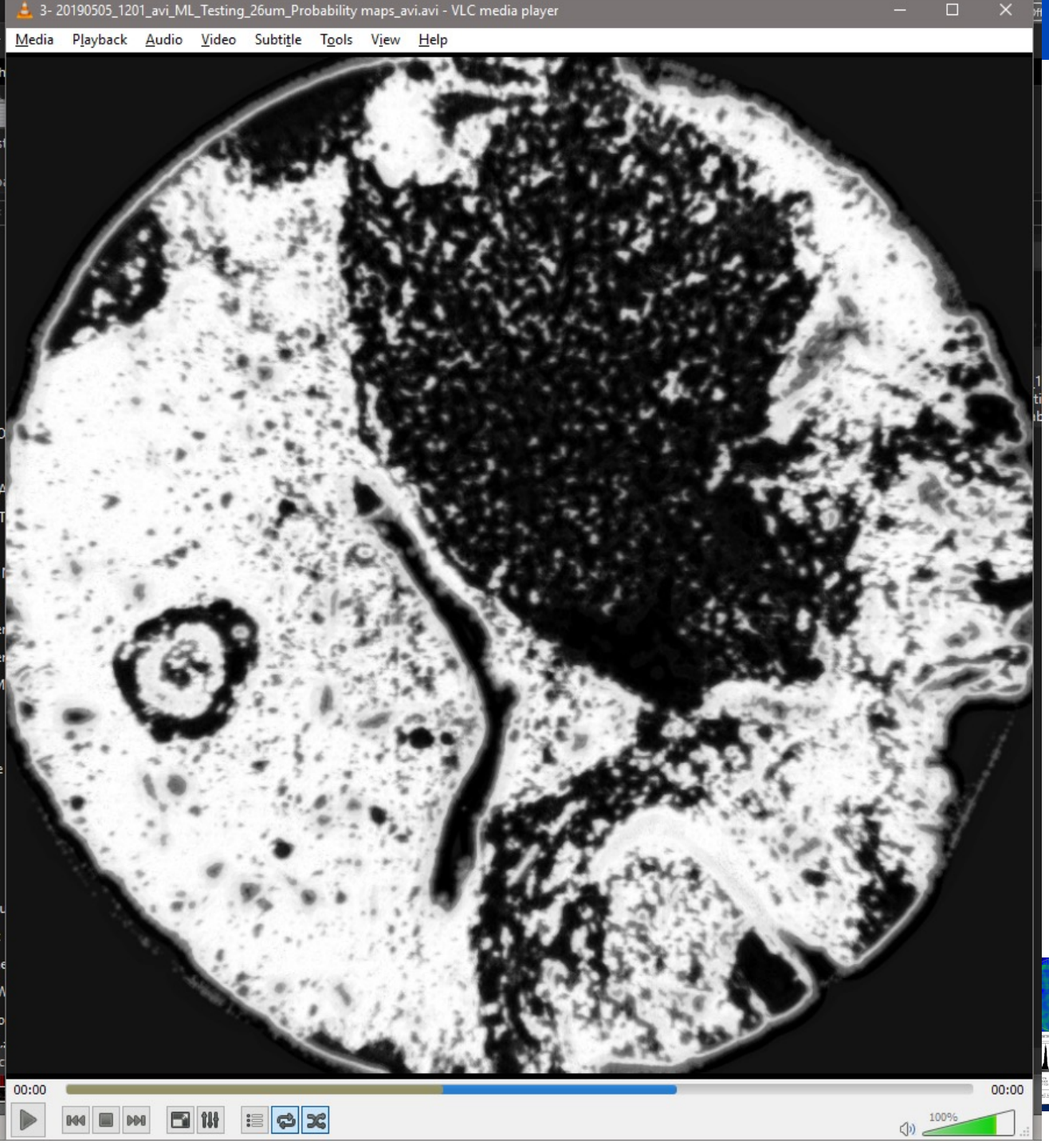
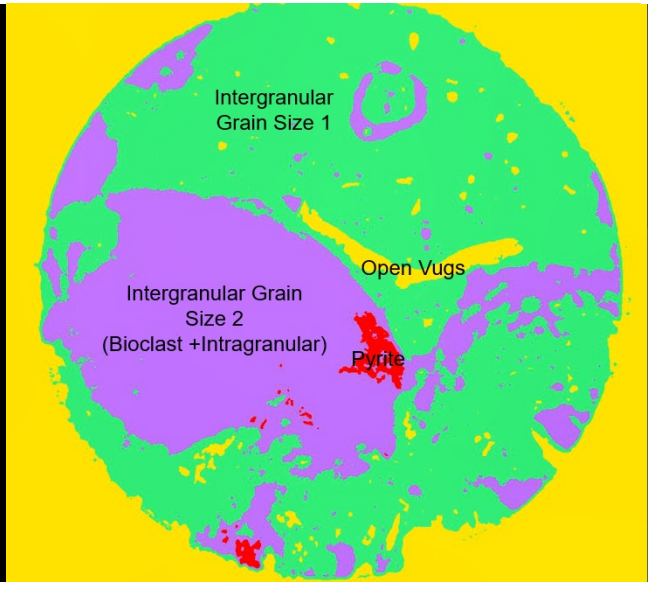
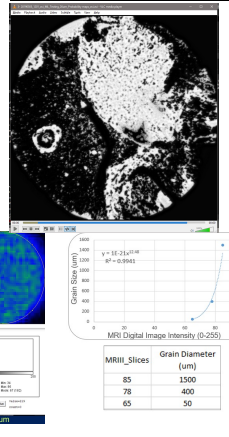
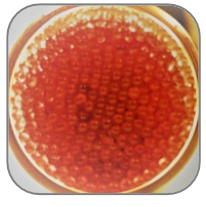


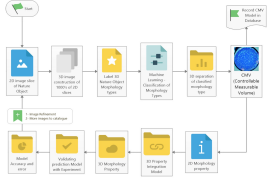
Image Processing Segregation of Morphology











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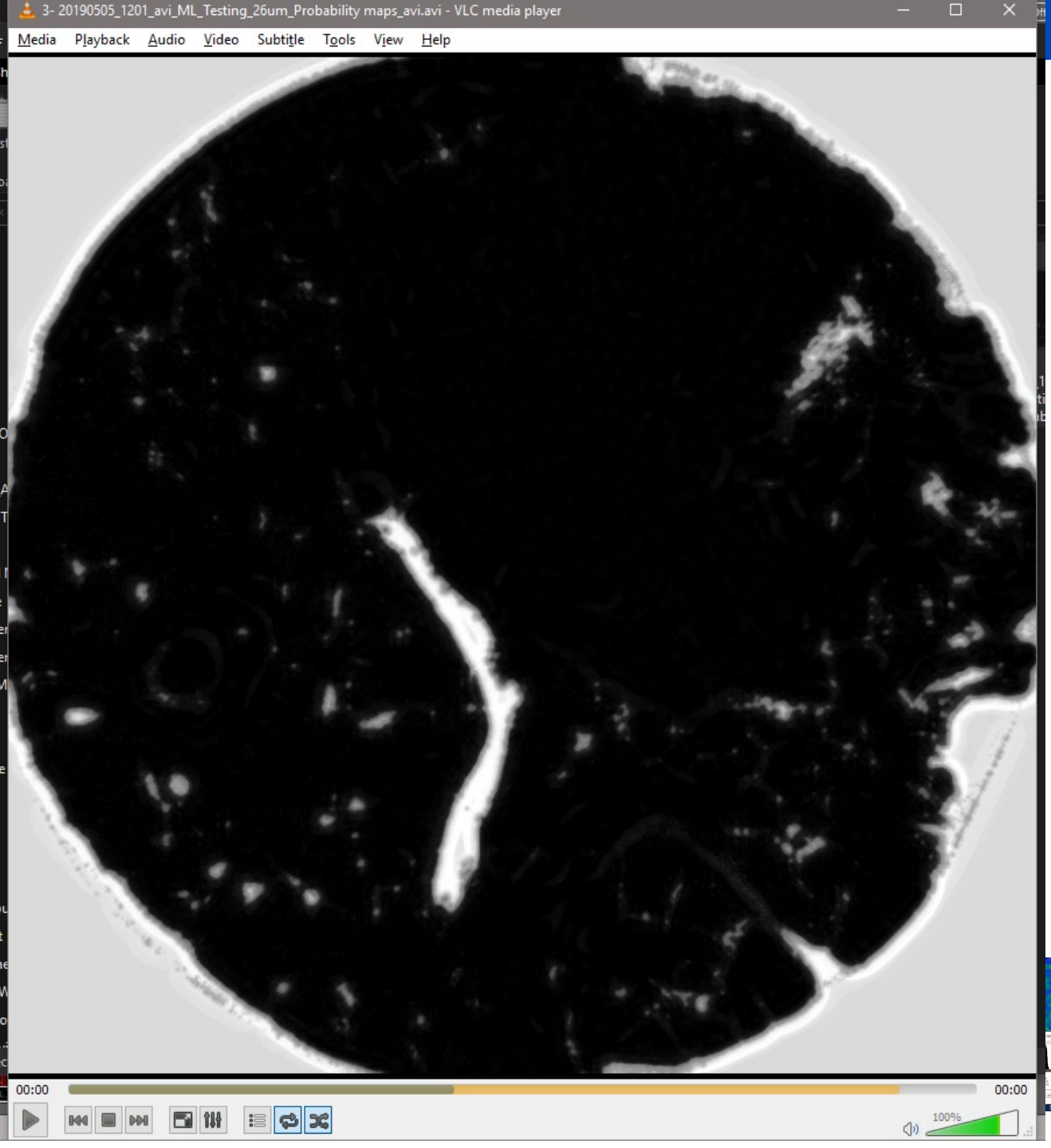
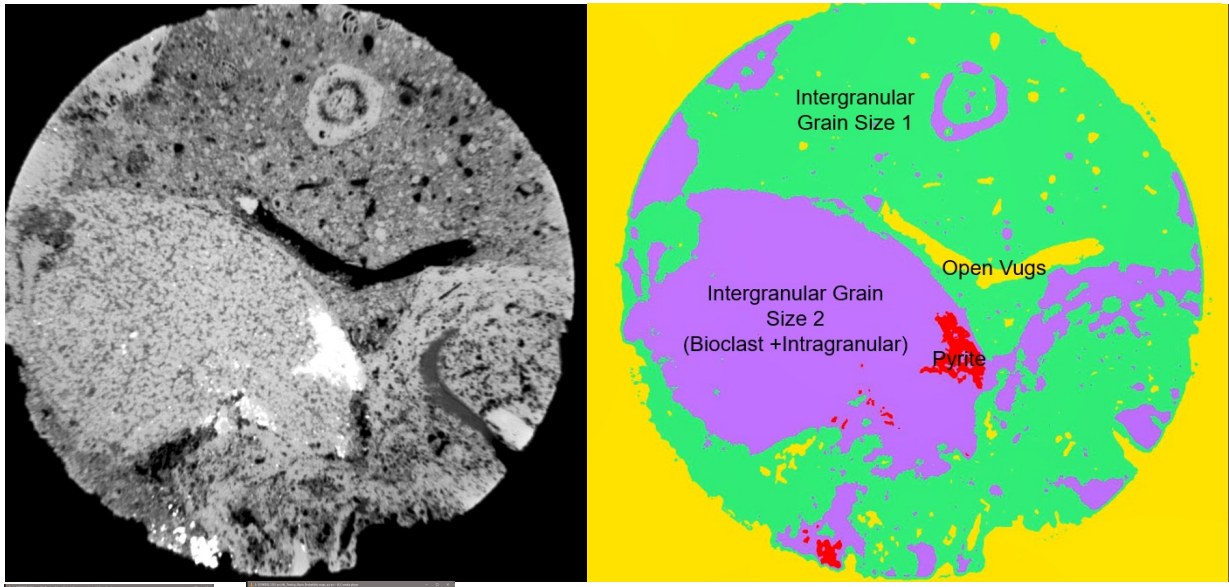




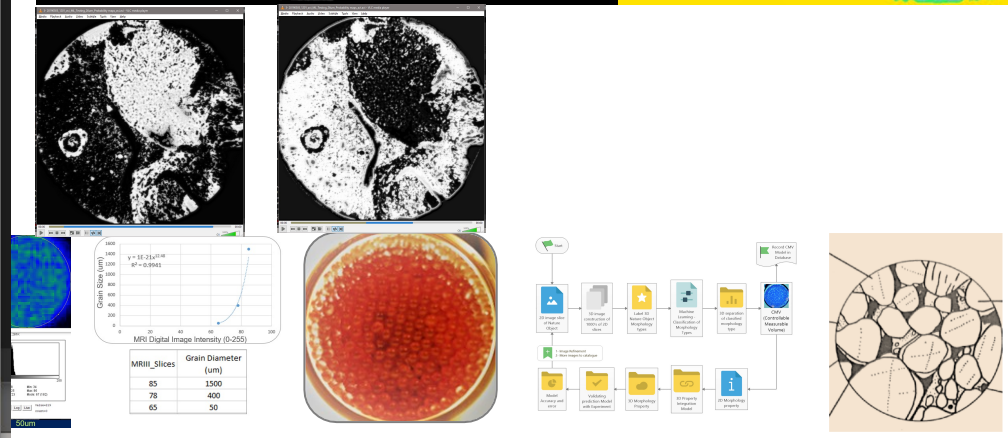
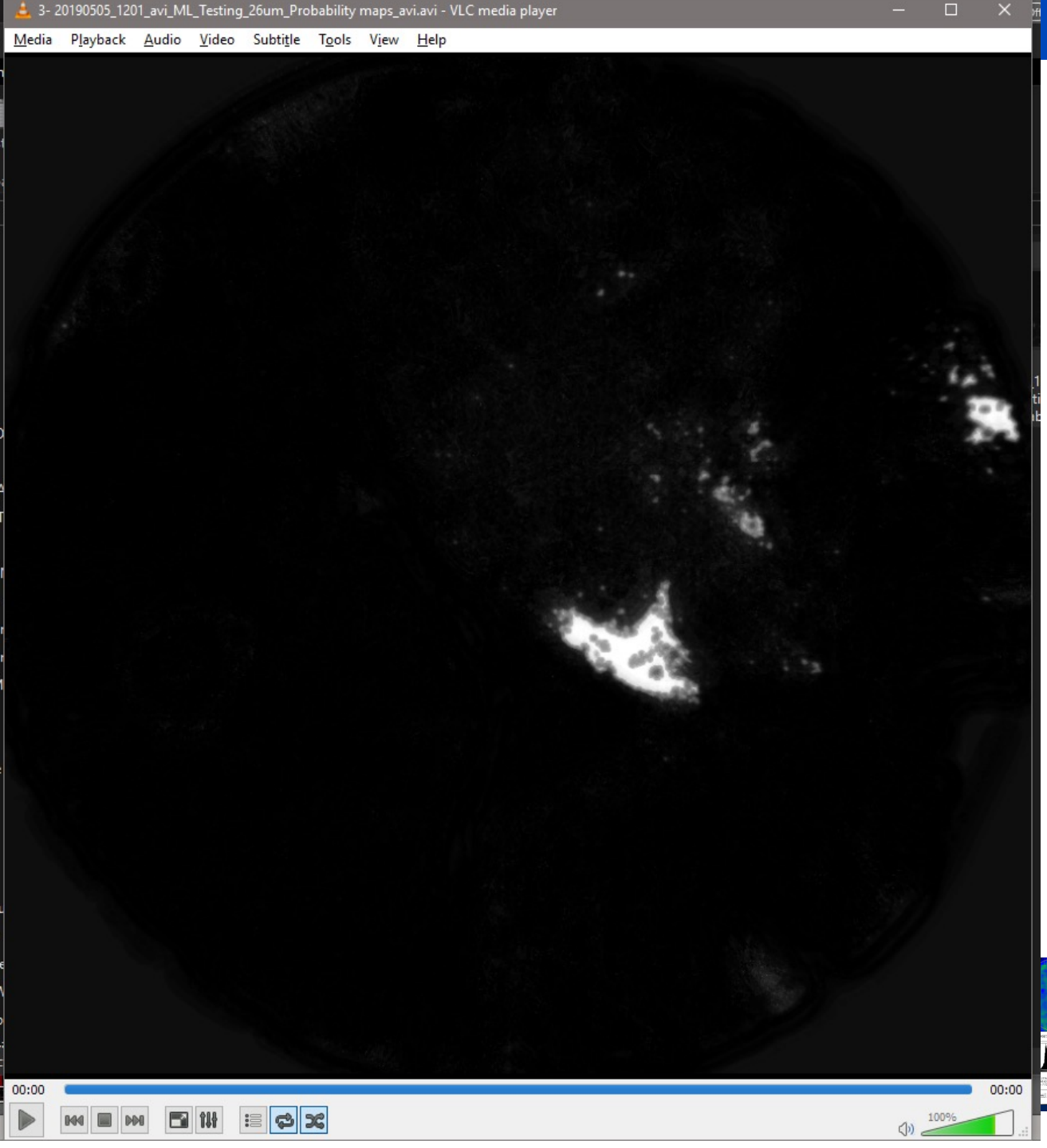
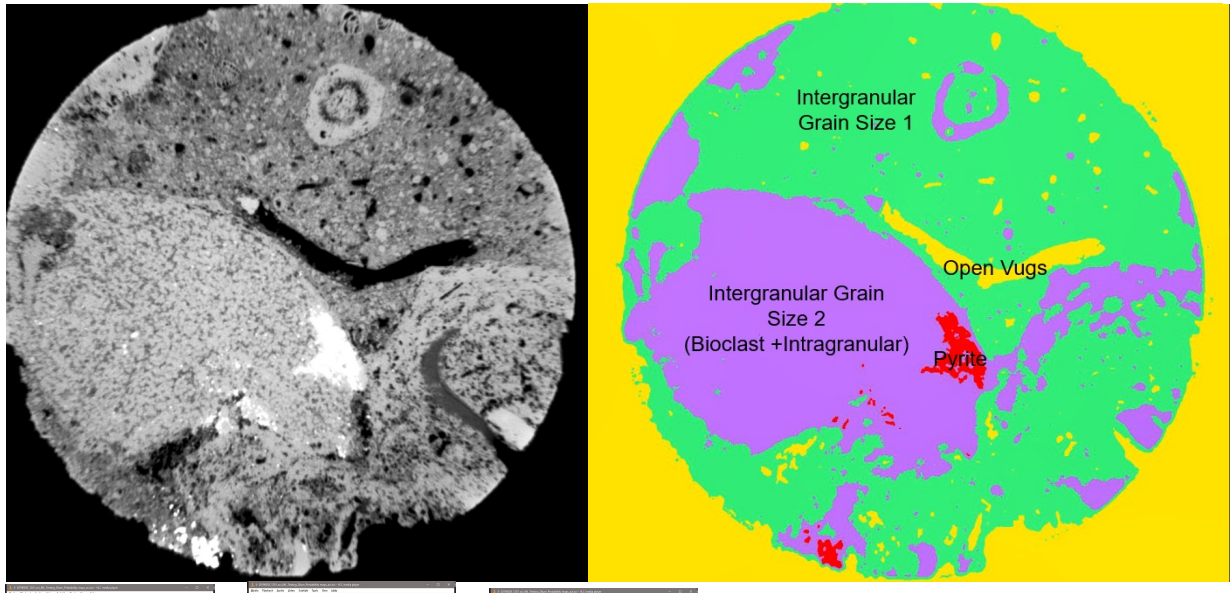
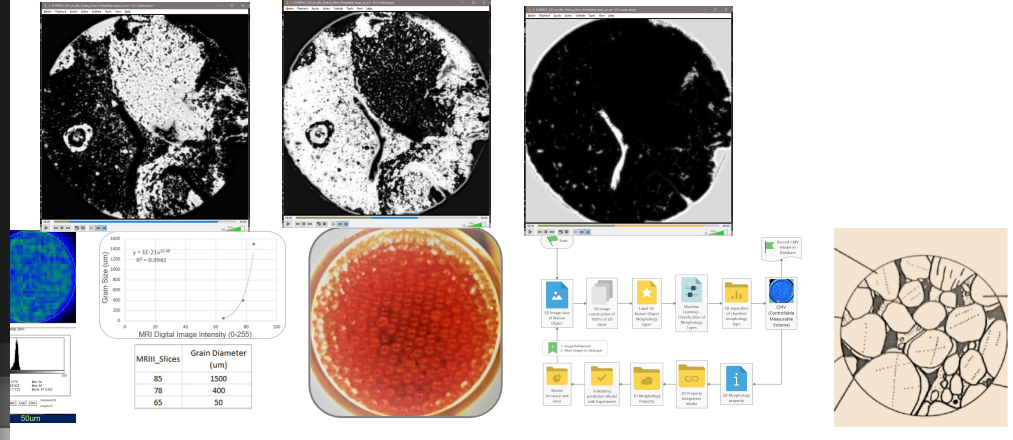


Image Processing Segregation of Morphology







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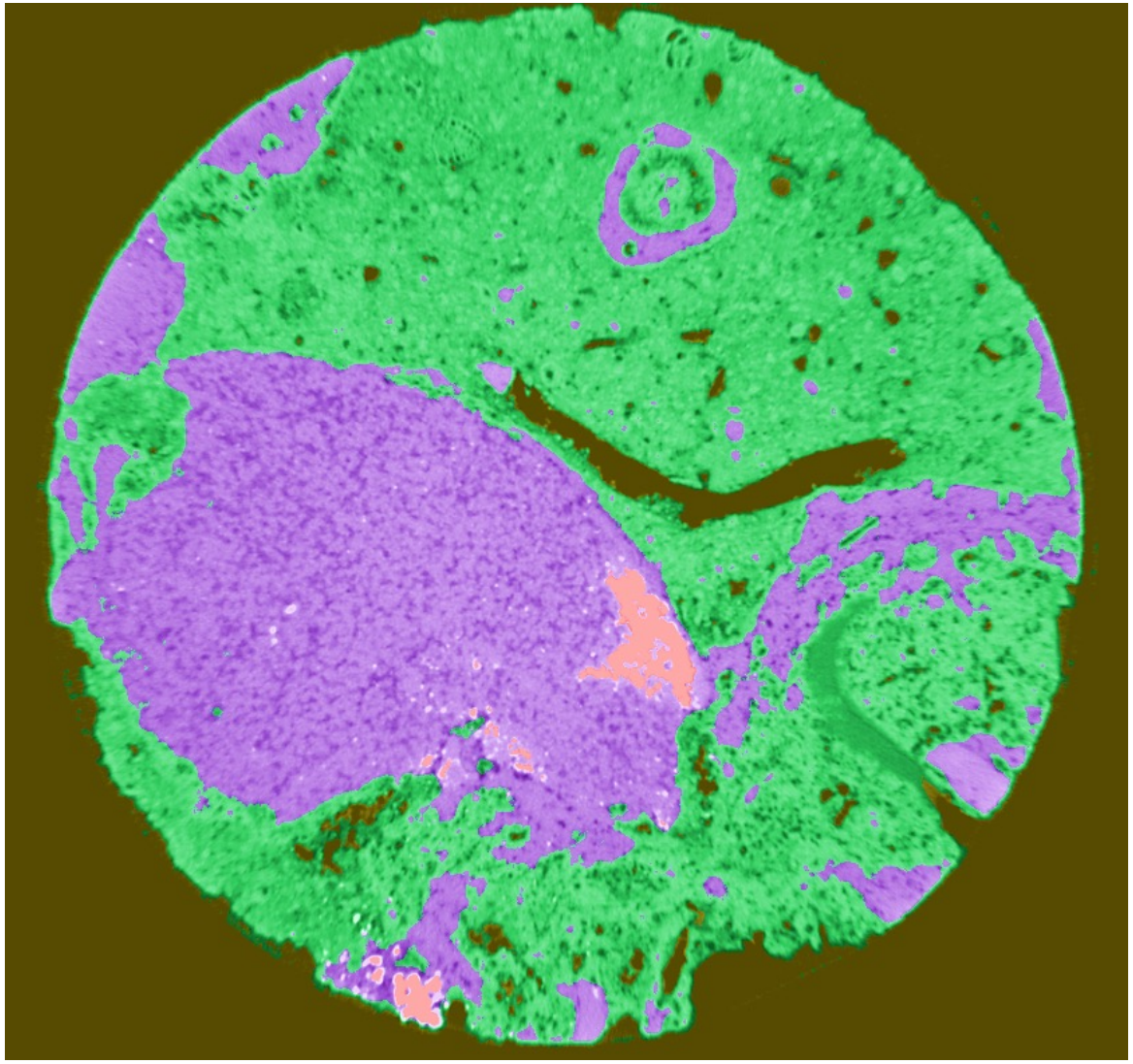

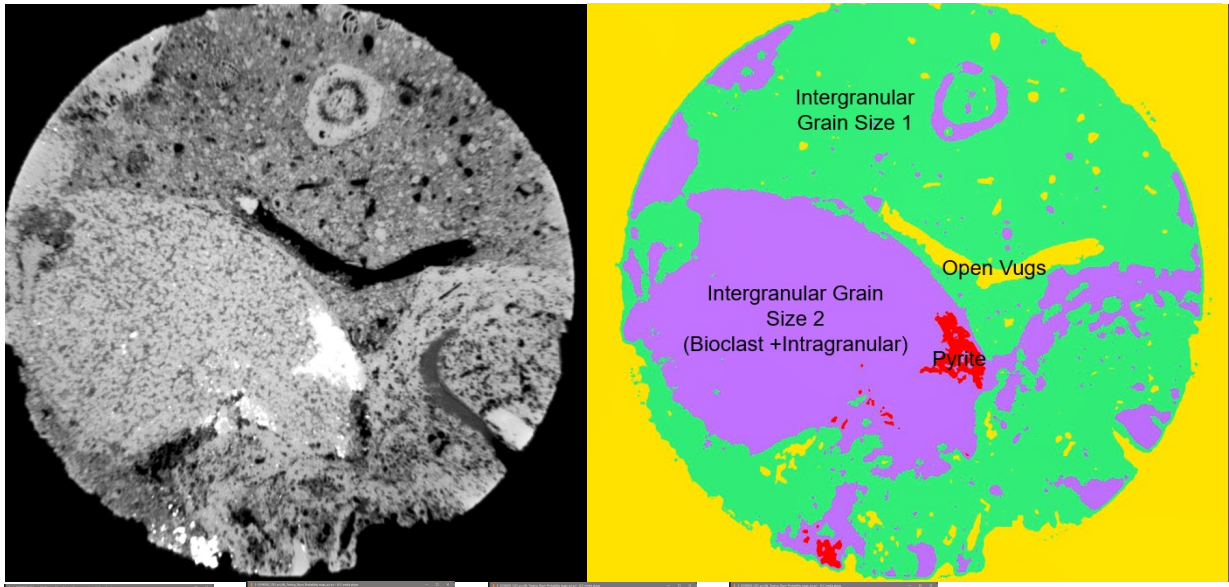

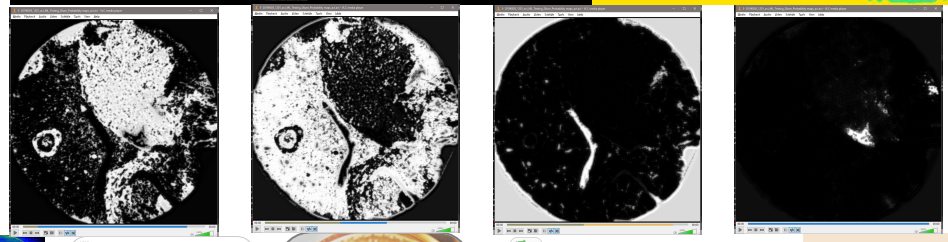

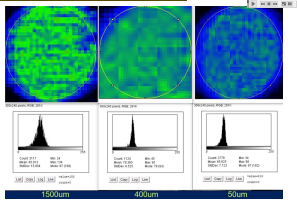

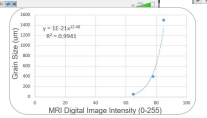

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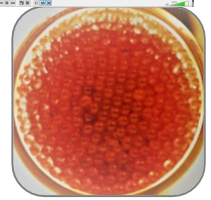
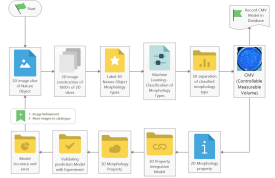
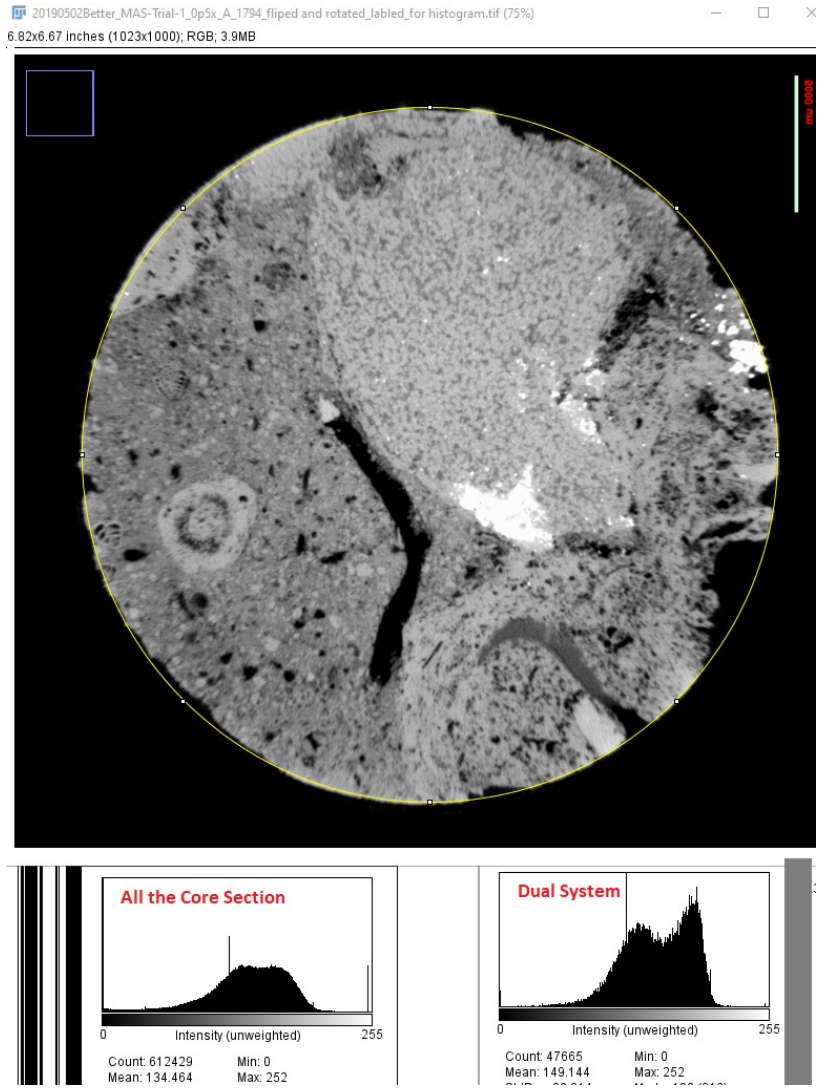
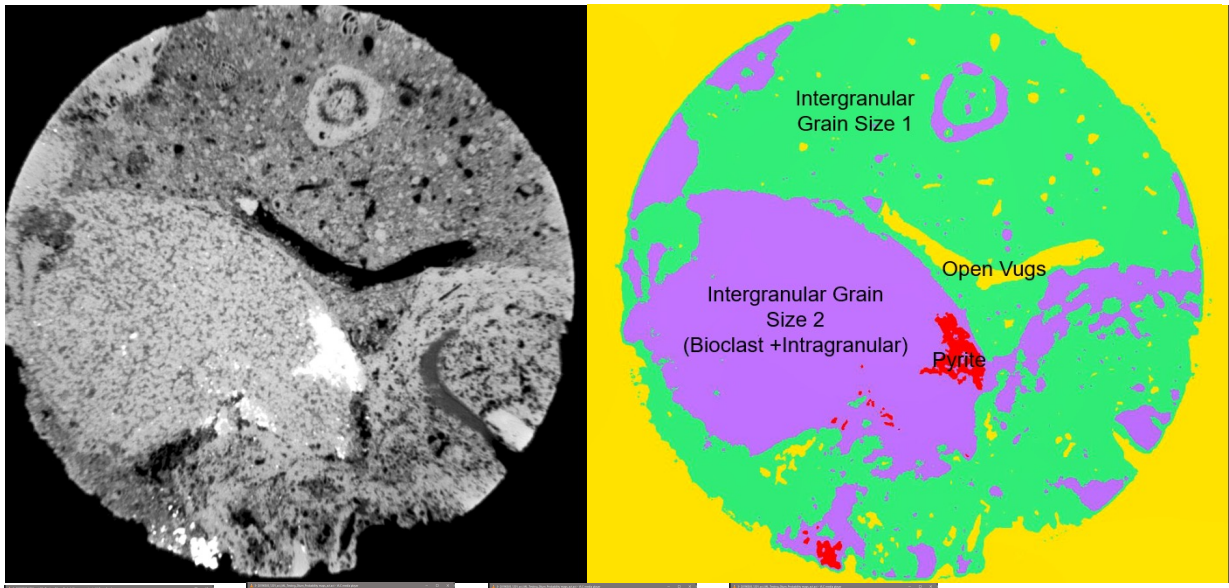
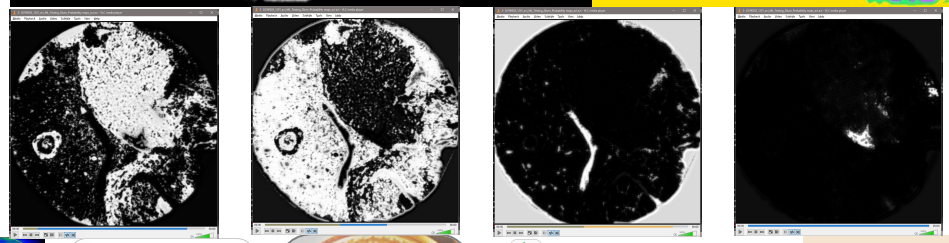


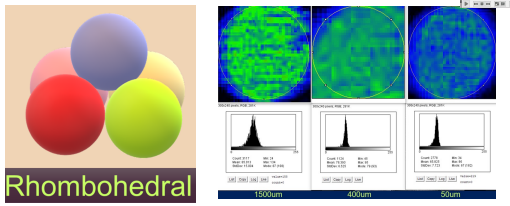


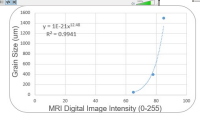
(Dual Pore system) identified by Image Processing Segregation of Morphology











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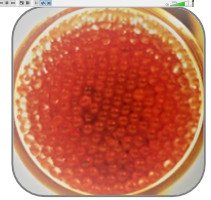
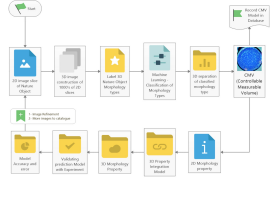
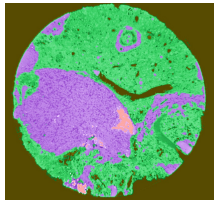


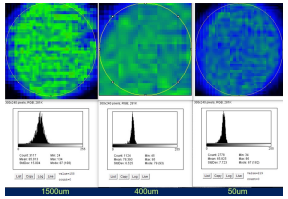


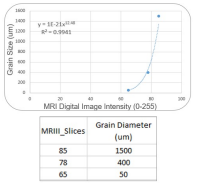


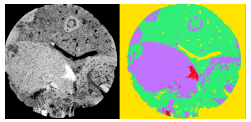
Machine Learning Heterogenous Morphology Segmentation

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

Darcy Equation







Machine Learning Heterogenous Morphology Segmentation

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

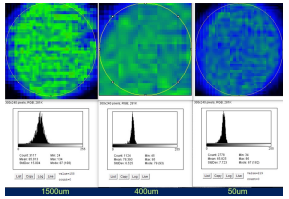
Darcy Equation

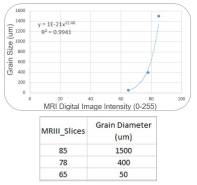
$$k = \left(\frac{q \,.\, l \,.\, \mu}{A \,.\, \nabla p}\right) = \left(\frac{A \,.\, l^2 \,.\, \mu}{t \,.\, A \,.\, \nabla p}\right) = \left(\frac{t \,.\, A \,.\, l^2 \,.\, F}{t \,.\, A \,.\, l^2 \,.\, \nabla p}\right) = \left(\frac{t \,.\, A^2 \,.\, l^2 \,.\, F}{t \,.\, A \,.\, l^2 \,.\, F}\right)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

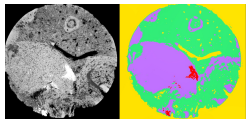
or $\boxed{Permeability\ (mD) = Area\ (um)^2}$

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

or $k = A$







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

Darcy Equation

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

or $\quad Permeability\ (mD) = Area\ (um)^2$

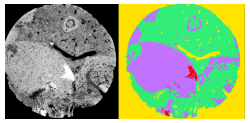
Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education.

or $\quad k = A$

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

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

$$PorTS_{rhombohedral_{3D_{Effective}}} = A_{surface_{grain}} = 0.02731\pi r_g^2 \qquad (9)$$



Machine Learning Heterogenous Morphology Segmentation

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

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

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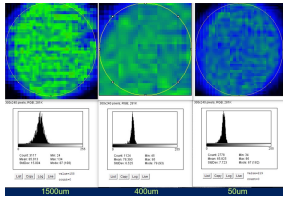
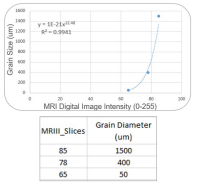
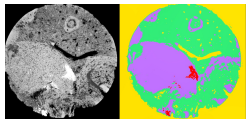
Permeability is a resultant of both grain size and grain configuration to form a proportional relation between permeability and grain surface area (*58*) " this physical aspect of permeability has been used to create empirical equations for prediction of permeability," as described below in Eq. 10:

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

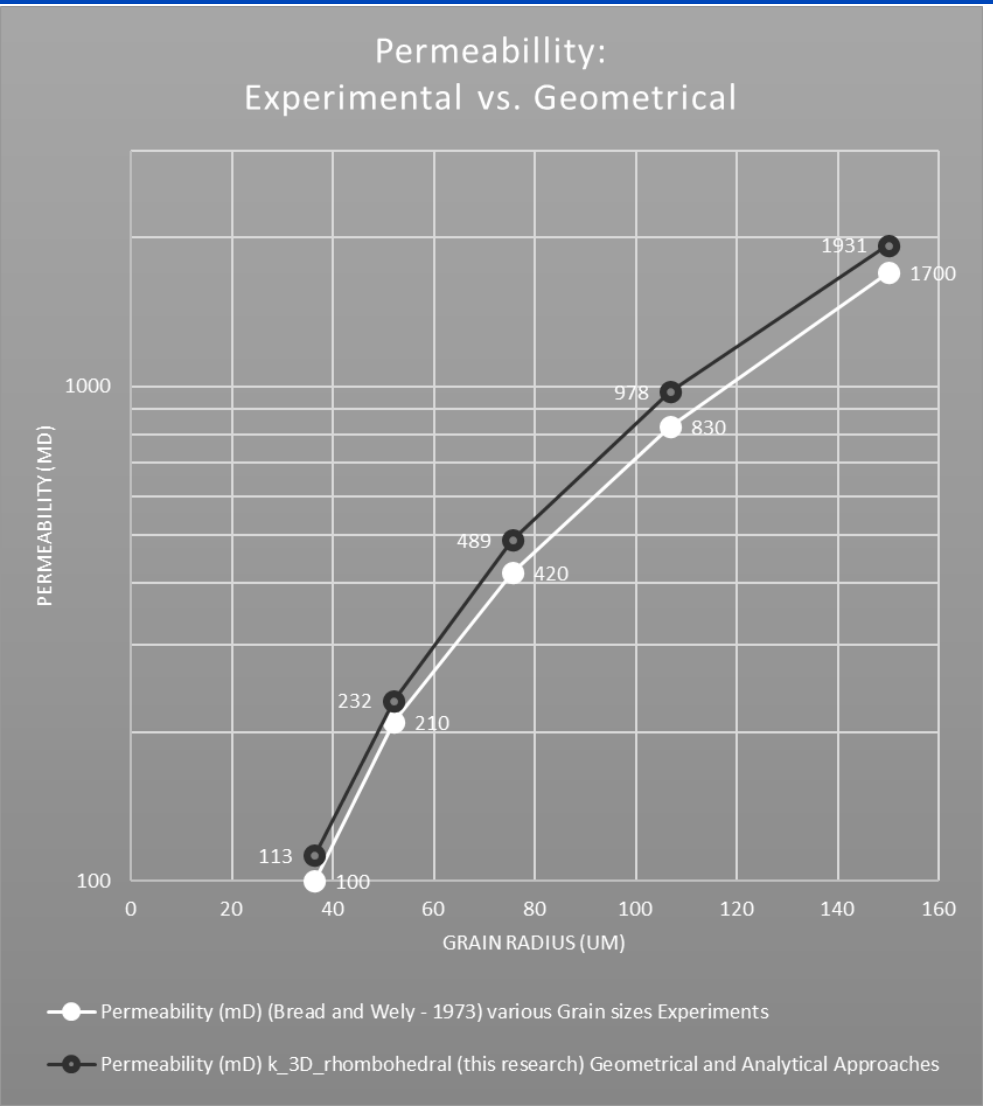
$$k_{3D_{rhombohedral}} = PorTS_{rhombohedral_{3D_{Effective}}} = 0.0858 r_g^2 \quad (11)$$





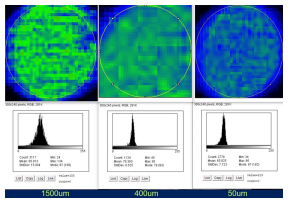


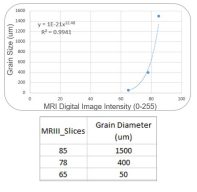
Permeability Equation Validation

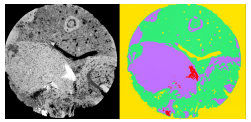


$$k_{3D_{rhombohedral}} = PorTS_{rhombohedral_{3D_{Effective}}} = 0.0858r_g^2$$

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



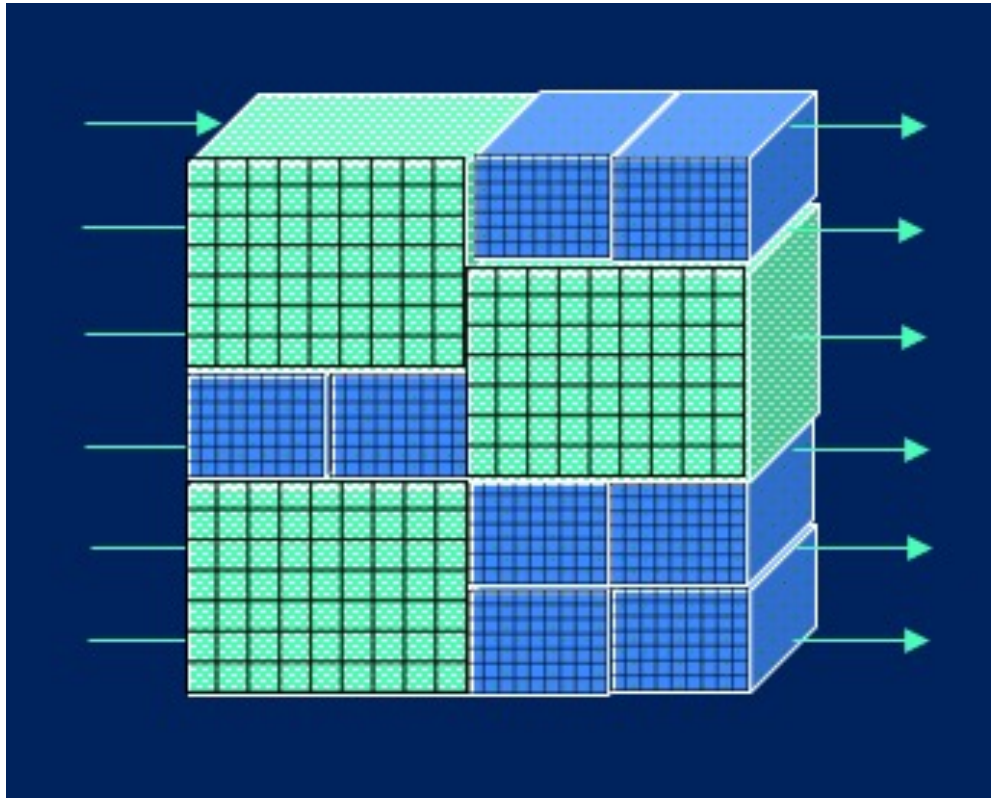




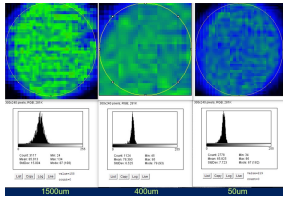
3D Permeability Equations

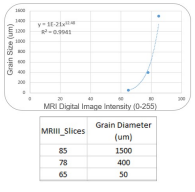
$$k_{avg\_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \qquad (4.5)$$

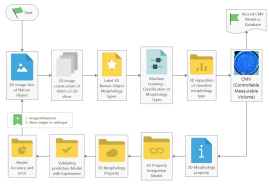
$$k_{avg\_Paralel} = \frac{h_1 * k_1 + h_2 * K_2}{h_1 + h_2} \qquad (4.6)$$

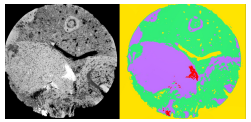


Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education. P-304.





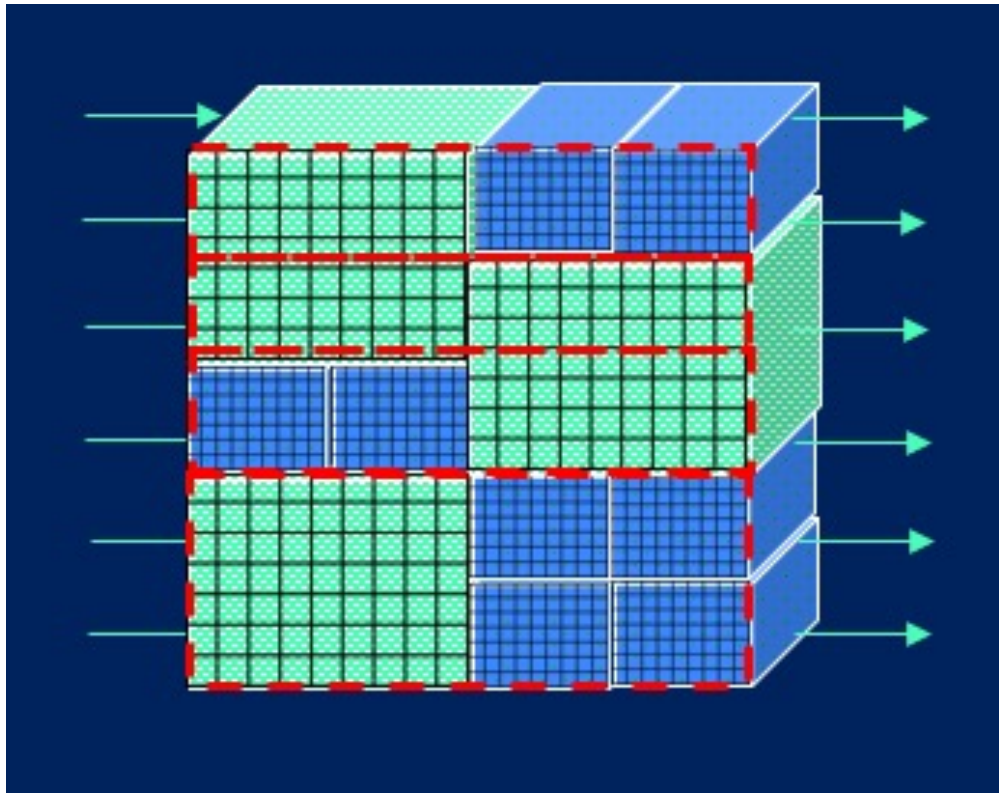


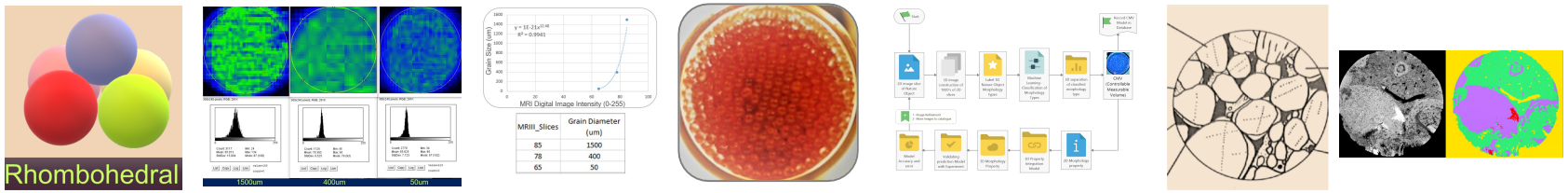


3D Permeability Equations for Heterogeneous Fabric

$$k_{avg\_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \qquad (4.5)$$

$$k_{avg\_Paralel} = \frac{h_1 * k_1 + h_2 * K_2}{h_1 + h_2} \qquad (4.6)$$

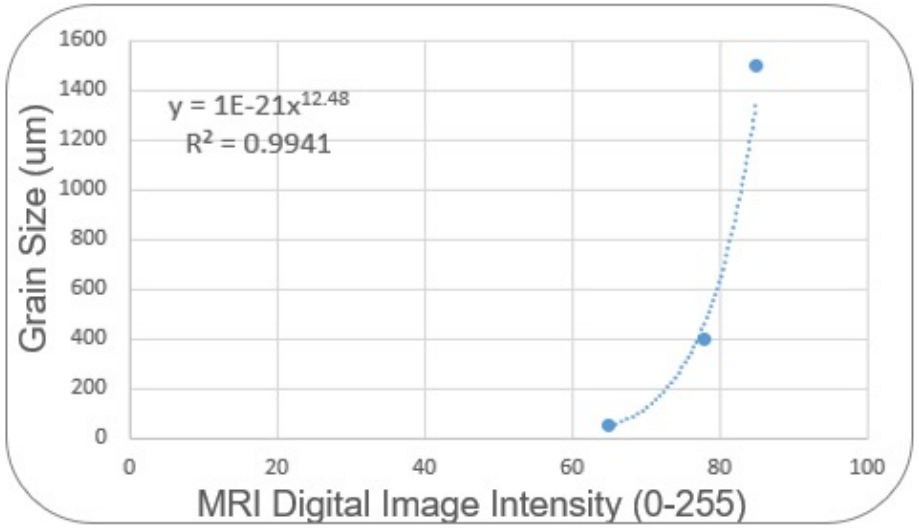




3D Permeability Equations and MRIII Model Validation

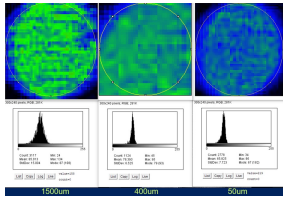
$$k_{avg\_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \qquad (4.5)$$

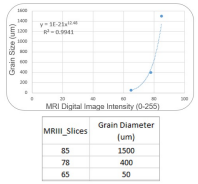
$$k_{avg\_Paralel} = \frac{h_1 * k_1 + h_2 * K_2}{h_1 + h_2} \qquad (4.6)$$

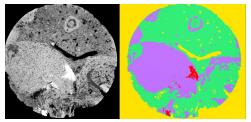


MRIII_Slices	Grain Diameter (um)
85	1500
78	400
65	50

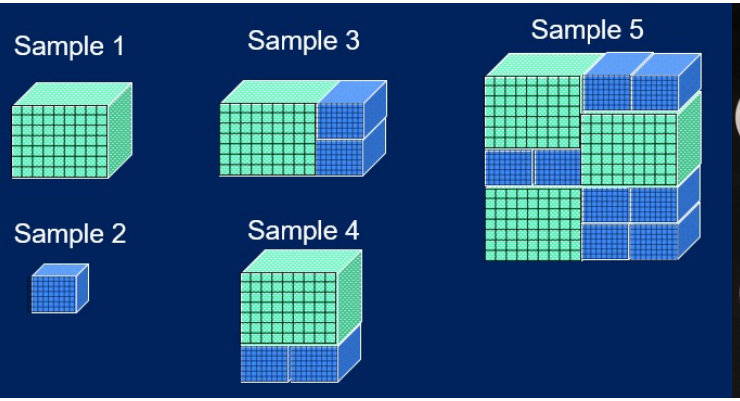
Ezekwe, N. (2010). Petroleum reservoir engineering practice. Pearson Education. P-304.

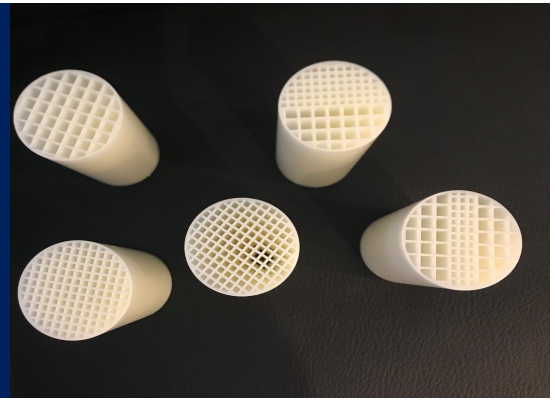






3D Permeability Equations





Designed five 3D models and 3D printed them

$$k_{avg\_Series} = \frac{l_1 + l_2}{\left(\frac{l_1}{k_1}\right) + \left(\frac{l_2}{k_2}\right)} \qquad (4.5)$$

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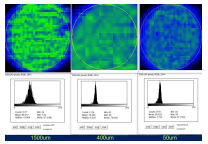
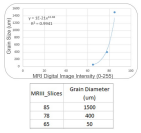
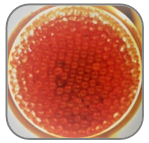
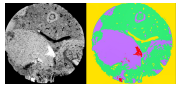
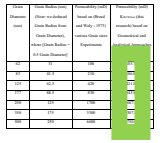


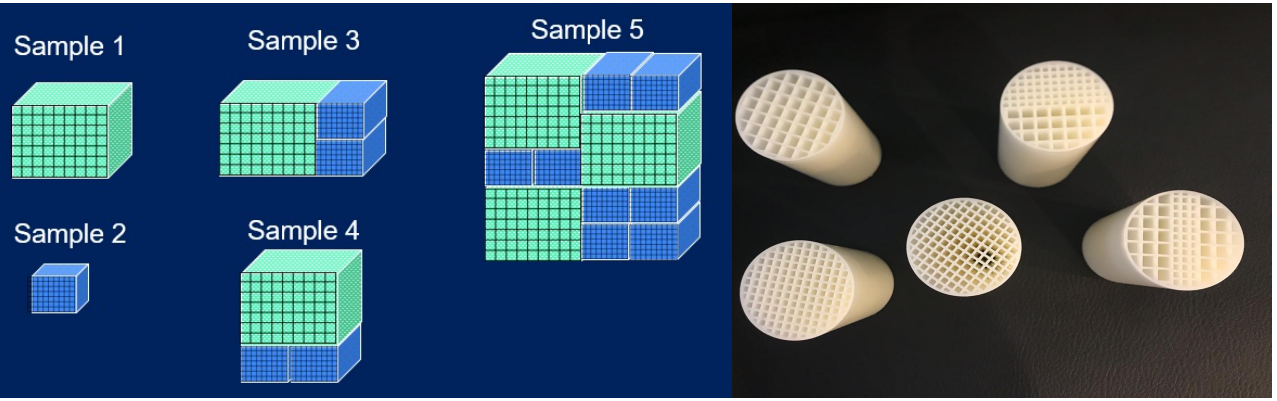








3D Permeability Equations



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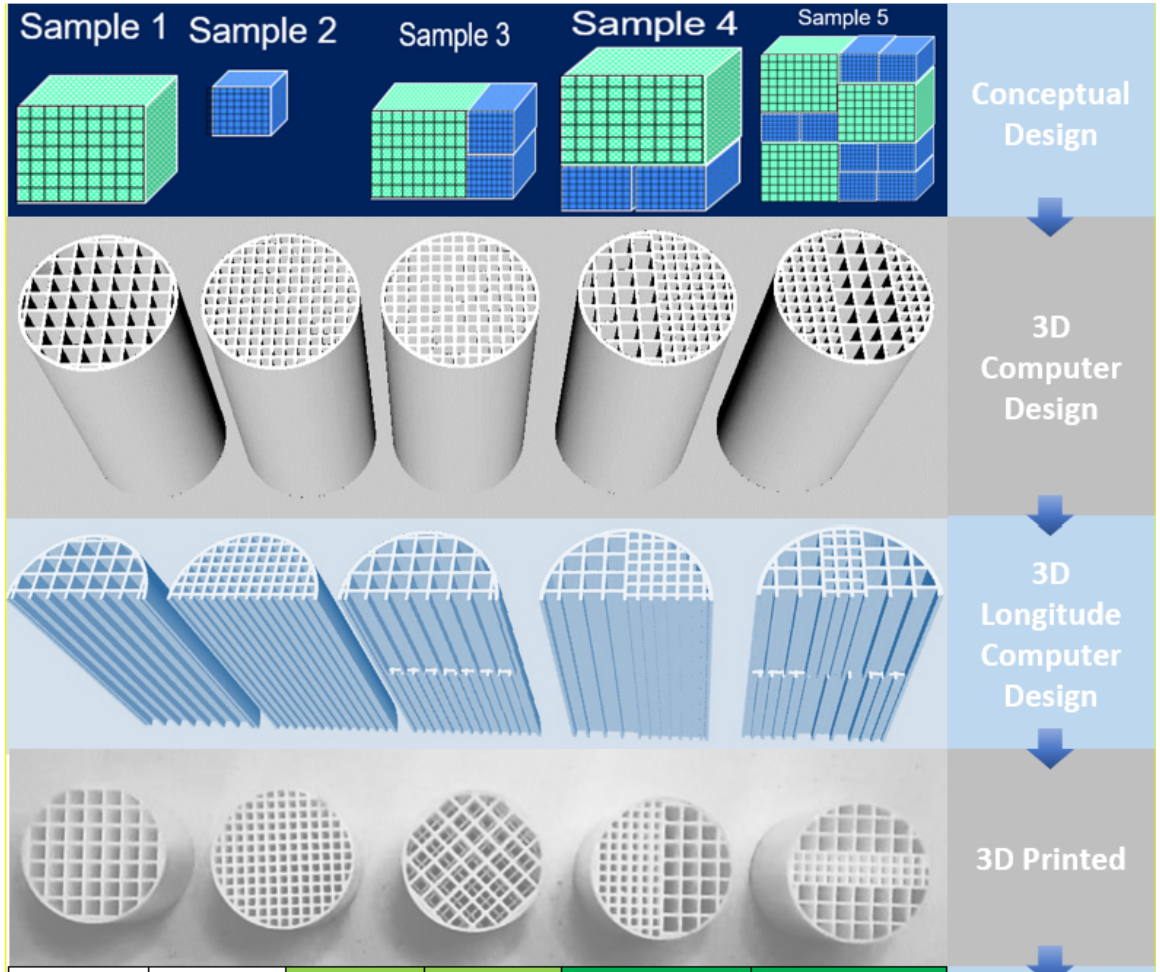
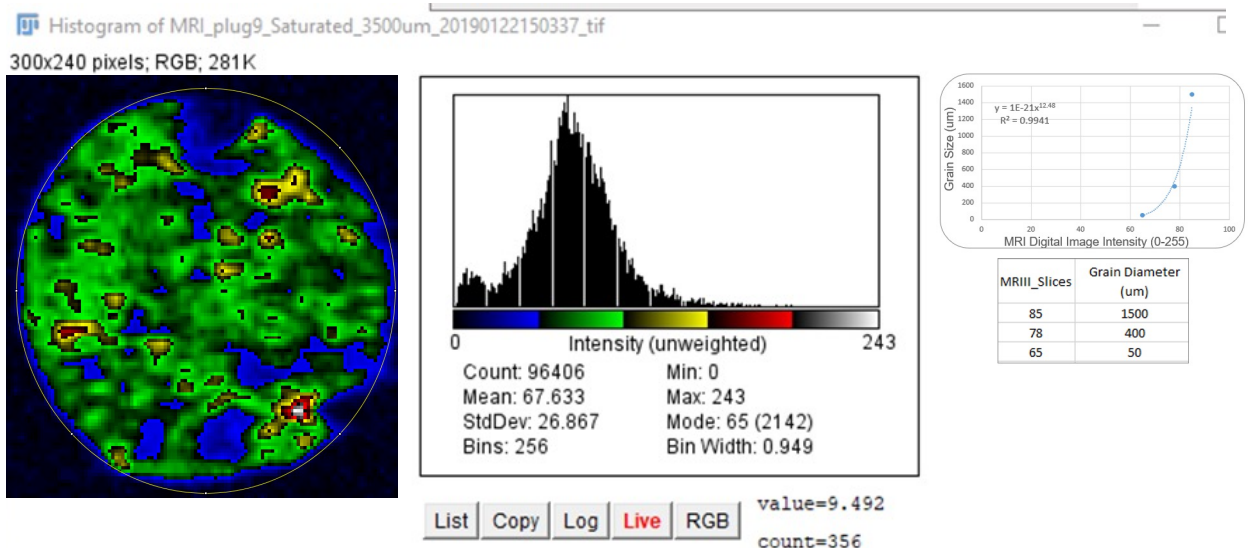


k_Large (Darcy) Measured	K_Small (Darcy) Measured	K_Serial (Darcy) Predicted	K_Serial (Darcy) Measured	K (Darcy) Heterogenous Predicted	K (Darcy) Heterogenous Measured
45.65	35.18	39.74	38.00	42.59	41.44

Journal Paper due for submission:

O. Al-Farisi[1,2,3*], A. Raza[1], H. Zhang[1], H. Li[1], D. Ozzane[4,5], M. Sassi[1], T. Zhang[1] , (2019) Decoding heterogeneity by 3D-vision machine learning reveals Cretaceous permeability.

MRIII Model Validation



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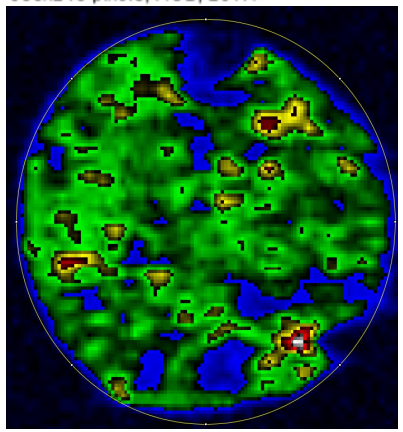
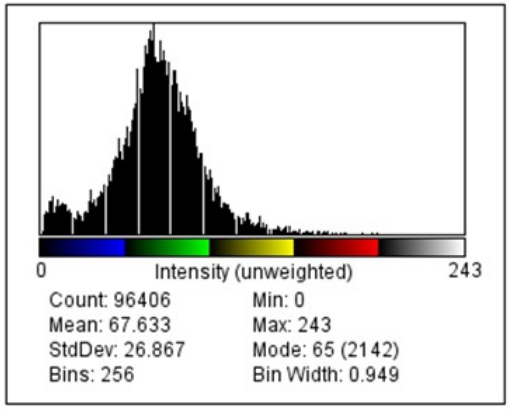
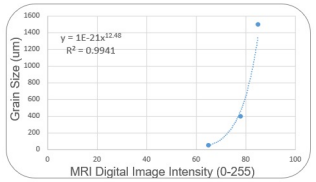
3D Permeability Equations and MRIII Model Validation

Histogram of MRI_plug9_Saturated_3500um_20190122150337_tif

300x240 pixels; RGB; 281K







MRIII_Slices	Grain Diameter (um)
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78	400
65	50

List | Copy | Log | Live | RGB

value=9.492

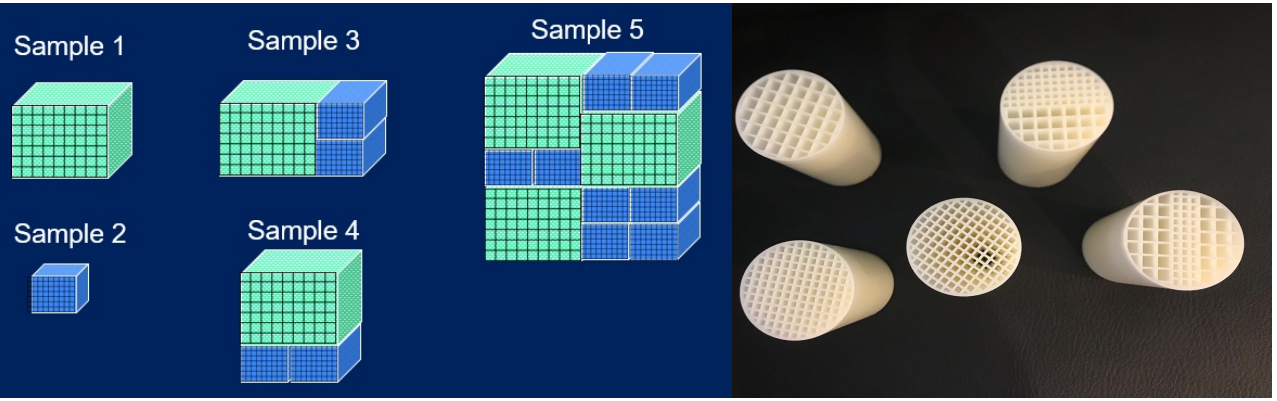
count=356

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

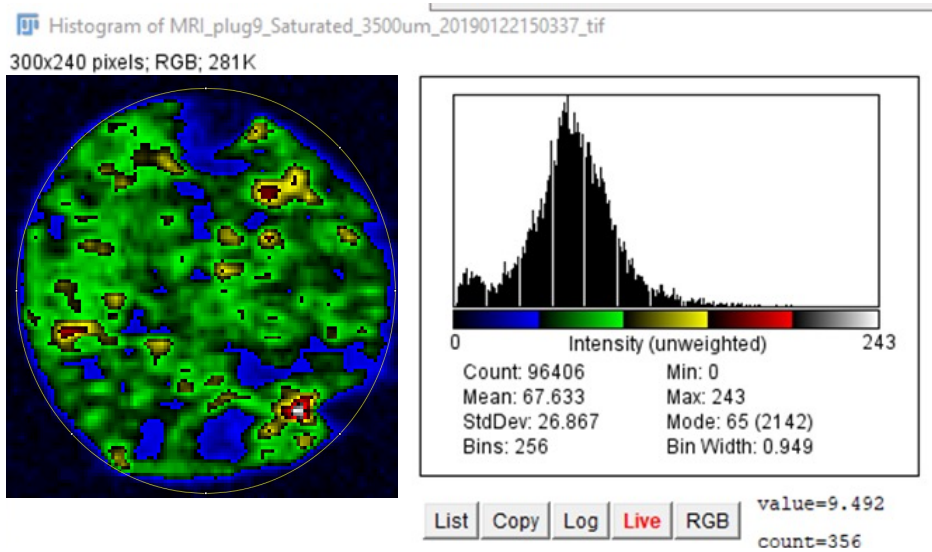
Journal Paper due for submission:

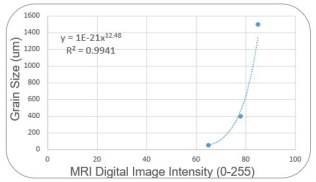
O. Al-Farisi[1,2,3*], A. Raza[1], H. Zhang[1], H. Li[1], D. Ozzane[4,5], M. Sassi[1], T. Zhang[1] , (2019) Decoding heterogeneity by 3D-vision machine learning reveals Cretaceous permeability.

3D Permeability Equations and MRIII Model Validation



Designed five 3D models and 3D printed them





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MRII_Slice from plug 9	Drain Diameter calculated from Chart	Permeability (mD) from K_Omar2019	Core Permeability
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$$k_{avg\_Series} = \frac{l_1+l_2}{\left(\frac{l_1}{k_1}\right)+\left(\frac{l_2}{k_2}\right)} \qquad (4.5)$$

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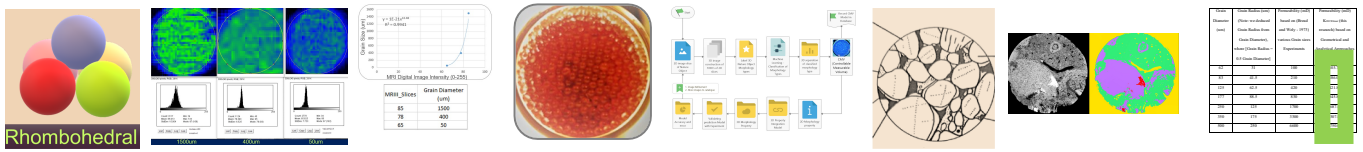
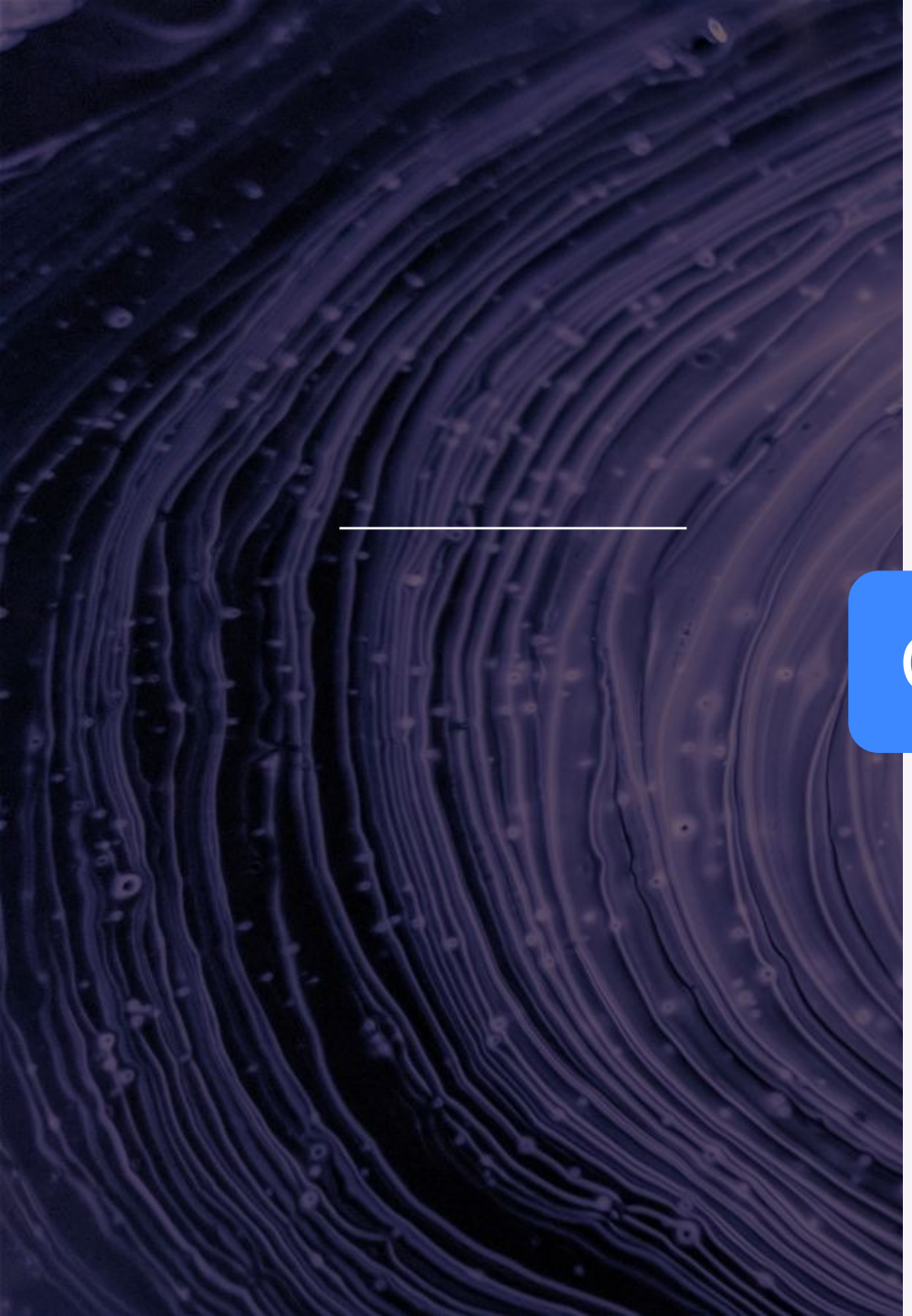
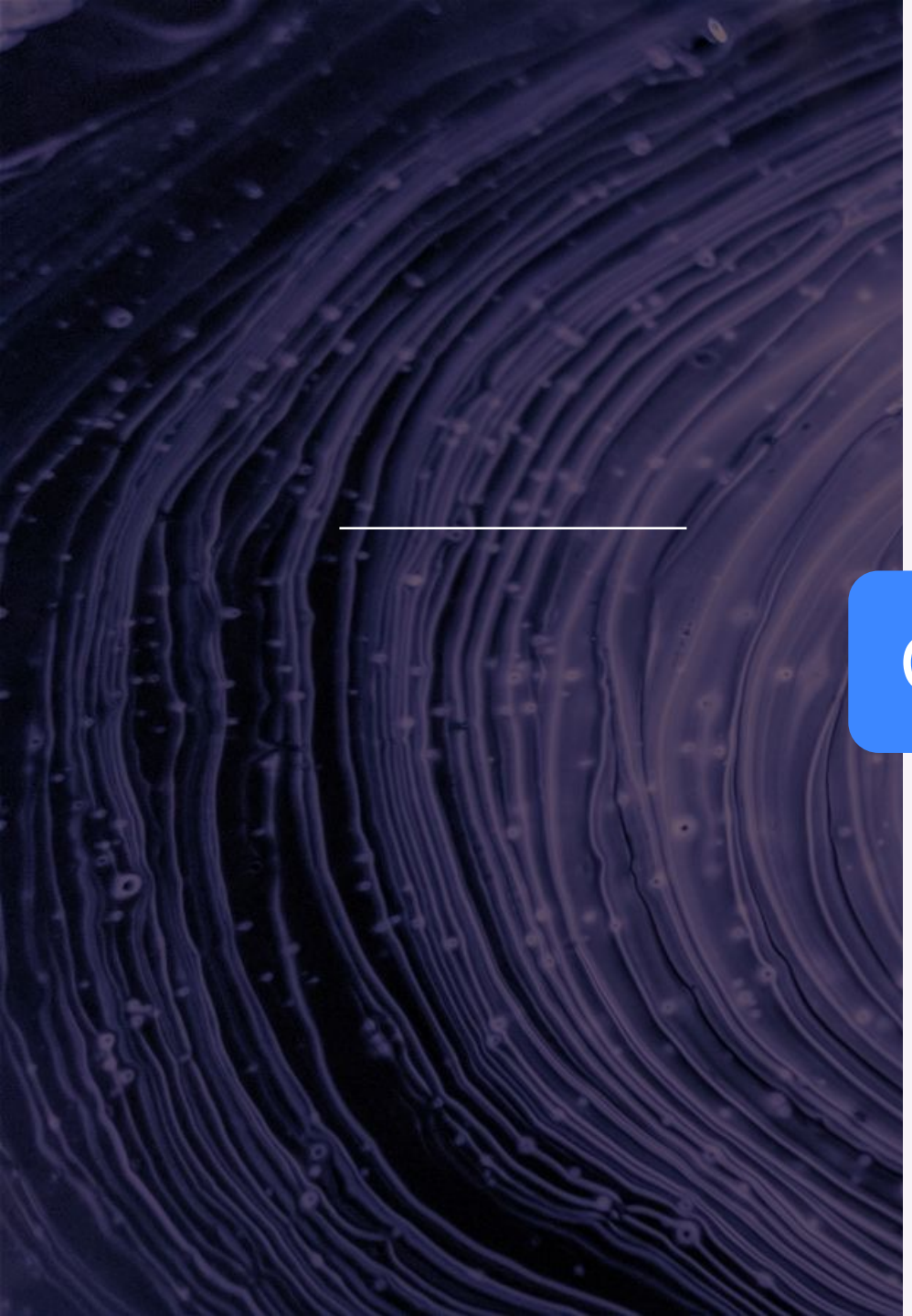




Content

Machine Learning 3D Image Recognition



Content

Machine Learning 3D Image Recognition

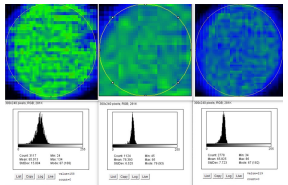
Pc (Capillarity) - Machine Learning Heterogenous Morphology

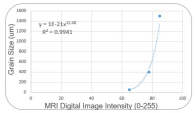
$$P_c = \frac{2\,\sigma\,cos\theta}{r} \qquad (1)$$

Where; r is the pore throat radius, which we also donate r_{PorTh},

σ is Interfacial Tension,

θ is the Contact Angle.





MRIII_Slices	Grain Diameter (um)
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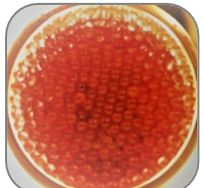

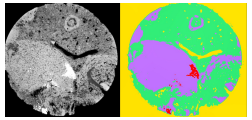

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Pc (Capillarity) - Machine Learning Heterogenous Morphology

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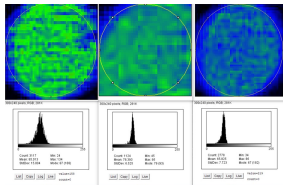

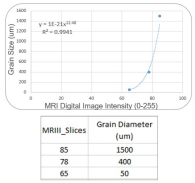

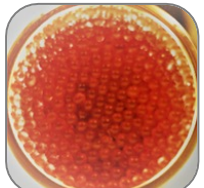

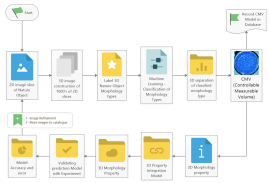

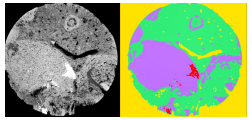

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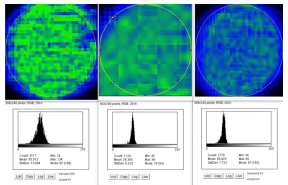

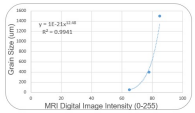

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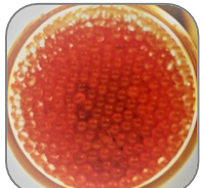

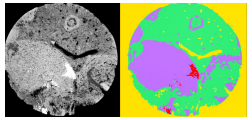

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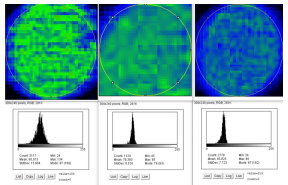

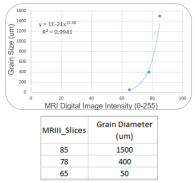

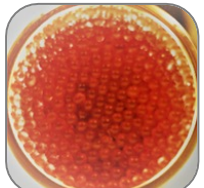

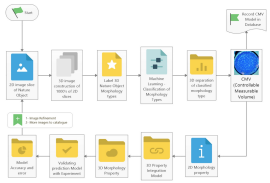

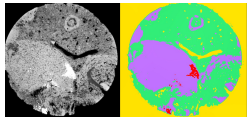

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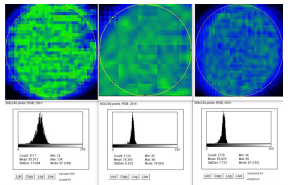

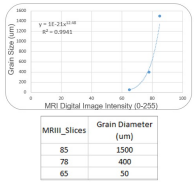

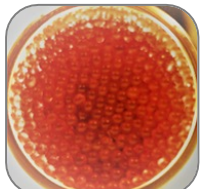

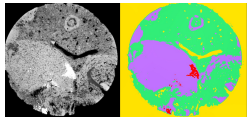

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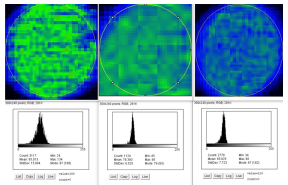

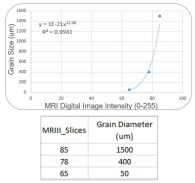

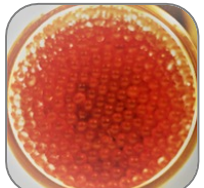

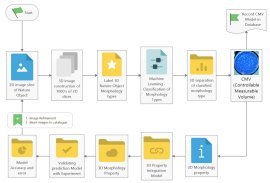

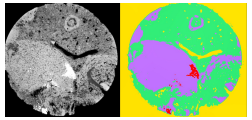

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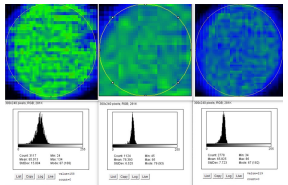

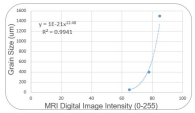

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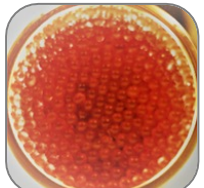

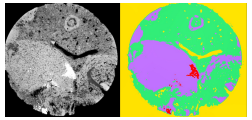

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31	5.77	100.00	103.79	104.75	9.69	
41.5	7.73	210.00	186.00	187.73	7.24	
62.5	11.64	420.00	421.88	425.78	4.80	
88.5	16.48	830.00	845.88	853.72	3.39	
125	23.28	1700.00	1687.50	1703.13	2.40	
175	32.60	3300.00	3307.50	3338.13	1.72	
250	46.57	6600.00	6750.00	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	
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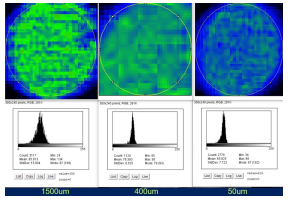

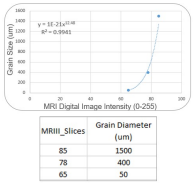

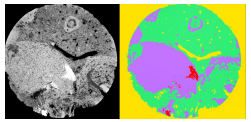

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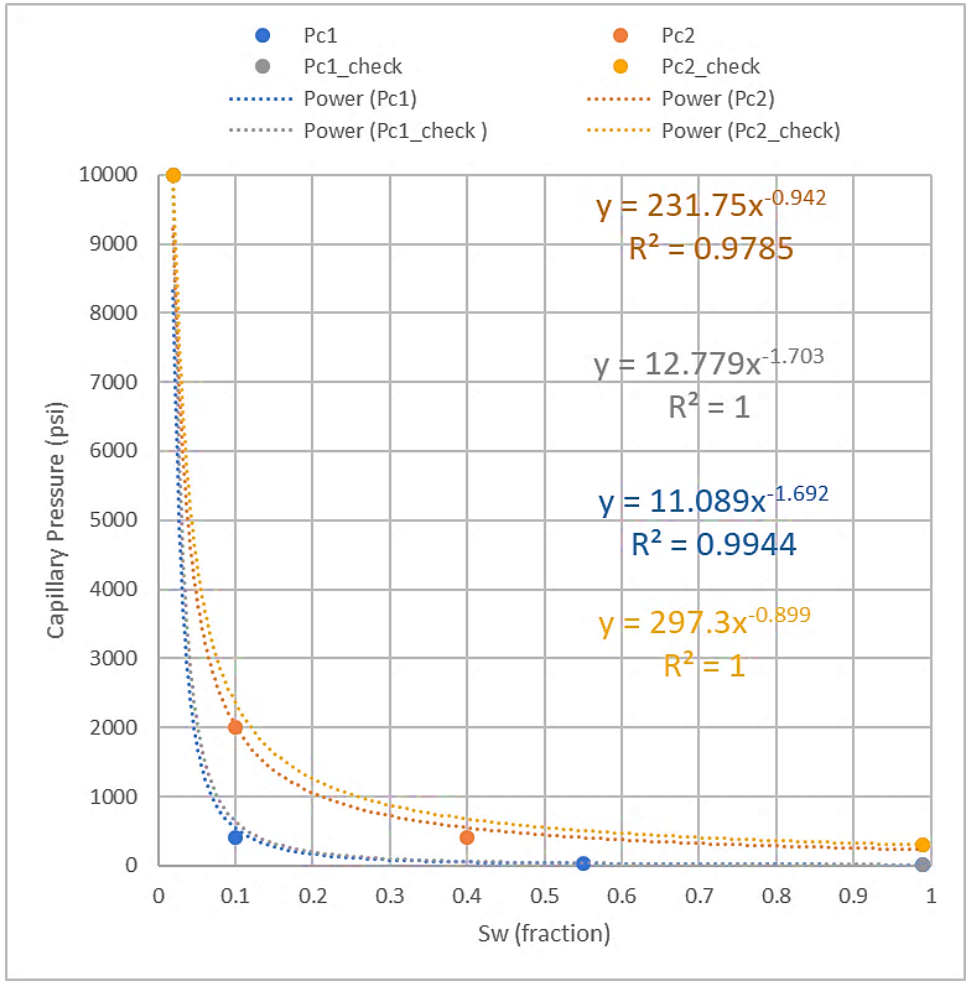

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250	46.57	6600.00	6750.00	6812.51	1.20	
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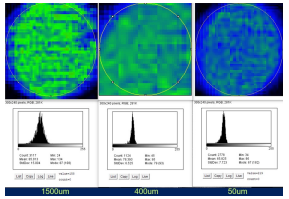
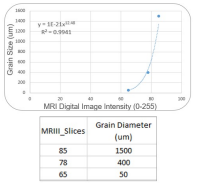
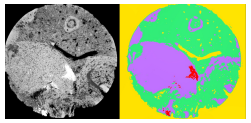
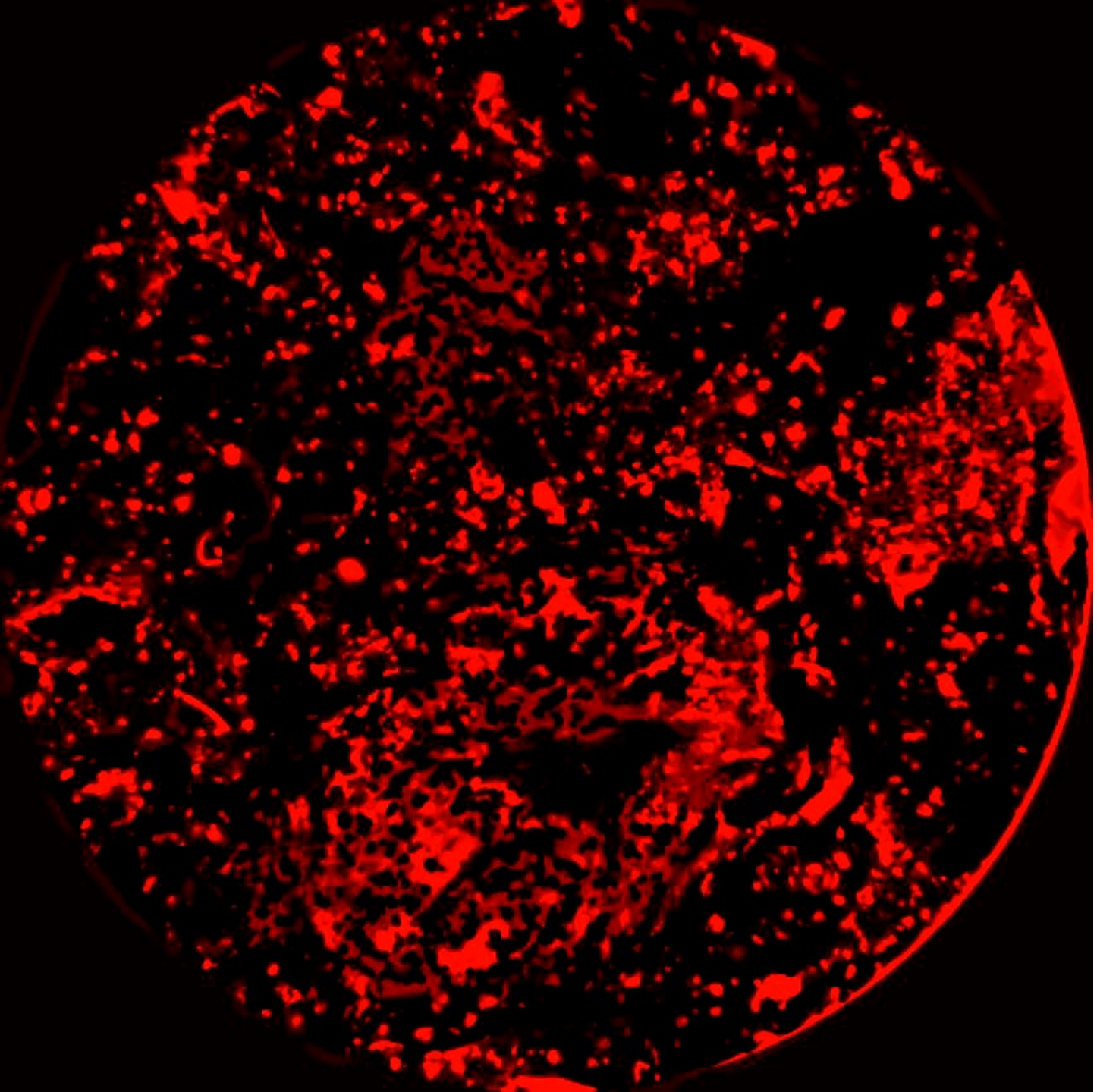
	Experimental Reference
	Converted to Reservoir Condition Field application

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*.









Thank you

Applying Machine Learning Image Recognition with on Carbonate Rock uCT Image