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Implementing Measurement Confidence within Nuclear Wasteform Inspection

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CONTENTS

- 01 Project Preface**
- 02 Spatial Resolution Determination**
- 03 Geopolymer Specimen Scan Results**
- 04 Conclusions**

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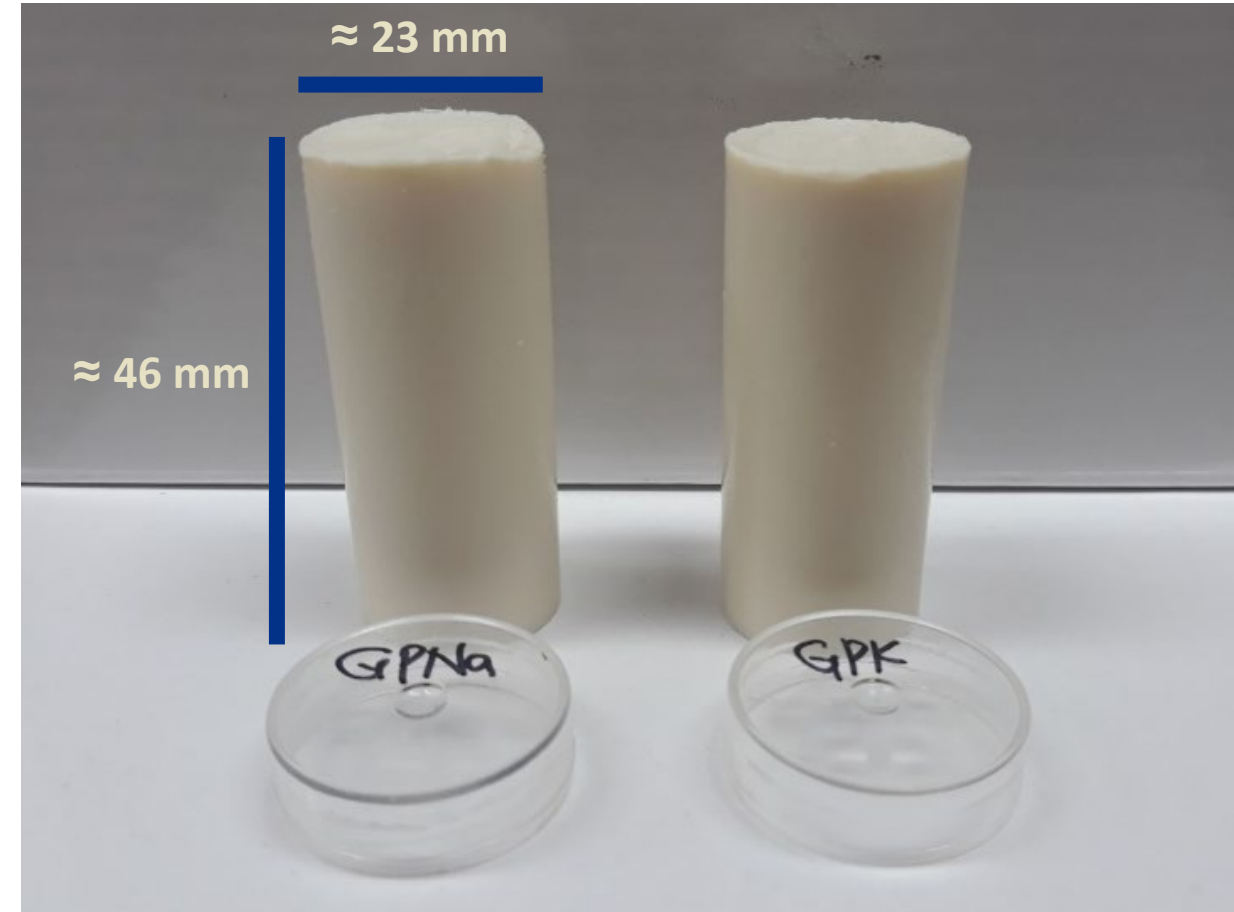
Preface – Geopolymer Specimens

Geopolymer-based Wasteform Potential

- Cement raw material supply chain issues
- Cement environmental impact concerns
- Potential alternative to cement-based wasteform
- Wide ranging compatibility with waste types:
 - Carbon-14 radioactive waste sources
 - Uranium containing waste sludges
 - Contaminated soil wastes
 - Salt wastes

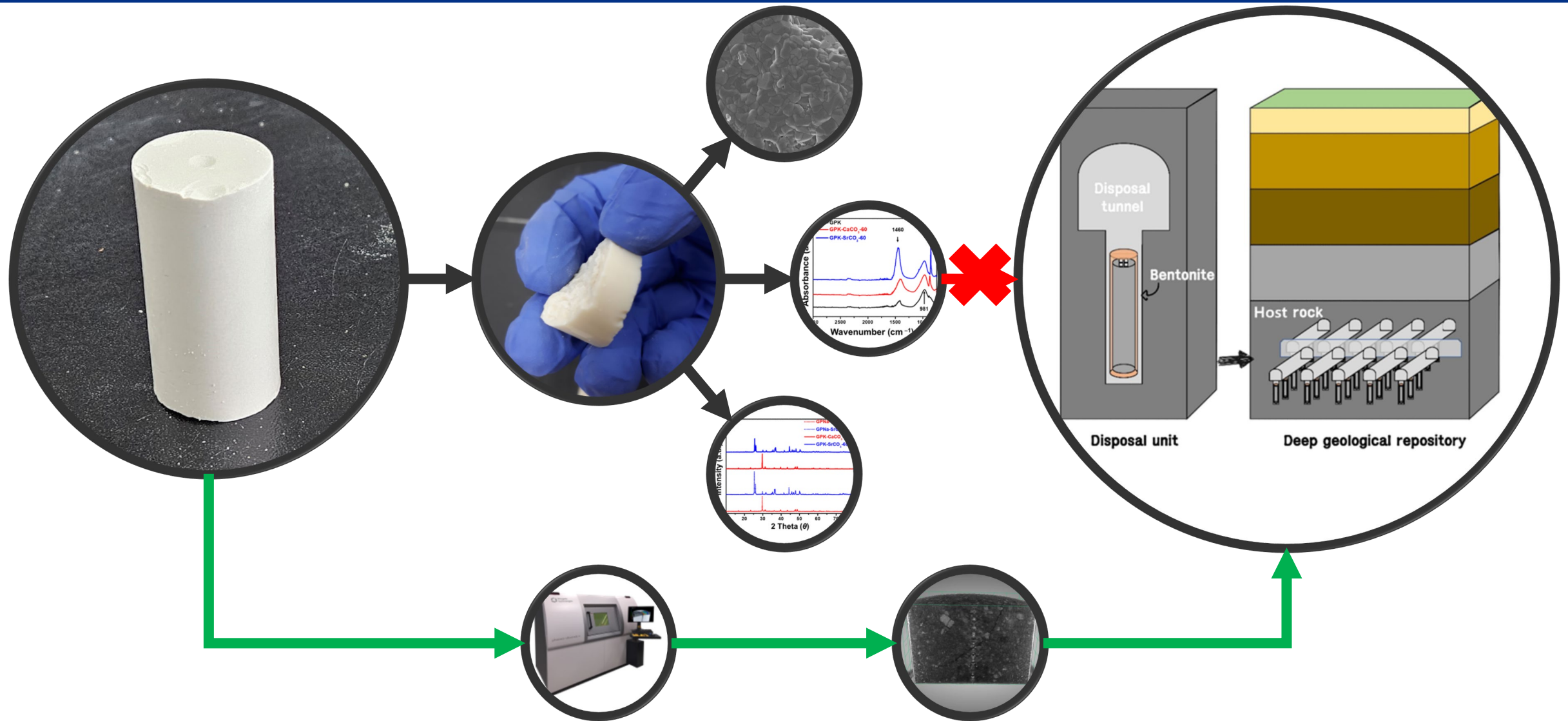
Geopolymer-based Wasteform Challenges

- Cement technology maturity
- Defining composition envelopes
- Curing profiles
- Waste acceptance criteria (WAC) validation
- Safety case development & industry acceptance
- **Lack of confidence?**



Wasteforms “Pristine GPNa” (Left) and “Pristine GPK” (Right).

Preface – Project Overview



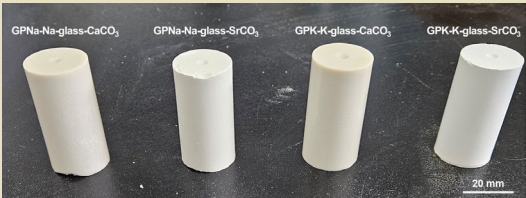
Preface – Project Execution



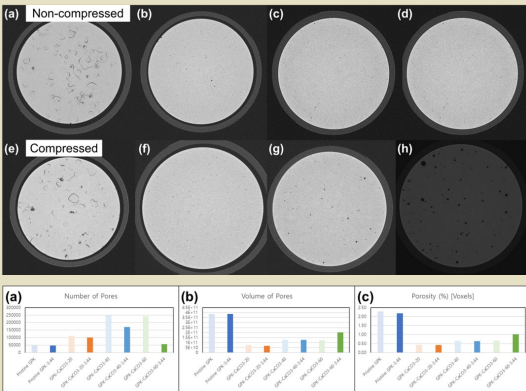
Korea Atomic Energy
Research Institute



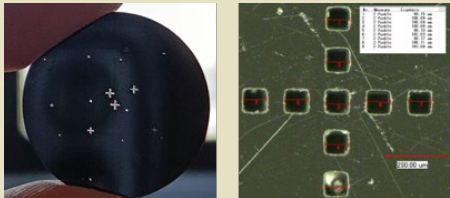
(1) Specimen fabrication & shipping



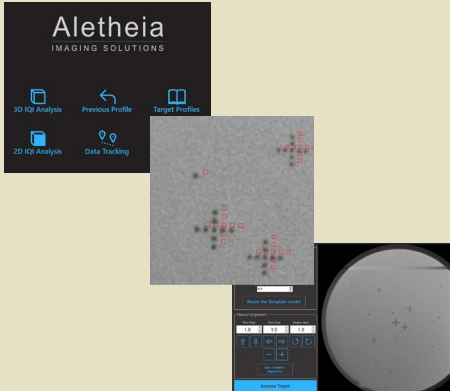
(5) Specimen data interrogation and result inference (with Aletheia)



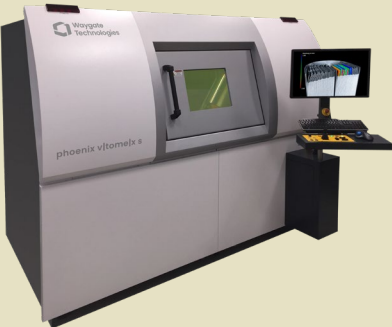
(2) Spatial resolution phantom preparation and beamtime acquisition



(4) Analysis, quantification & measurement confidence determination



(3) Specimen scan acquisition (in collaboration with Aletheia)



CONTENTS

01 Project Preface

02 Spatial Resolution Determination

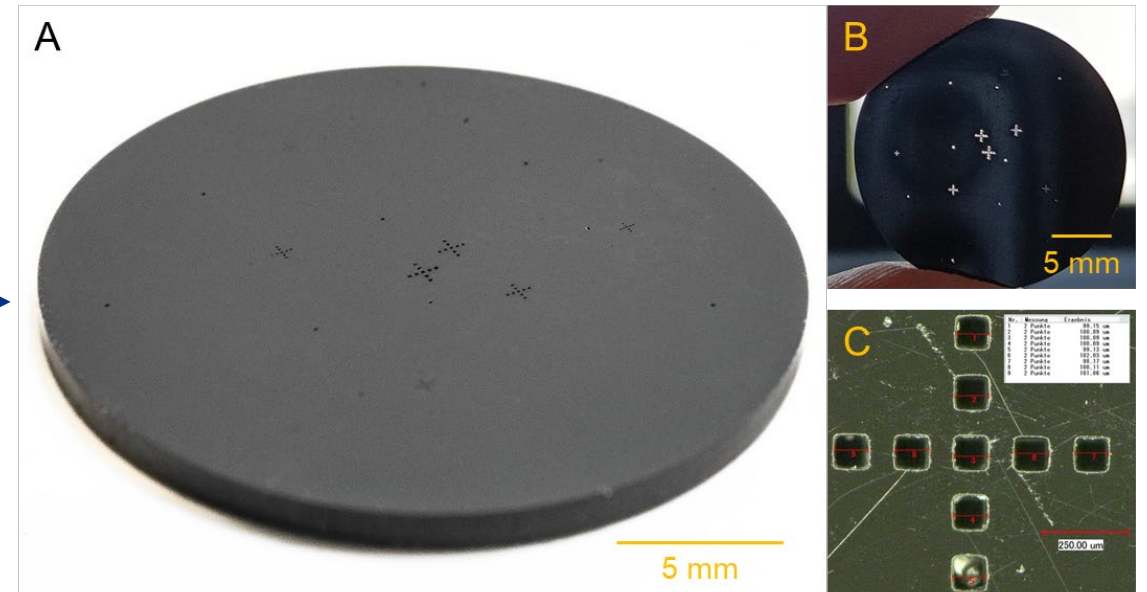
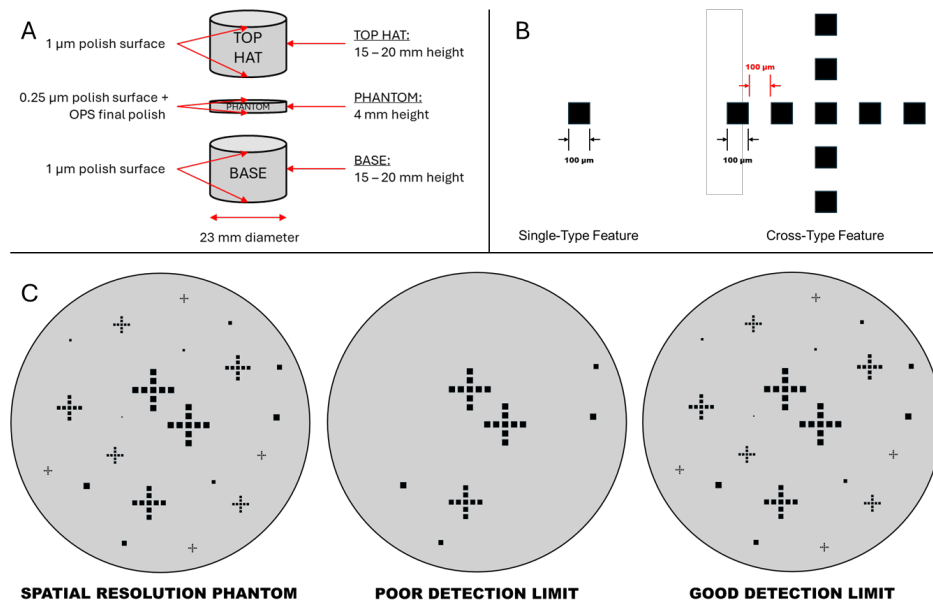
03 Geopolymer Specimen Scan Results

04 Conclusions

Spatial Resolution Phantom – Representative Quality Indicator (RQI)

Spatial Resolution Phantom

- **3D Printing** proved **successful** to fabricate the spatial resolution phantom
- Necessary spatial resolution **phantom features** could be **accurately 3D printed**

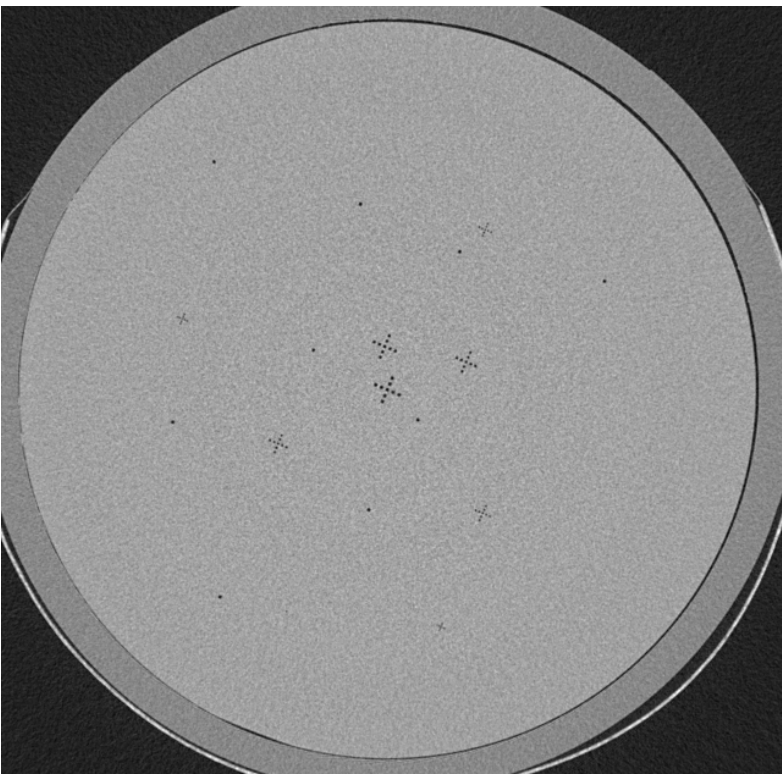


Spatial Resolution Phantom – Representative Quality Indicator (RQI)

Spatial Resolution Phantom

- Phantom scanned on the **same equipment** used for the scanning of **all 26 specimens**
- Scanning of the target used **identical scan parameters** as used for the low resolution and high resolution specimen scans
- Spatial resolution, measurement error, and measurement confidence determined by in-house software developed by Aletheia

Low Resolution Scan

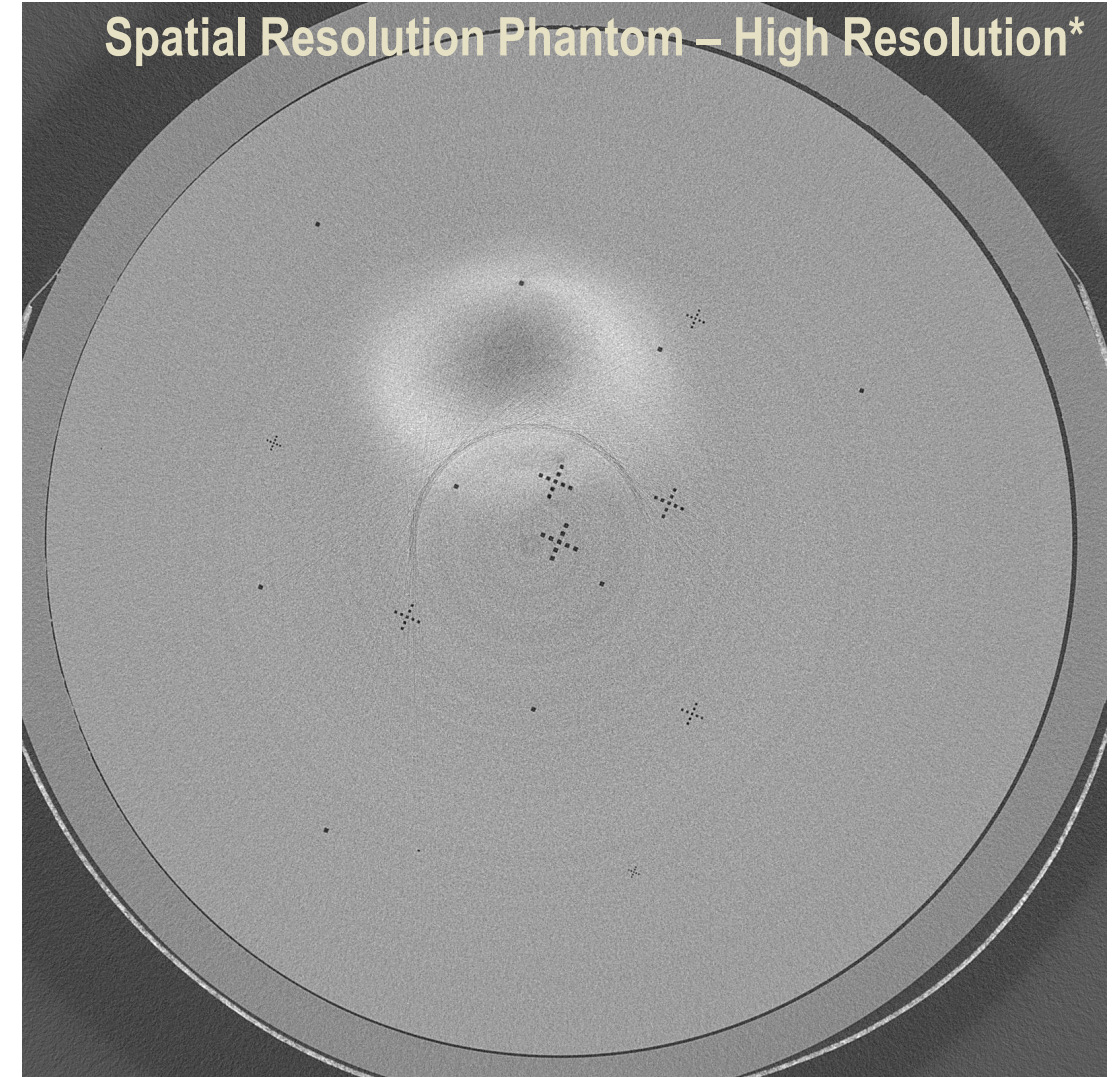
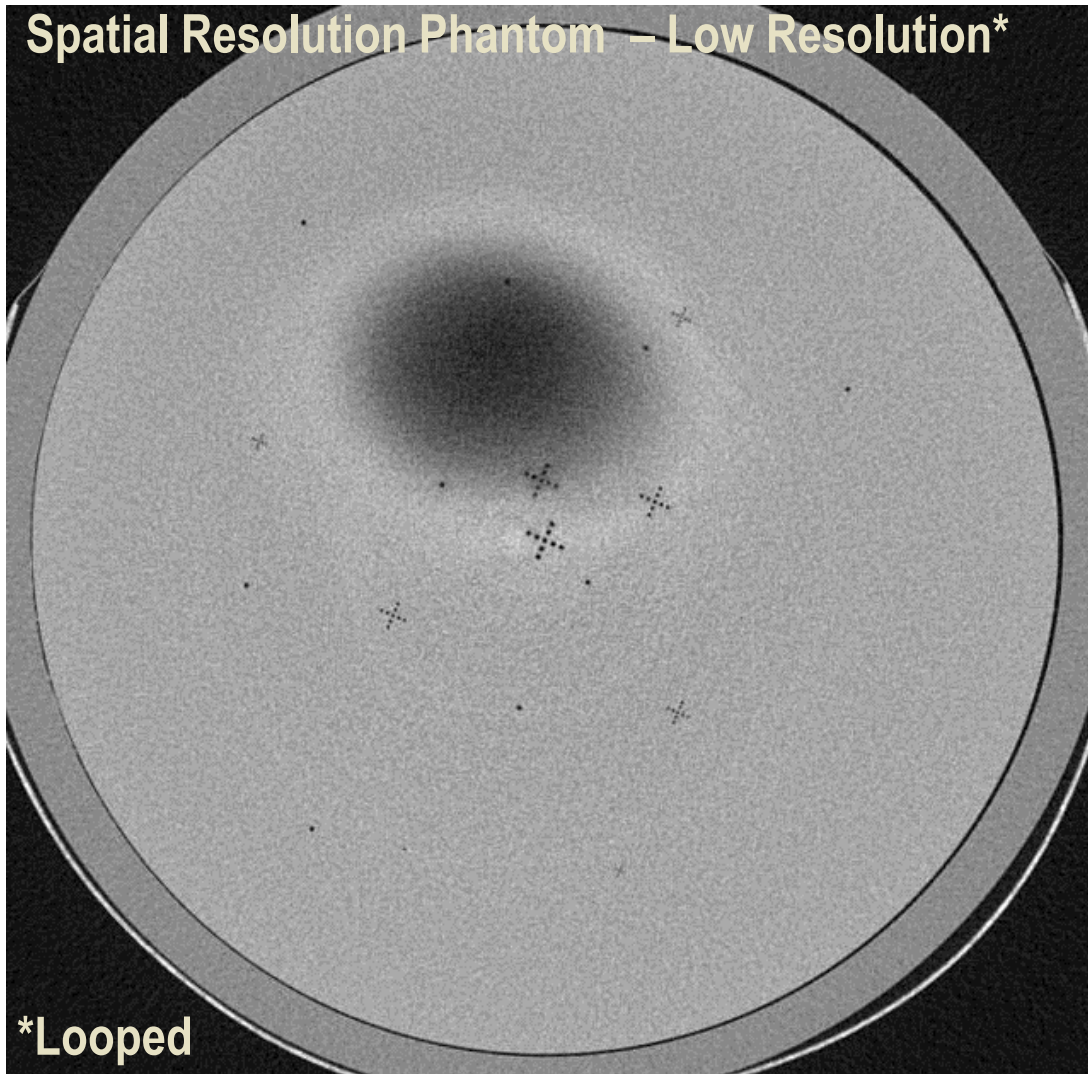


High Resolution Scan

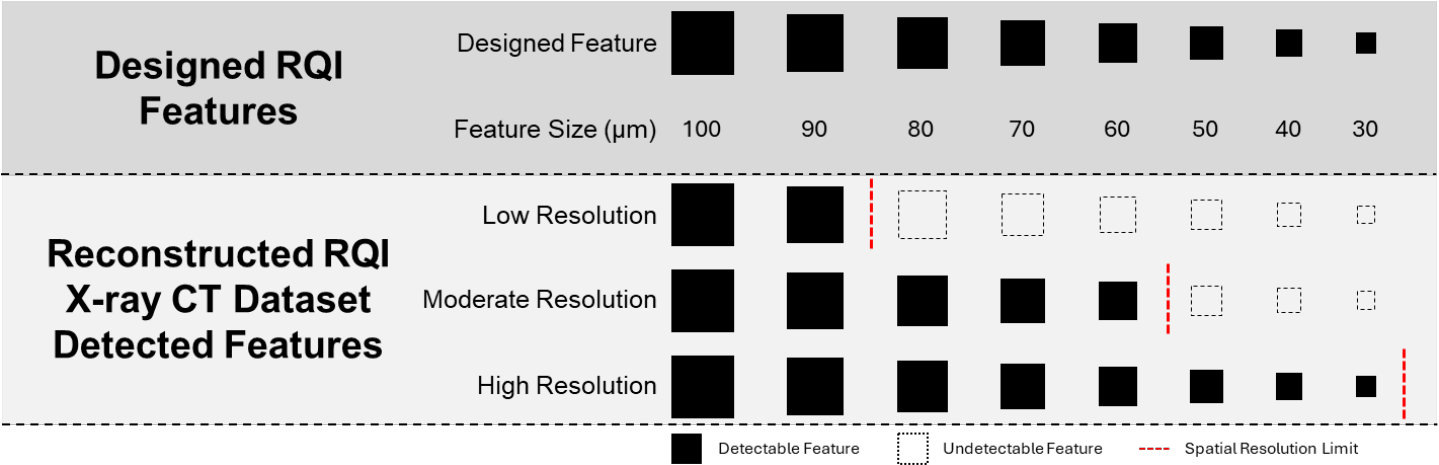


	Low Resolution	High Resolution
Voltage (keV)	100	100
Current (μA)	350	160
FOD ^a (mm)	153.24	60.52
FDD ^b (mm)	806.57	806.57
EPS ^c (μm)	38.00	15.01
^a Focus-to-Object Distance, ^b Focus-to-Detector Distance, ^c Effective Pixel Size,		

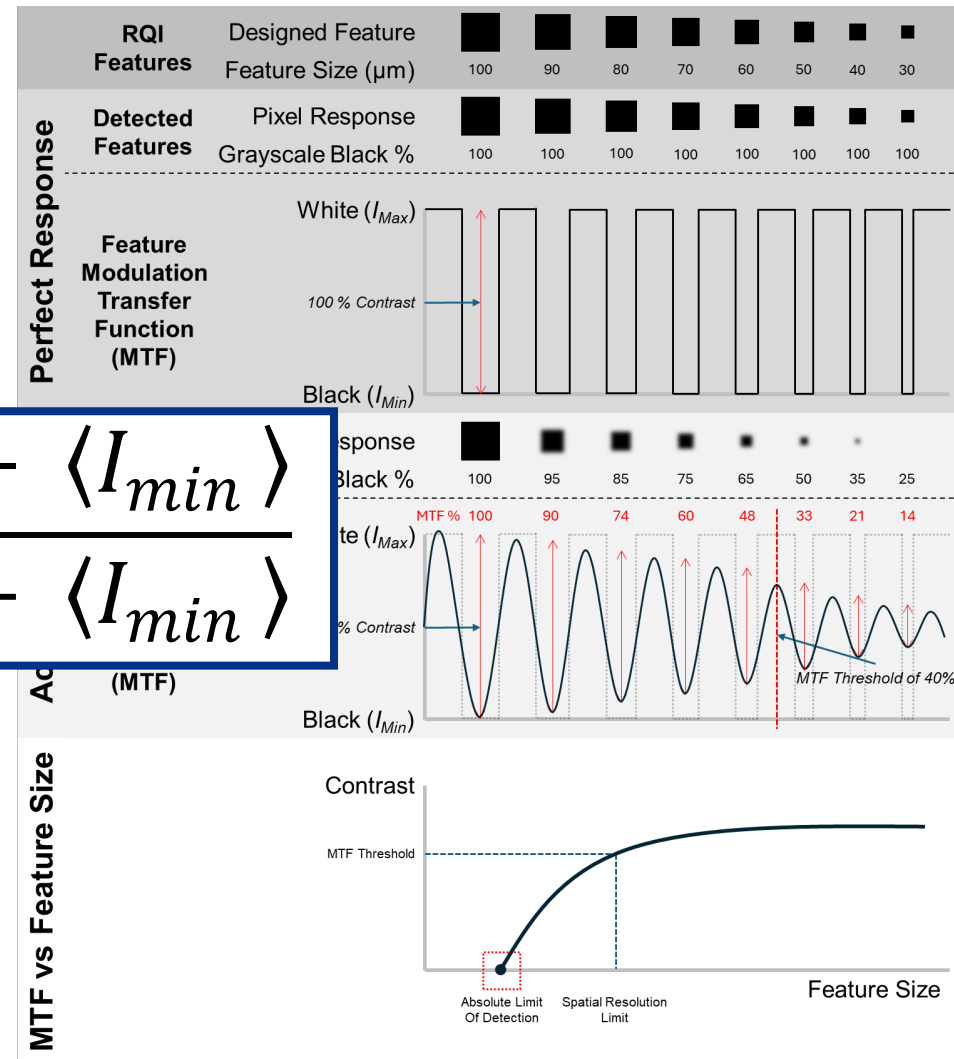
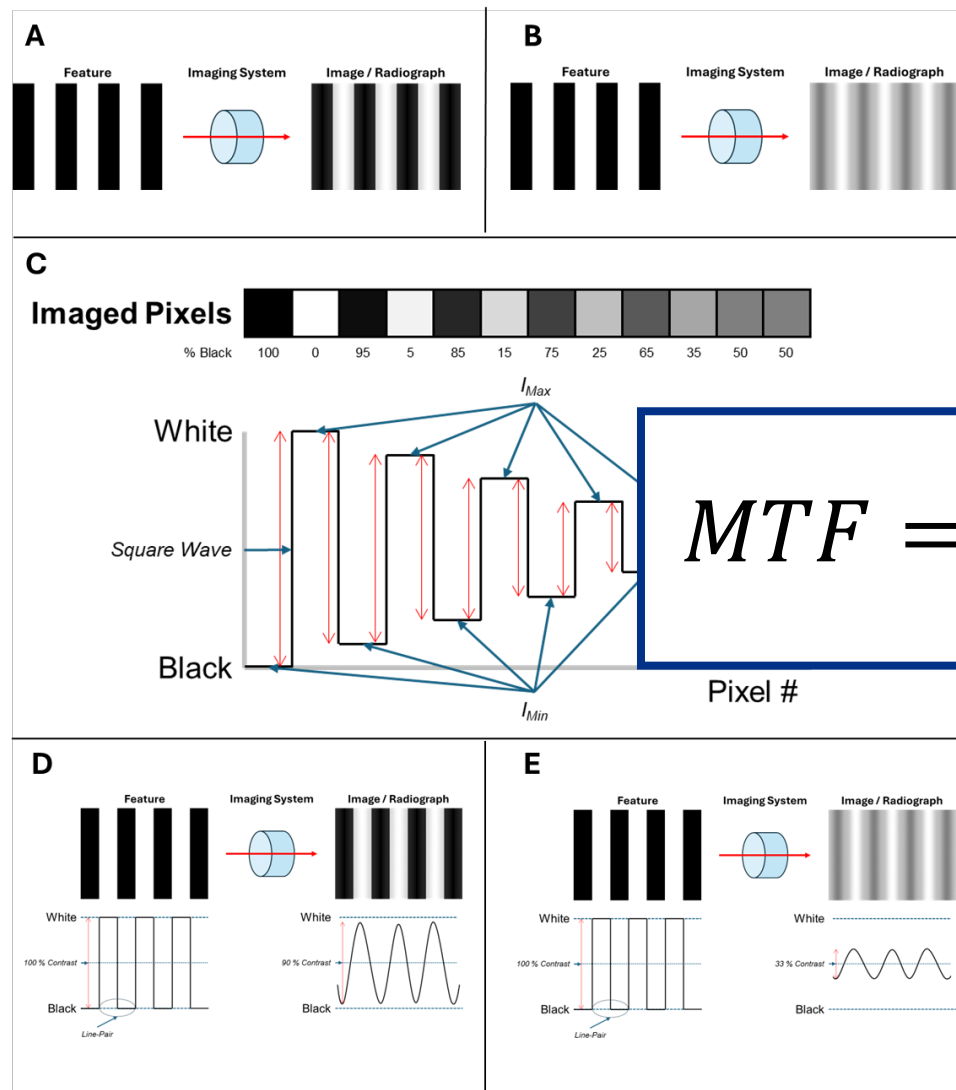
Scan Results – Low Resolution vs High Resolution Comparison



Feature Detection



Feature Detection – Modulation Transfer Function

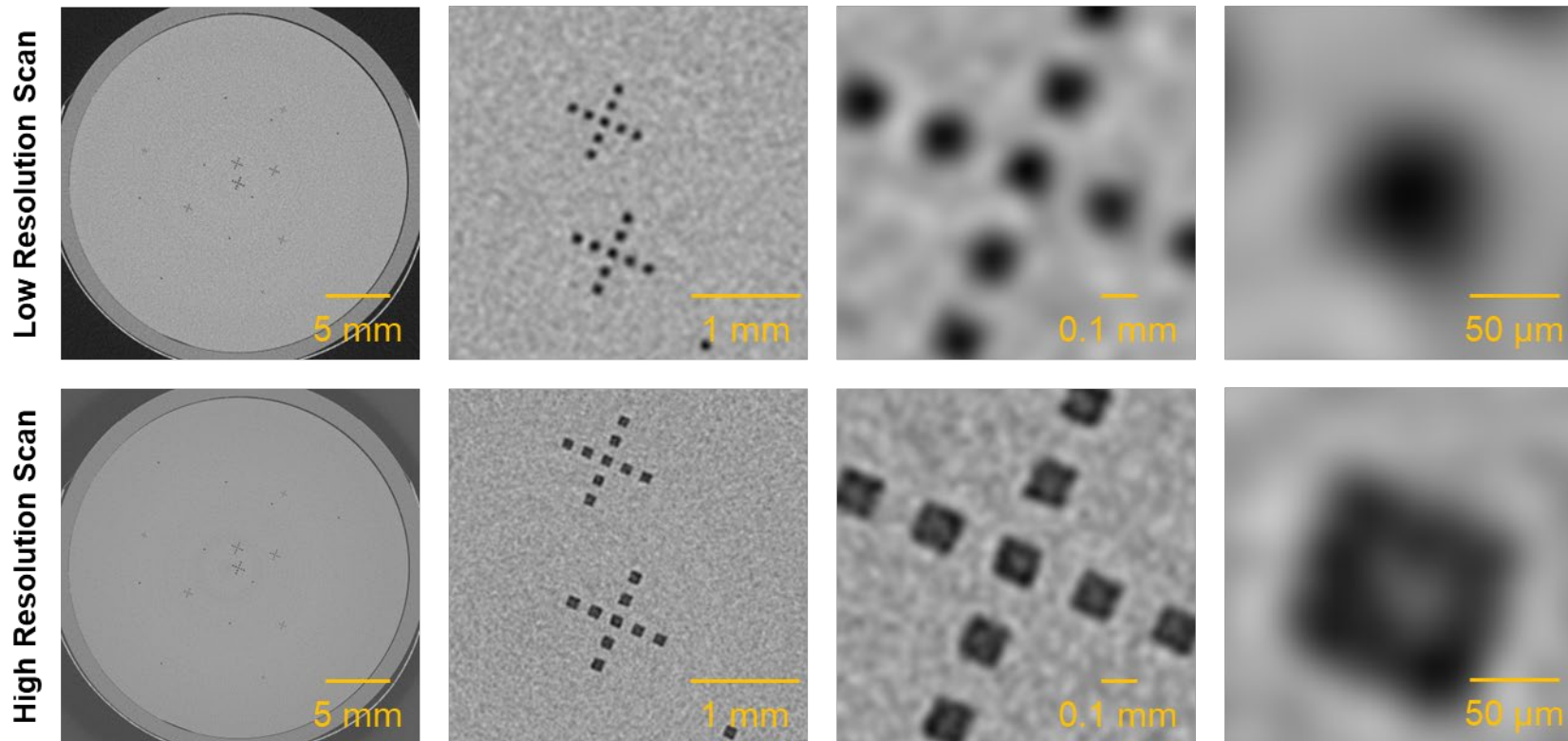


MTF, as defined in the ASTM standard E2002-2015

Spatial Resolution Phantom – Representative Quality Indicator (RQI)

Spatial Resolution Phantom

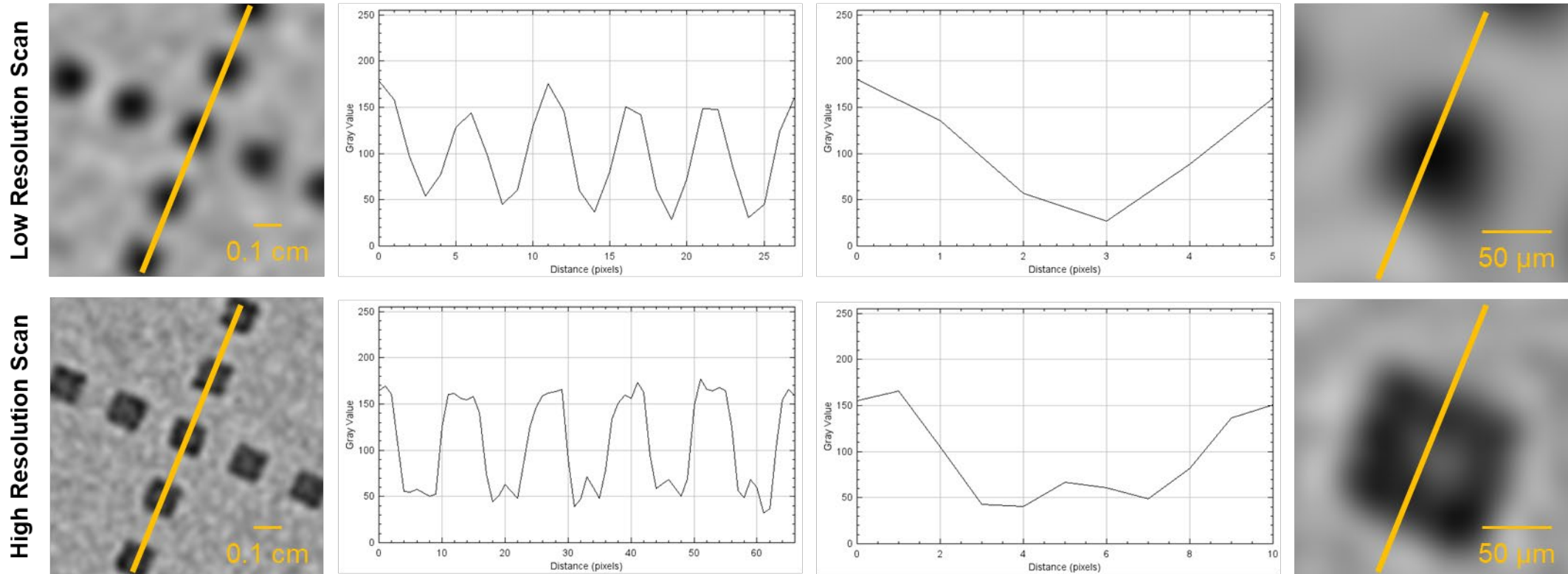
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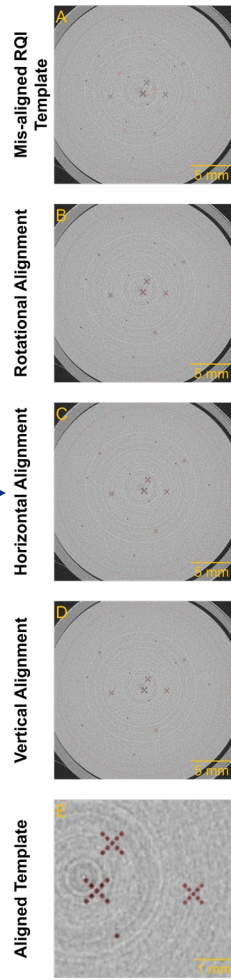
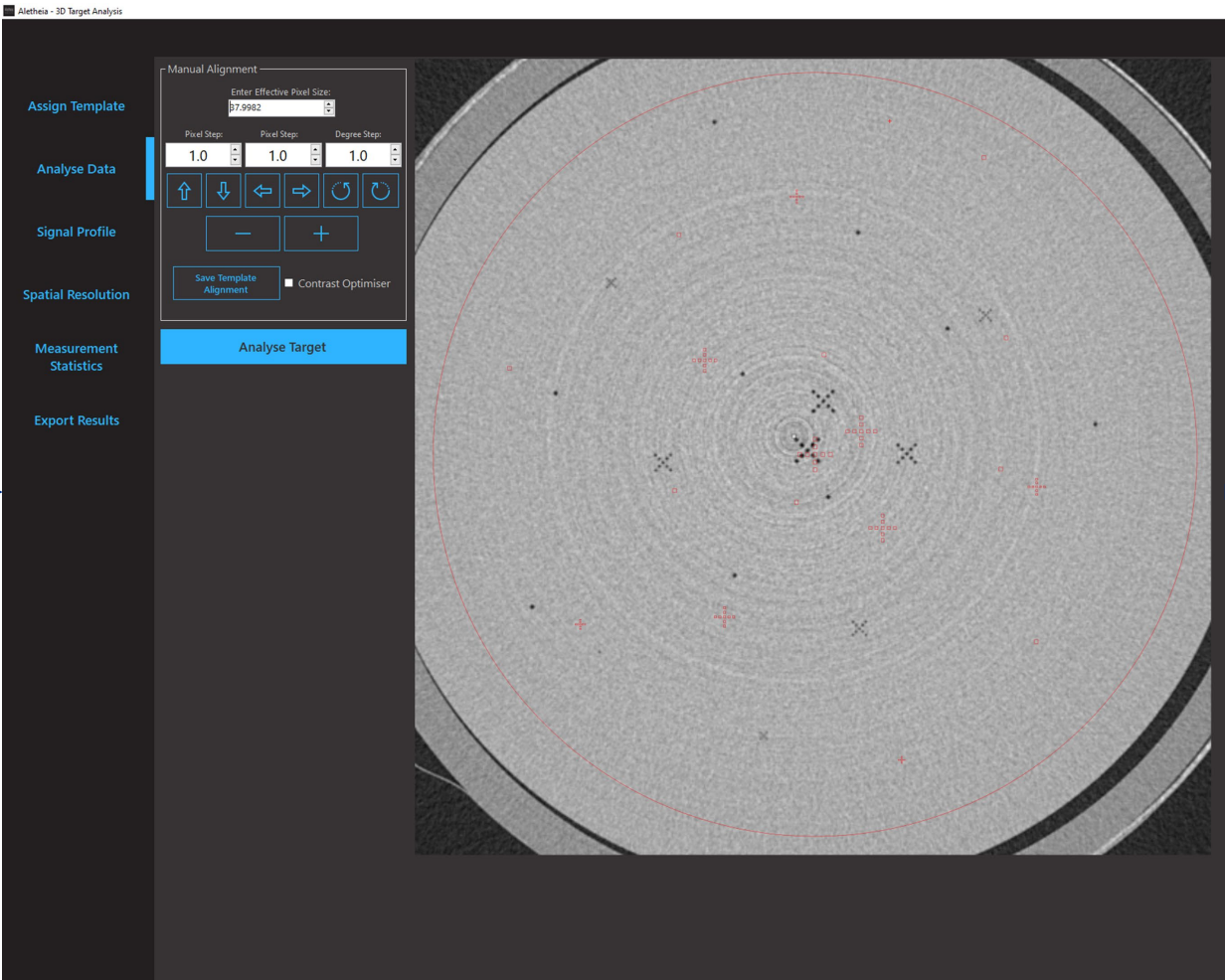
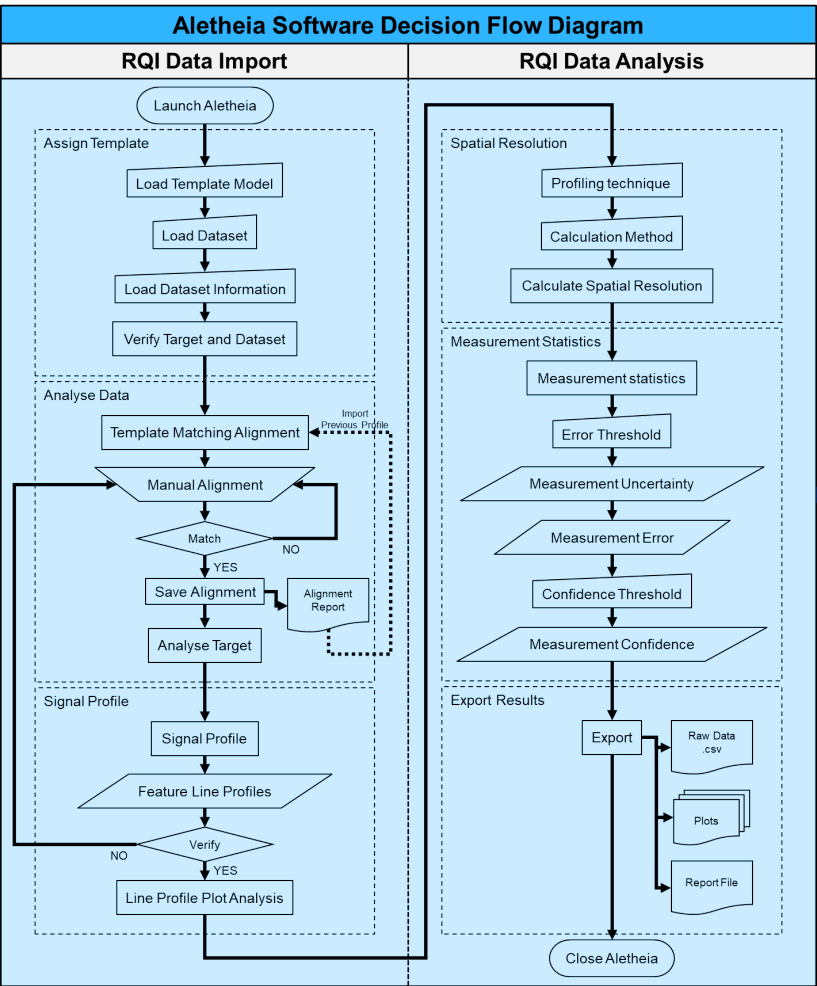
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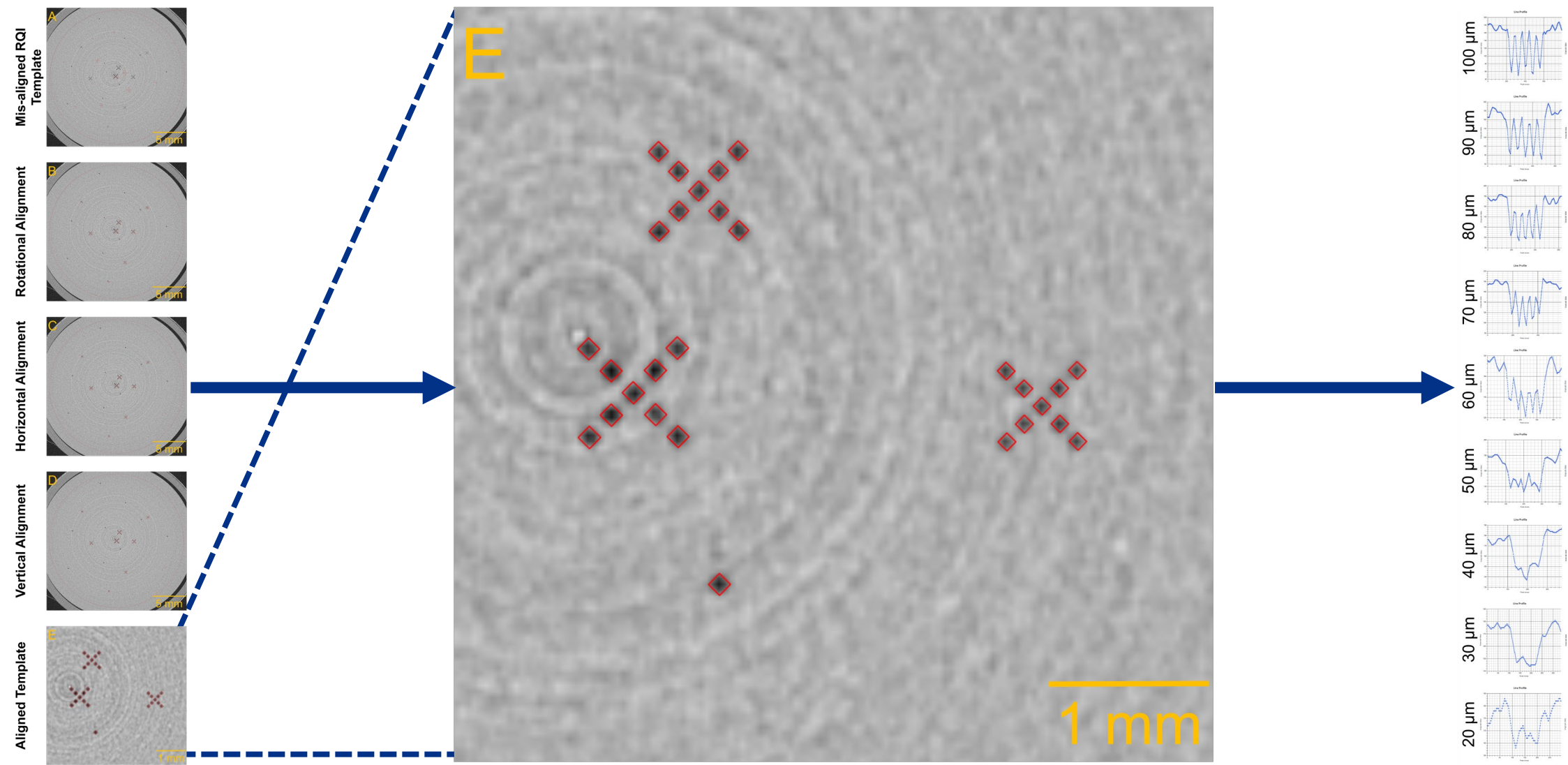
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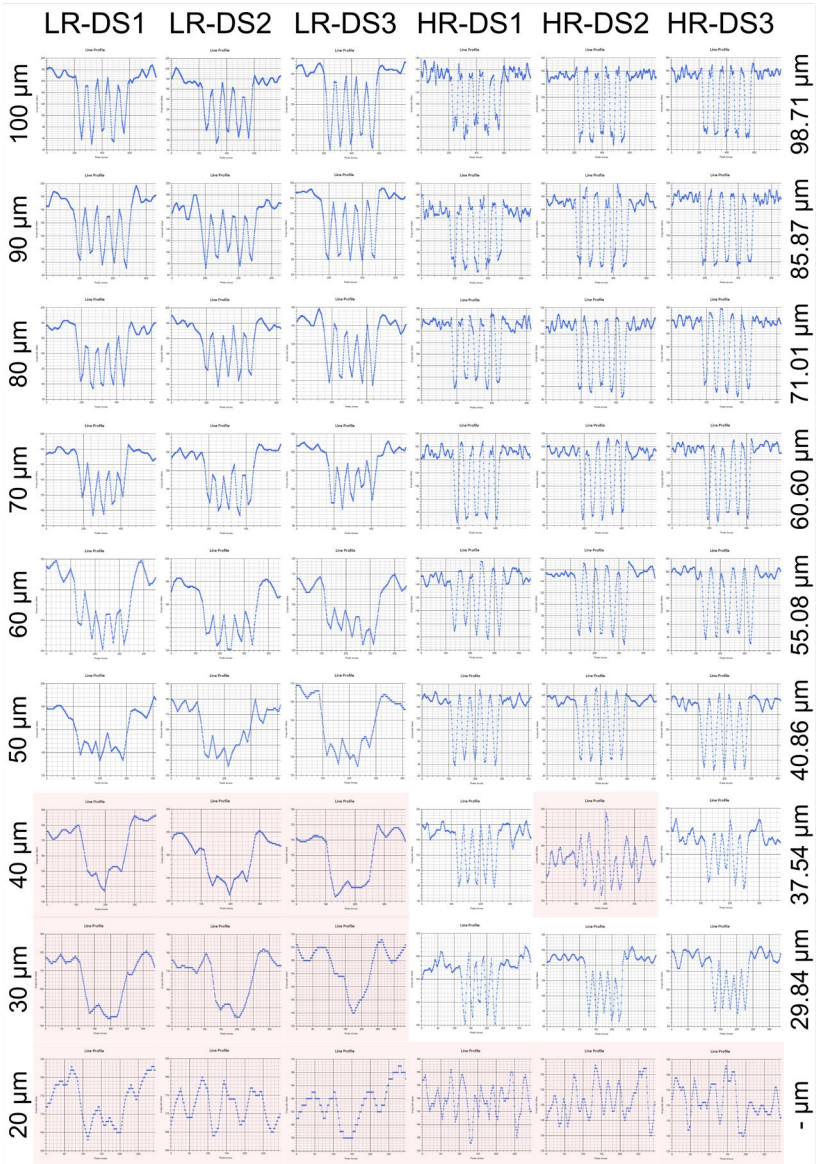
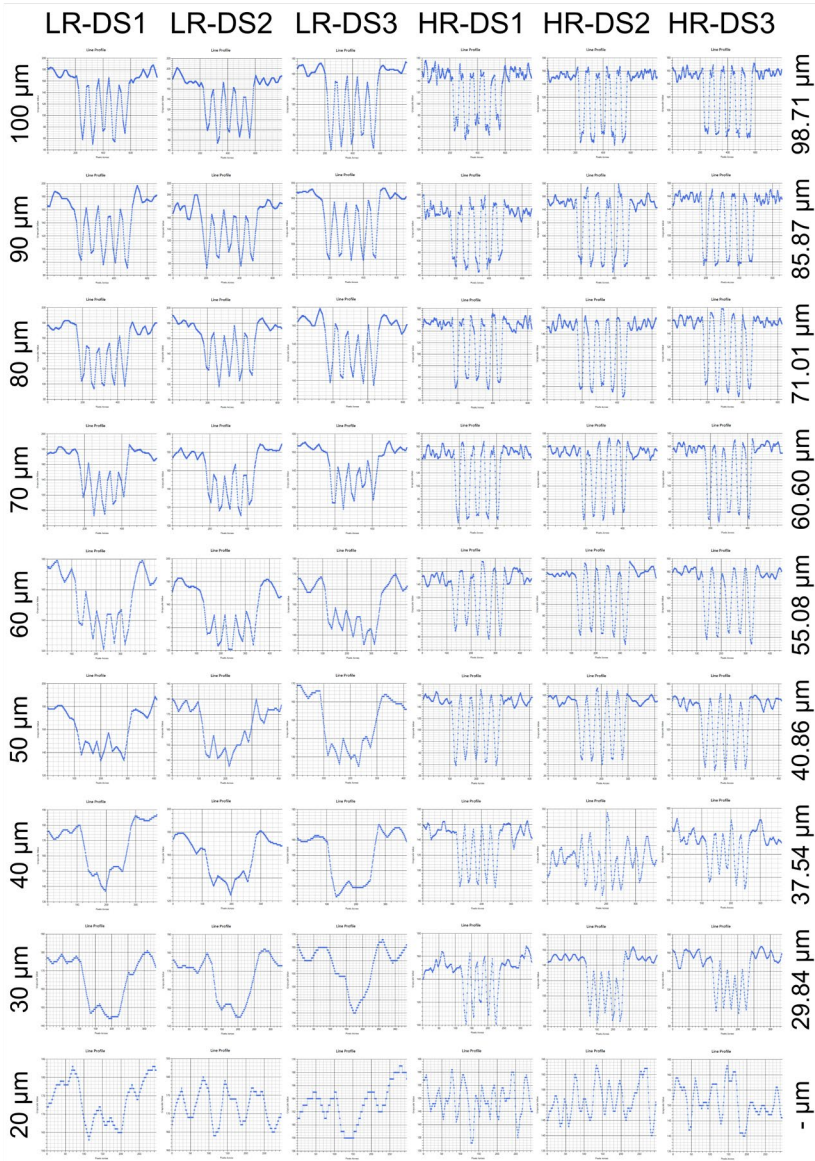
Spatial Resolution Determination – Template Matching



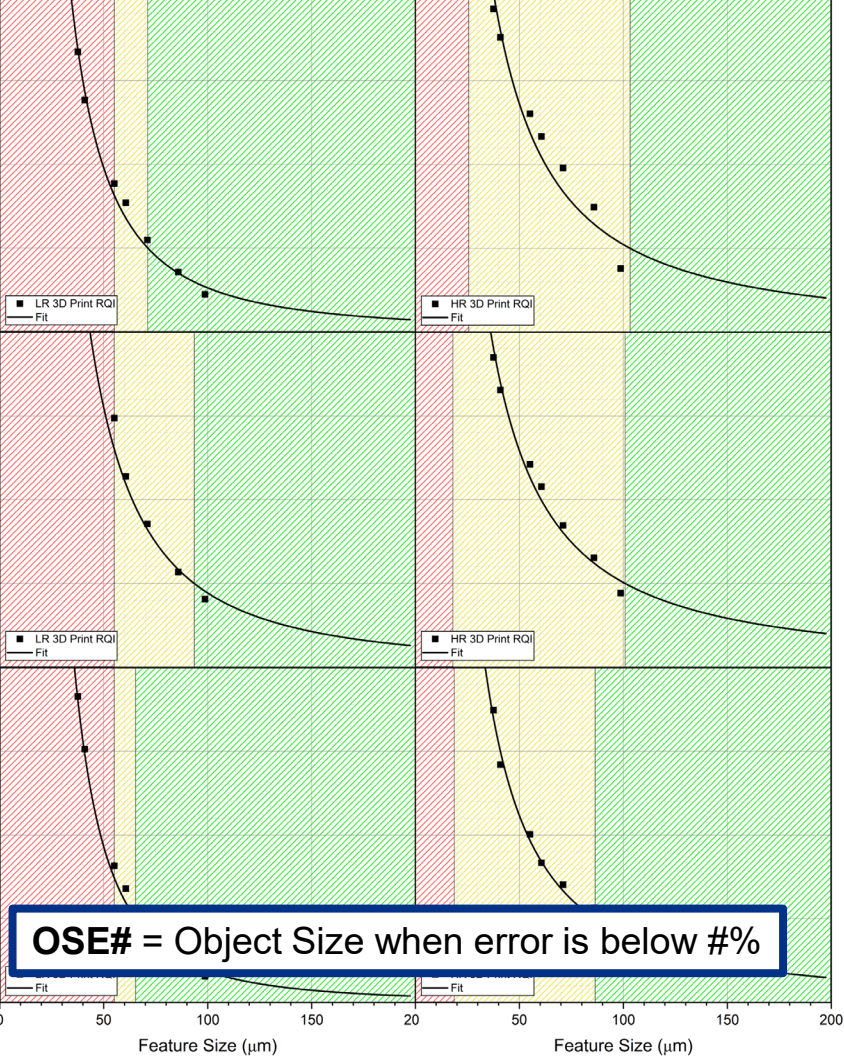
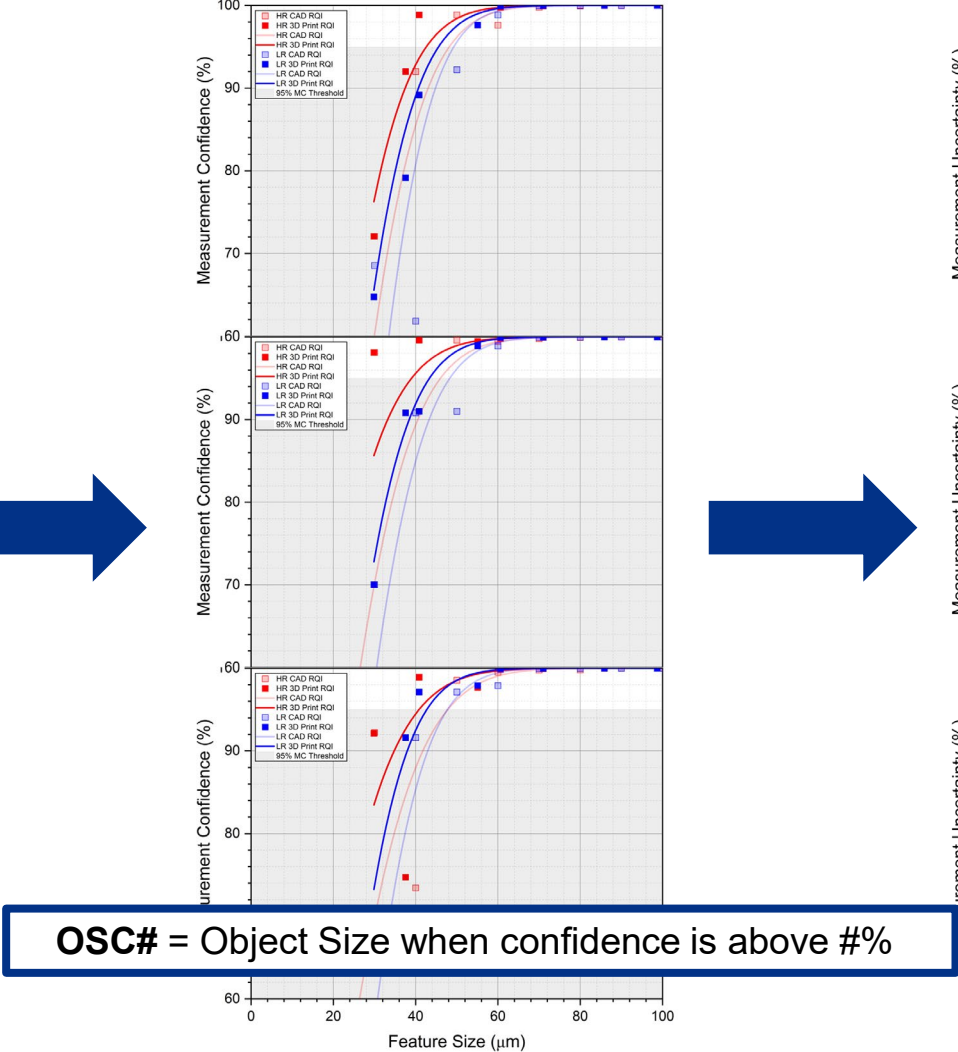
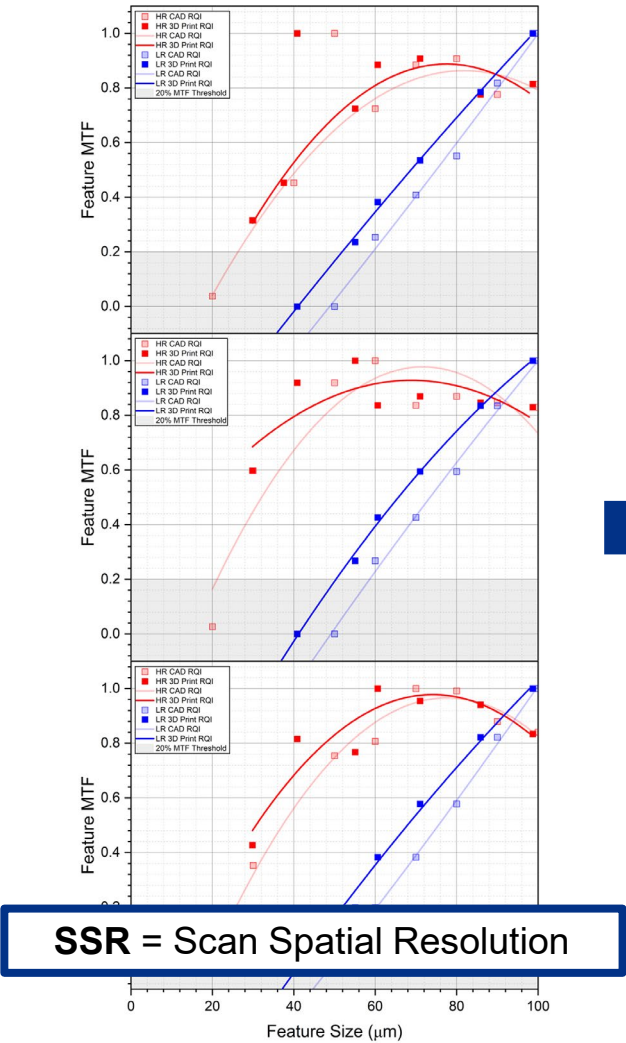
Spatial Resolution Determination – Template Matching



Spatial Resolution Determination – Signal Profiles



Spatial Resolution Determination – Measurement Uncertainty



Spatial Resolution Determination – Measurement Uncertainty

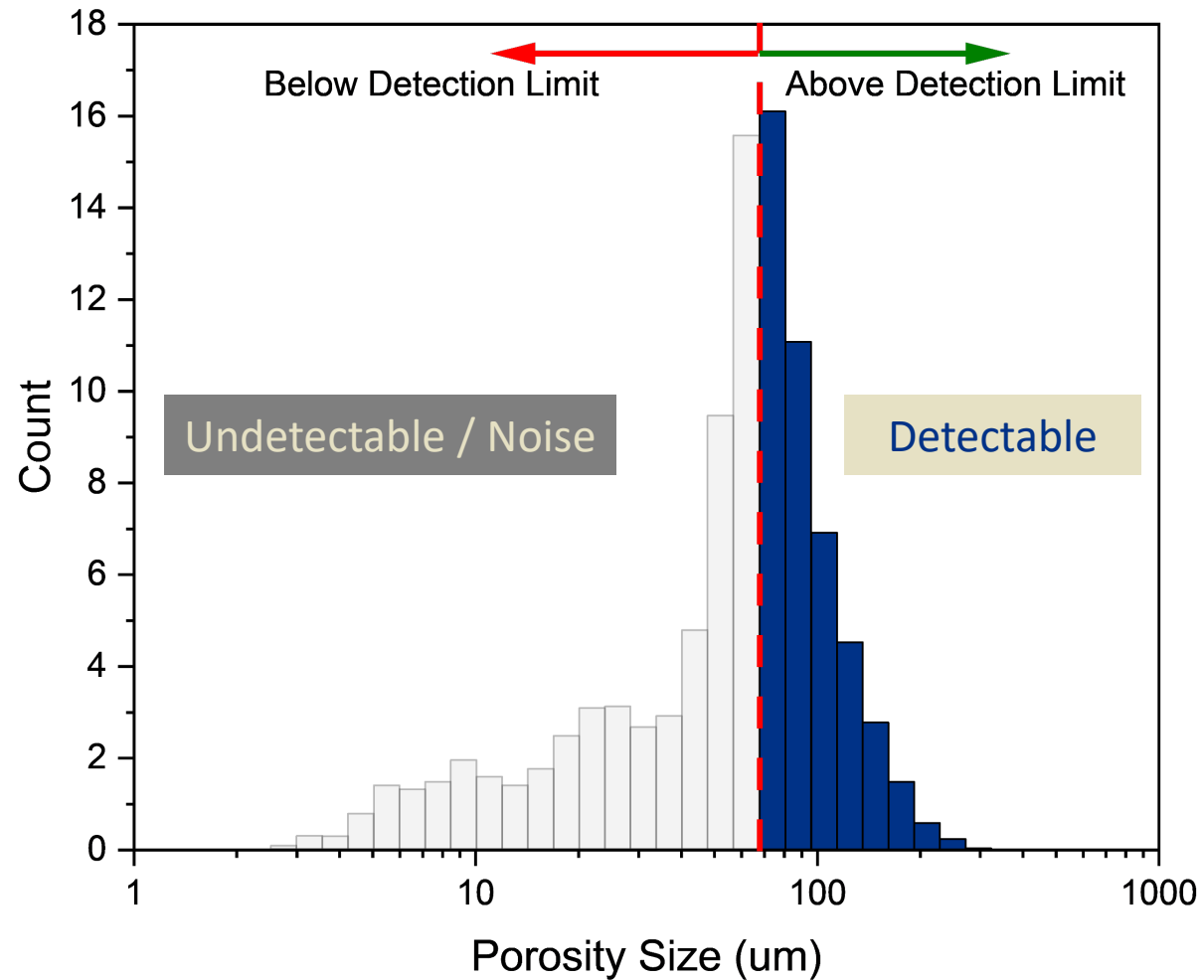
Scan Type	Description	EPS ^a (µm)	Template Match ^b	No. Features Analysed ^c	SSR ^d (µm)	RLMC ^e (%)	OSC99 (µm)	OSE5 ^f (µm)
Low Resolution	Full Wasteform Scan	37.99	Designed Features	85 (89)	60.00	99.35	58.00	93.10
	(LR-DS1)		Printed Features	86 (89)	55.08	98.99	54.84	71.20
	Full Wasteform Scan		Designed Features	85 (89)	60.00	99.30	58.00	102.10
	(LR-DS2)		Printed Features	86 (89)	55.08	99.32	52.84	93.60
	Full Wasteform Scan		Designed Features	85 (89)	60.40	99.48	57.00	68.70
	(LR-DS3)		Printed Features	86 (89)	55.08	99.46	51.84	65.40
	Centre of Wasteform Scan		Designed Features	89 (89)	26.29	46.27	58.00	110.7
	(HR-DS1)		Printed Features	89 (89)	25.72	64.77	52.84	103.3
	Centre of Wasteform Scan		Designed Features	89 (89)	21.15	40.60	57.00	106.3
	(HR-DS2)		Printed Features	89 (89)	1.34	-6.86	50.84	100.9
High Resolution	Centre of Wasteform Scan	15.01	Designed Features	88 (89)	30.00	69.78	60.00	91.5
	(HR-DS3)		Printed Features	89 (89)	18.72	58.02	52.84	86.5

^aEffective Pixel Size.
^bTemplate feature sizes calibrated to the designed feature sizes or printed feature sizes.
^cNumber of successfully analysed features. Total of 89 features possible for analysis in parentheses.
^dScan Spatial Resolution.
^eResolution Limit Measurement Confidence.
^fFeature size when error falls below 5%

Measure	Acronym	Description	Unit
Effective Pixel Size	EPS	Size of radiograph pixel as a function of CT system parameters	µm
Scan Spatial Resolution	SSR	Smallest detectable feature as determined by MTF	µm
Feature Measurement Confidence	FMC	Ascribed percentage of confidence of a feature of a defined size.	%
Resolution Limit	RLMC	Also referred to as Probability of Detection (POD). Measurement confidence in the scan spatial resolution detection limit expressed as a percentage.	%
Object Size Confidence	OSC#	Size of quantifiable feature when confidence falls below choosen value	µm
Object Size Error	OSE#	Size of quantifiable feature when error falls below choosen value	µm

Determined Measurement Confidence						
Scan Configuration	Specimen	RQI Dataset	SSR	OSC99	OSE5	OSE1
			µm	µm	µm	µm
Low Resolution	#01 - #08	LR-DS1	55.08	54.84	71.20	166.10
	#09 - #26	LR-DS3	55.08	51.84	65.40	130.98
High Resolution	#01 - #08	HR-DS1	25.72	52.84	103.30	330.98
	#09 - #26	HR-DS3	18.72	52.84	86.50	259.02

Spatial Resolution for X-ray CT Metrology



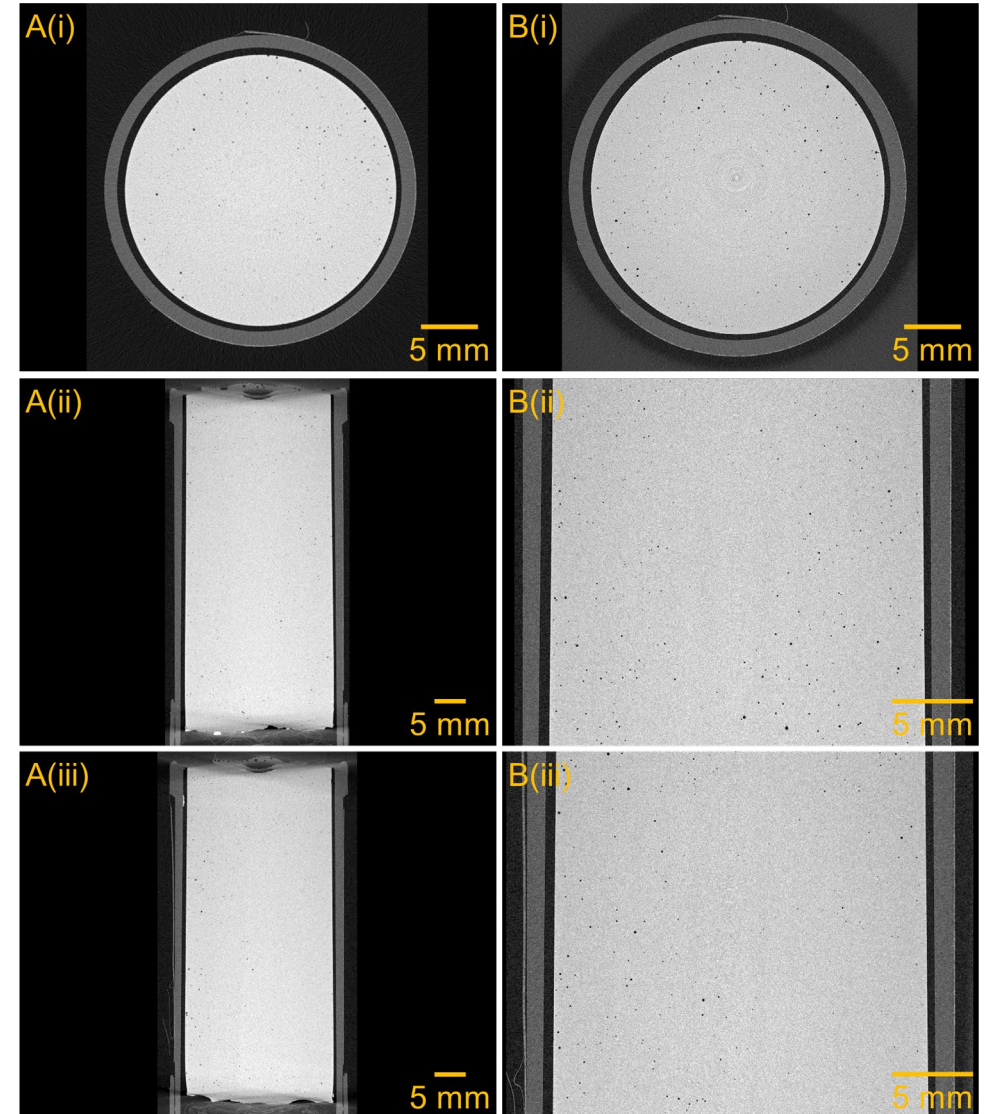
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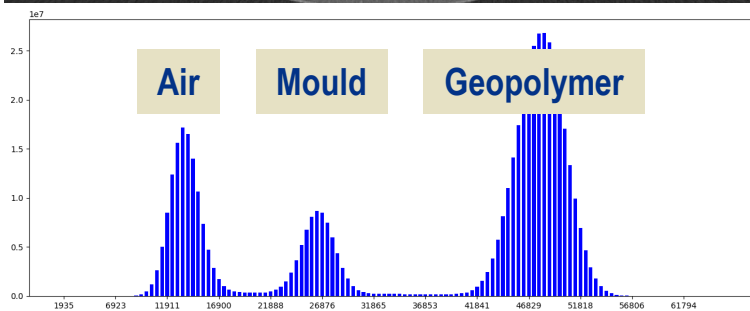
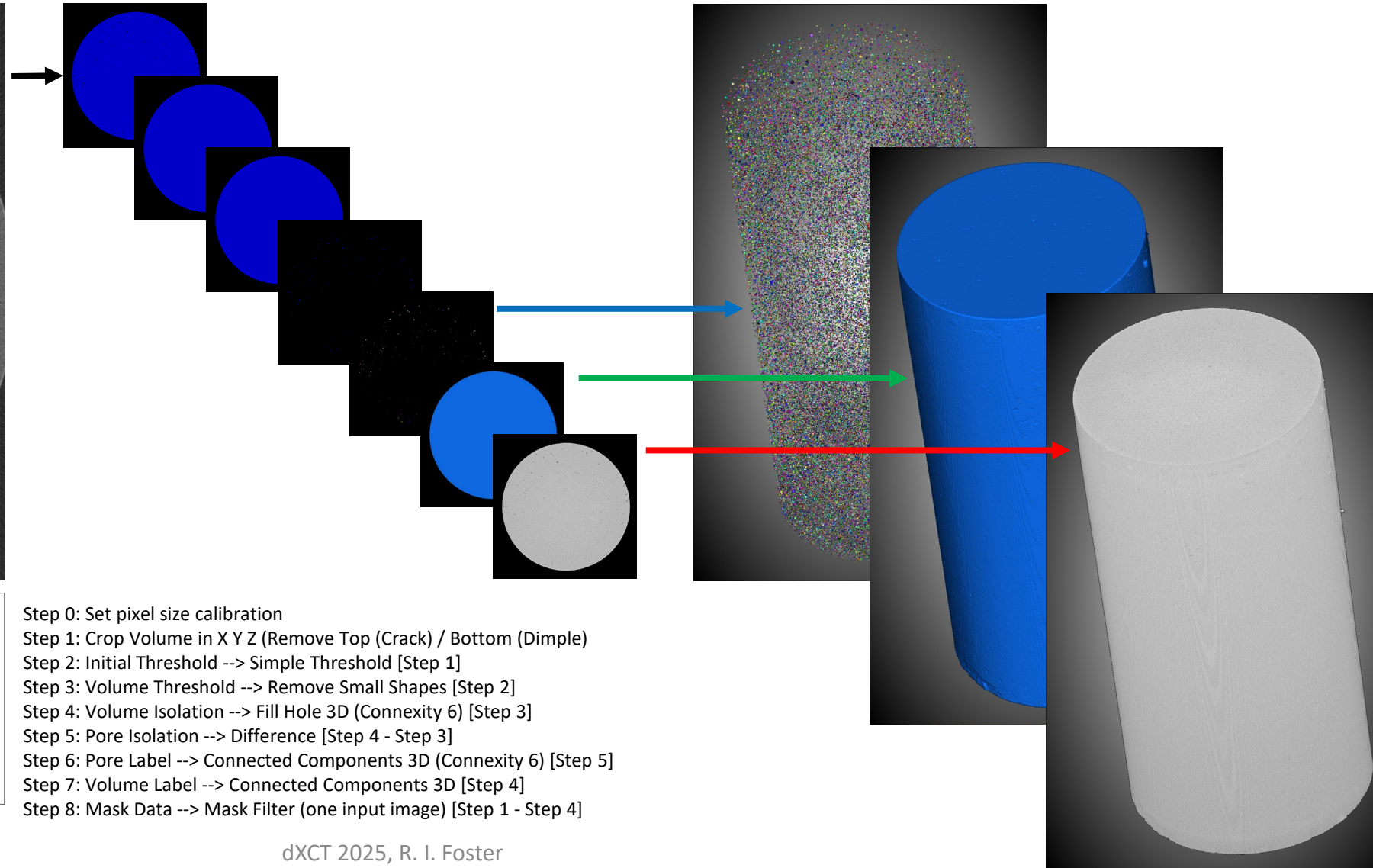
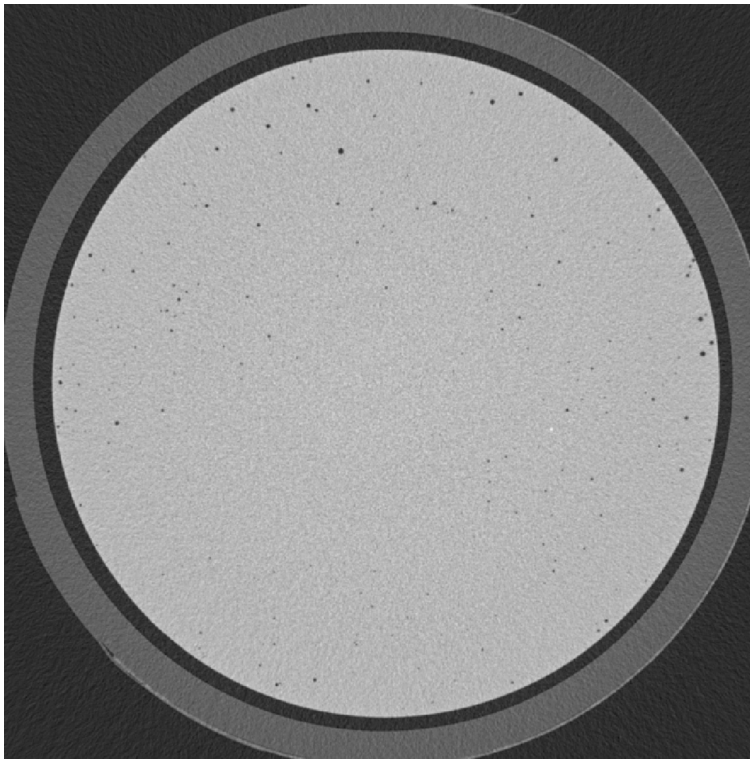
Geopolymer Specimens – X-ray CT Scan Results

Geopolymer-based Wasteforms

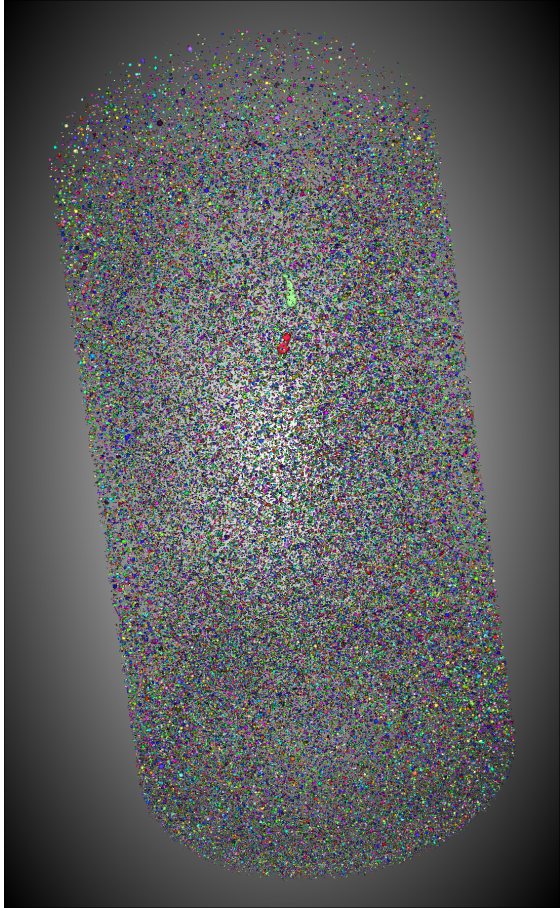
- Specimens left in moulds to reduce beam hardening
- Geopolymer easily identified
- Geopolymers show homogeneous internal structure
- Apparent porosity throughout, assumed air pockets
- Internal defect detection important



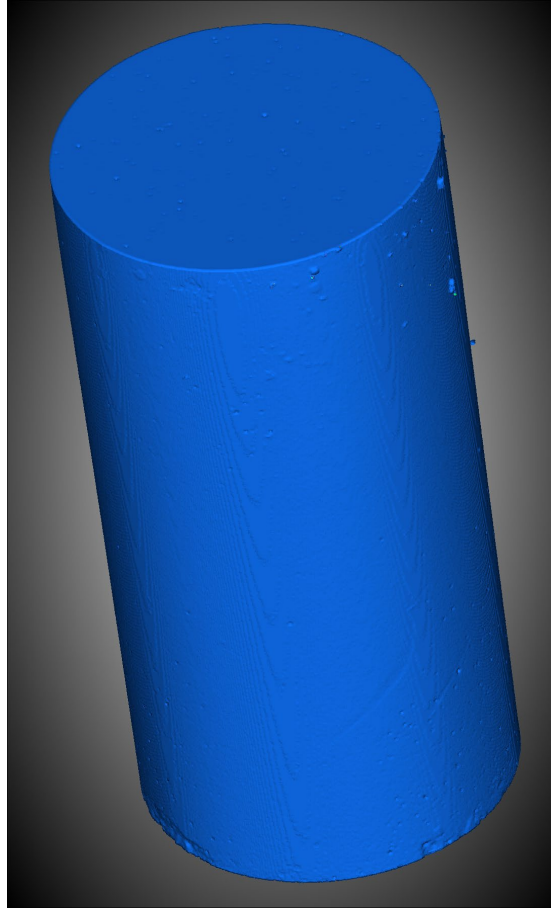
X-ray CT Data Processing (Segmentation)



X-ray CT Data Processing (Segmentation)



Pores

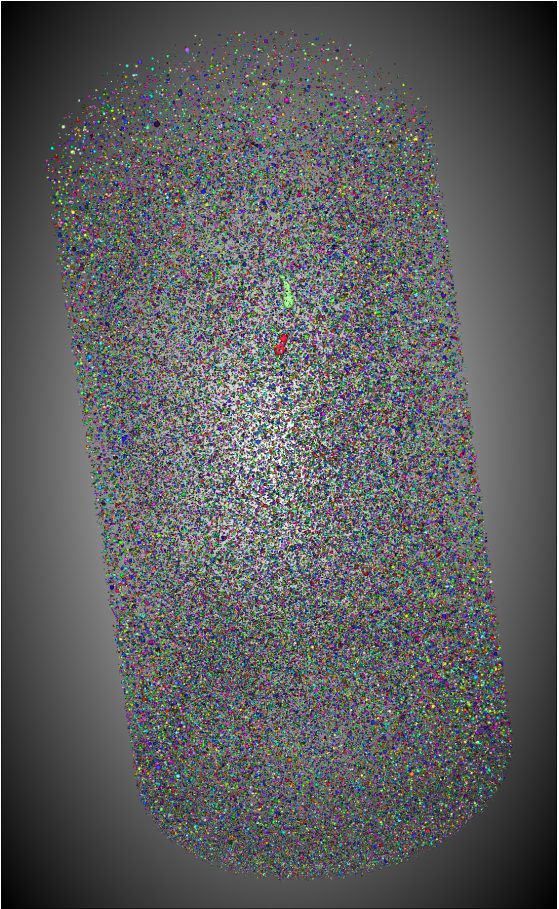


Volume

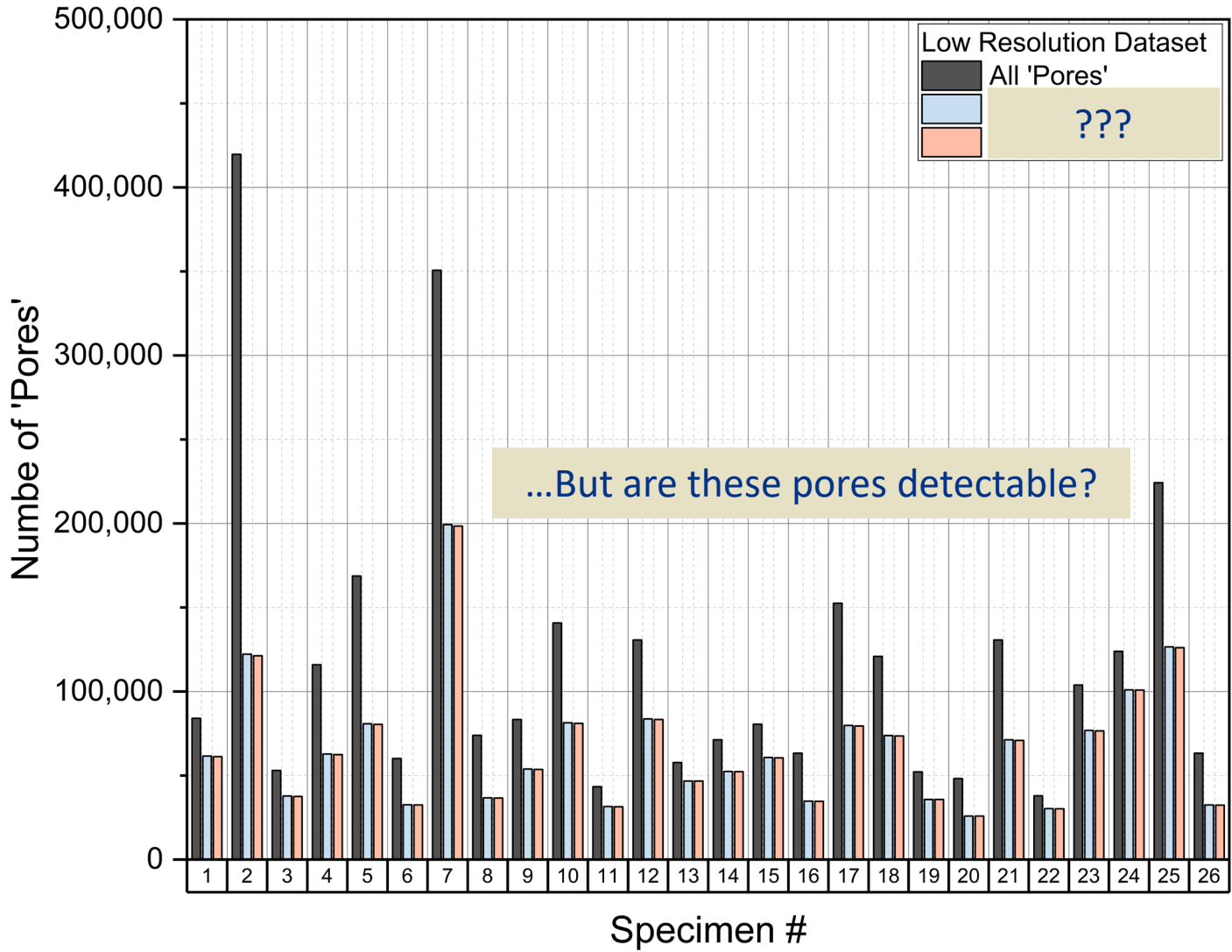


Mask

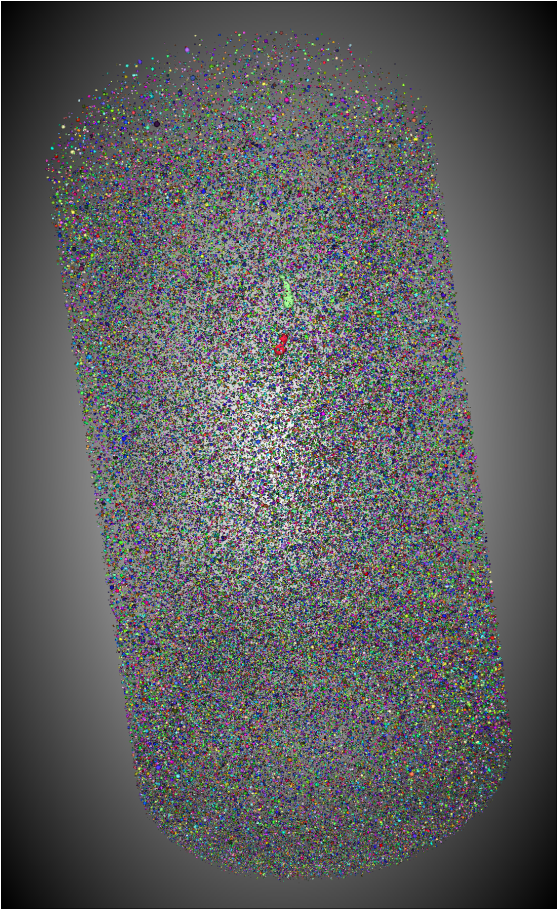
Pore Quantification



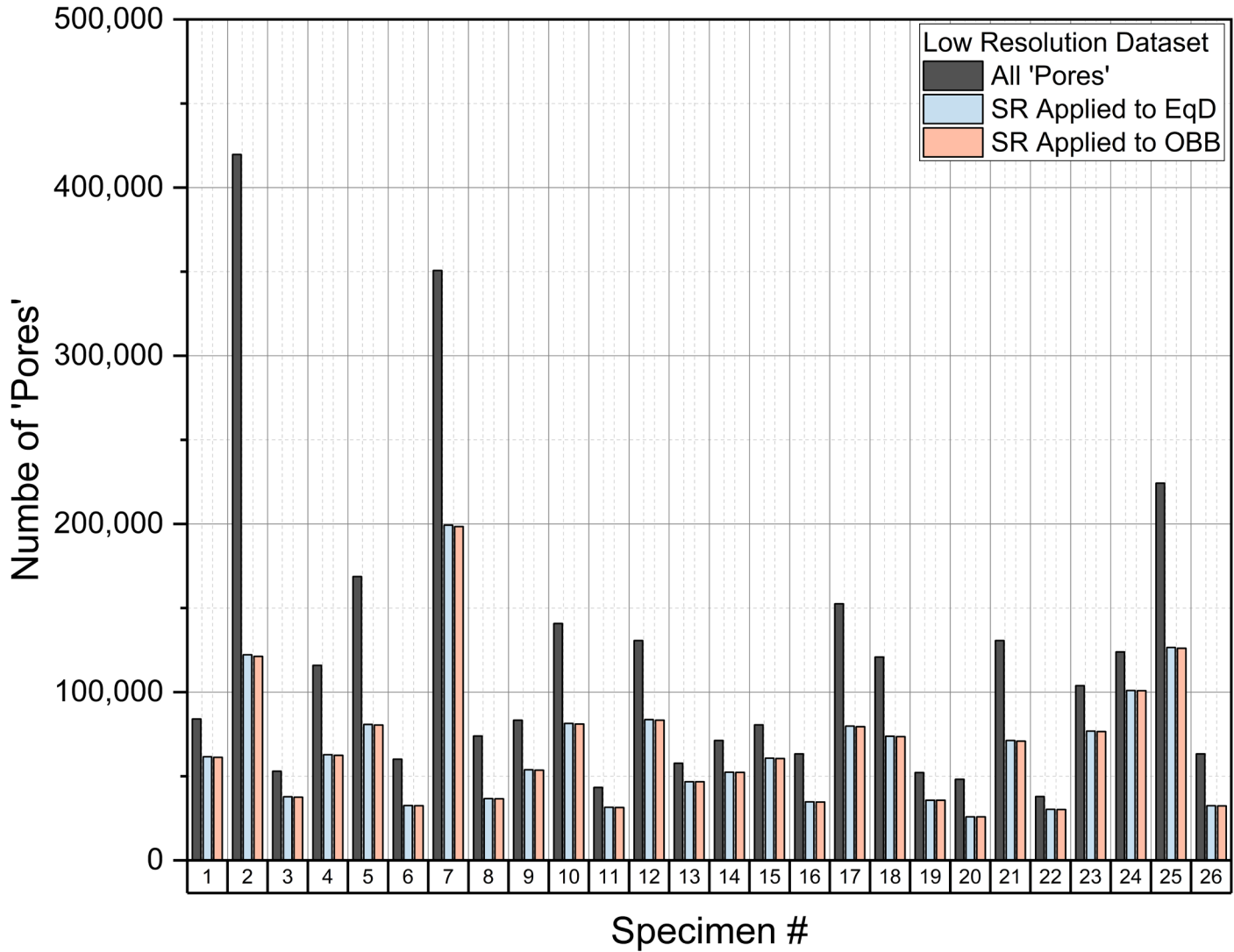
Pores



Pore Quantification



Pores

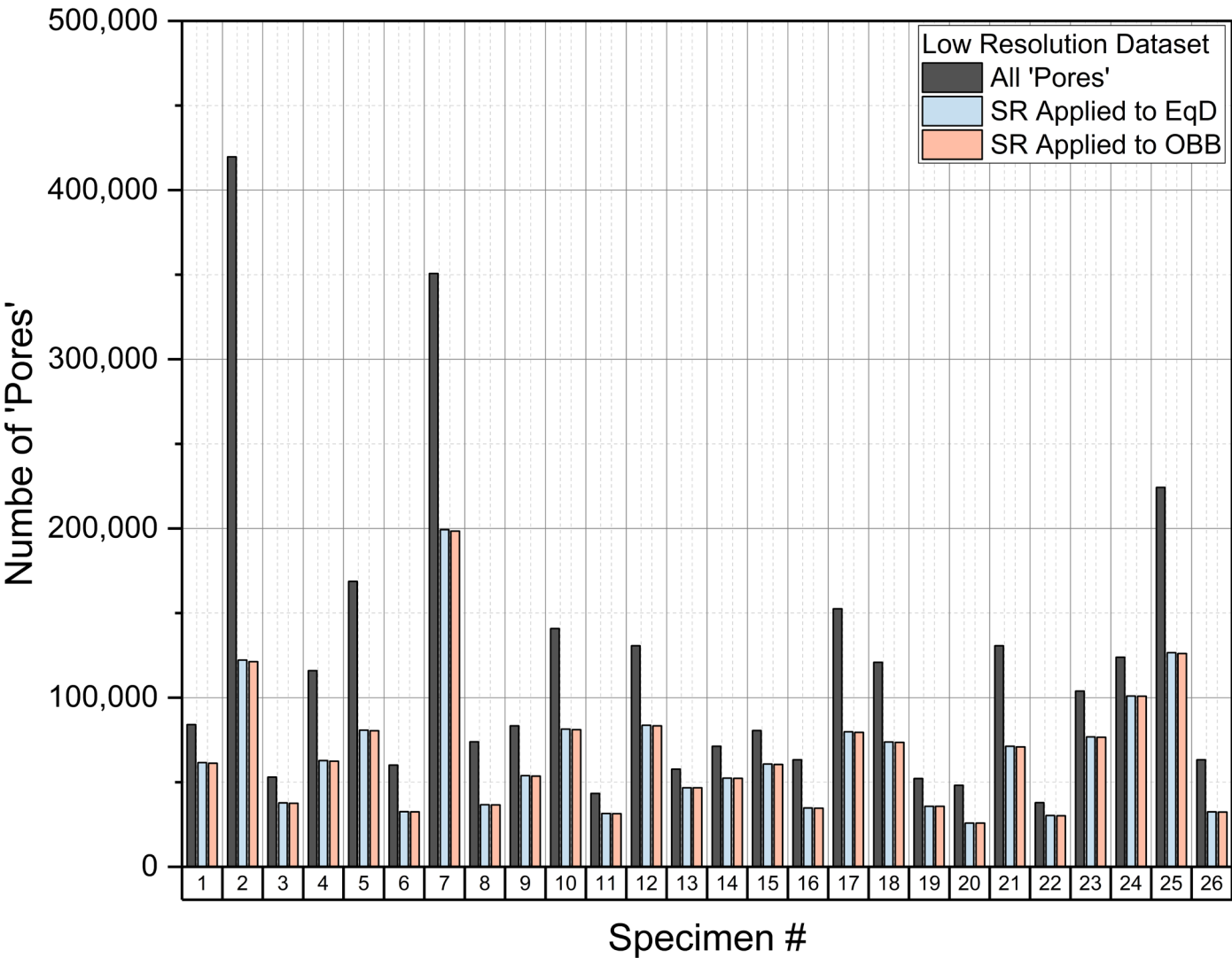


Pore Filtering – Application of Measurement Confidence Thresholds

Specimen Pore Determination

- Provides means of filtering “undetectable” pores
- Applied thresholding results in the number of pores
- Reduces the number of false-positives
- Eliminates erroneous noise
- OBB thresholding considered most appropriate

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Scan Configuration	Specimen	RQI Dataset	SSR μm	OSC99 μm	OSE5 μm	OSE1 μm
Low Resolution	#01 - #08	LR-DS1	55.08	54.84	71.20	166.10
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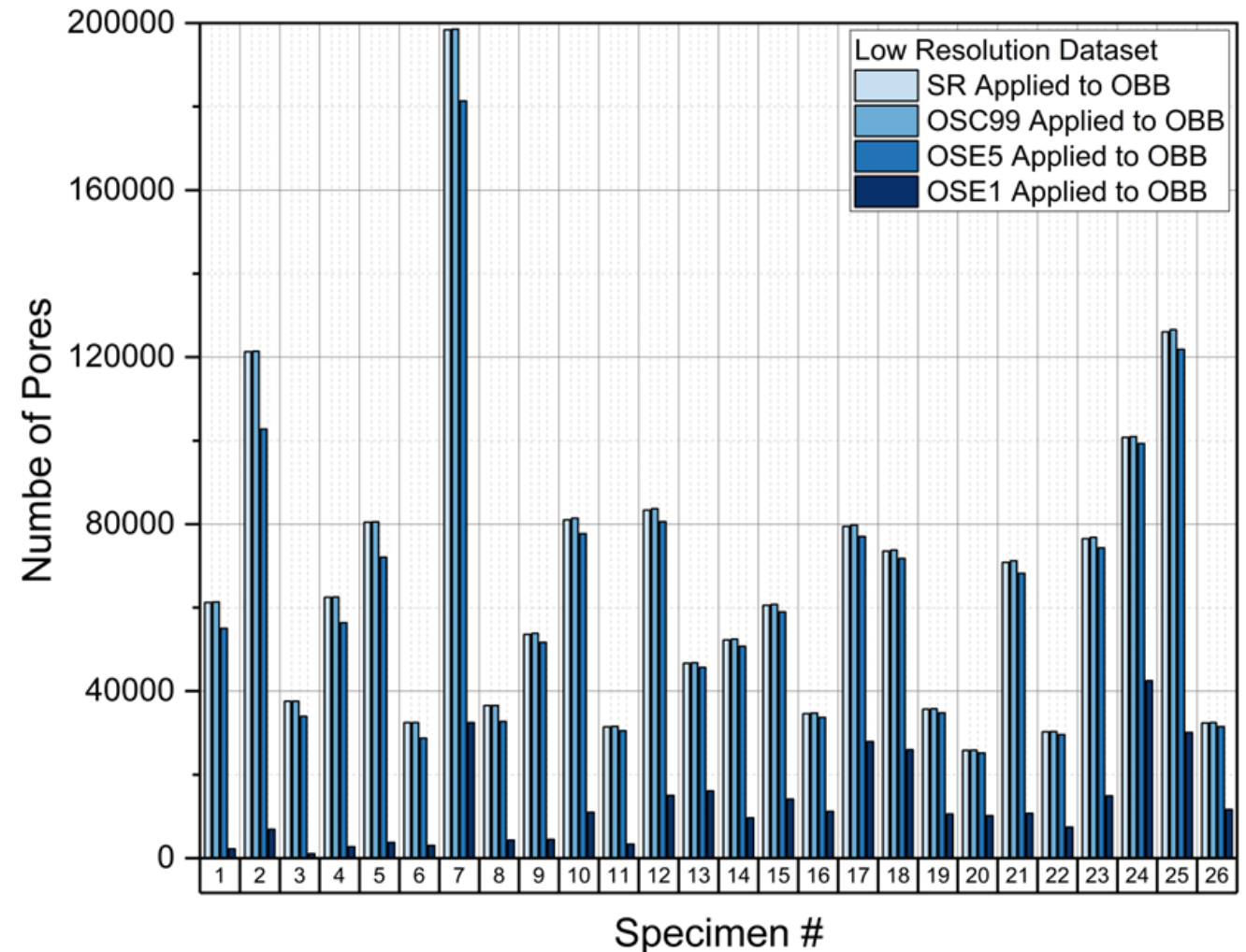
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Applied Confidence Measures

- SSR values only reflect associated detection limits
- LR datasets have an associated RLMC of 99.26%
- HR datasets have an associated RLMC of 60.27%
- OSC99 and OSE1 allow for better comparison
- OSE1 noticeable drop off but significant MC



Pore Filtering – Application of Measurement Confidence Thresholds

Specimen Pore Determination

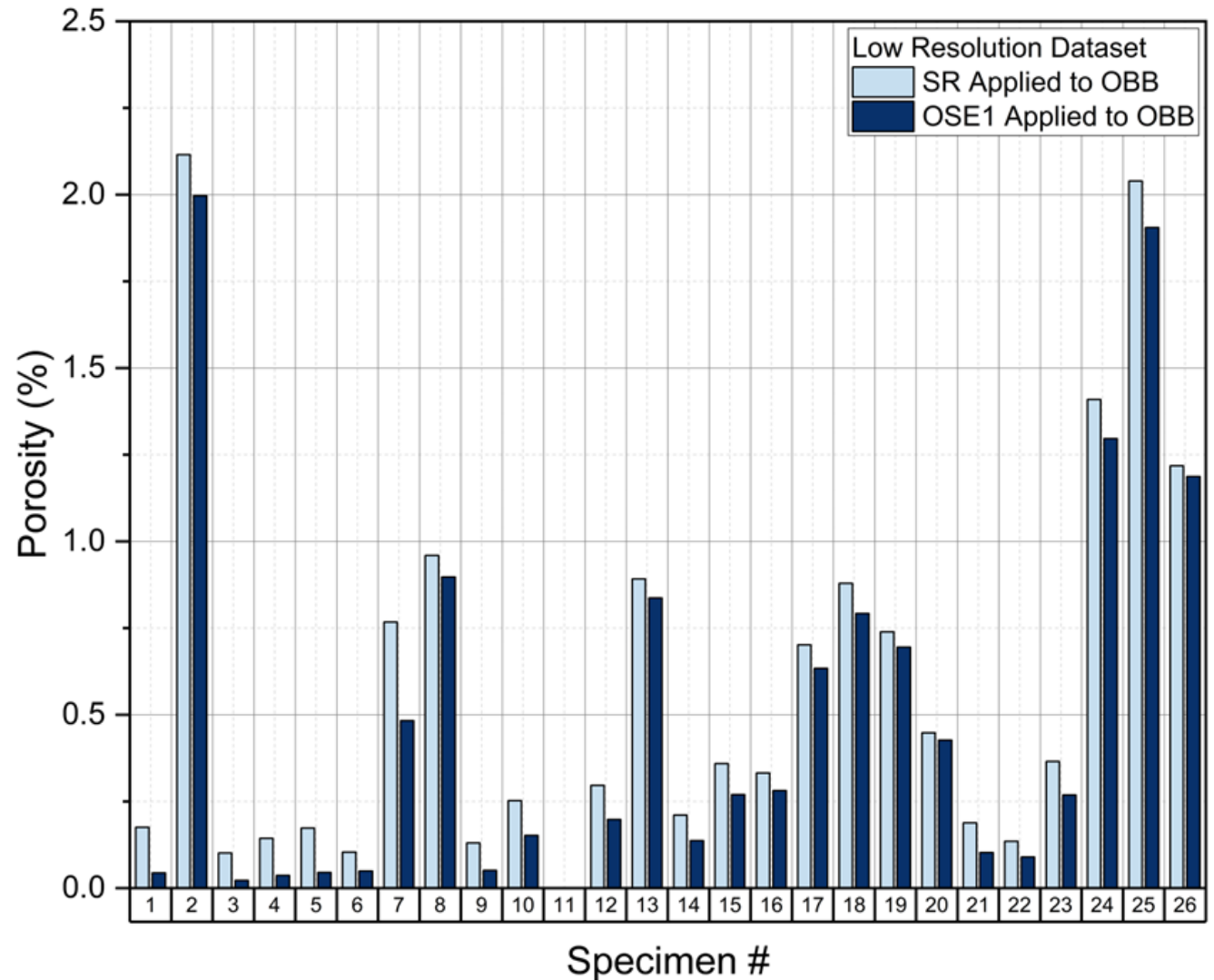
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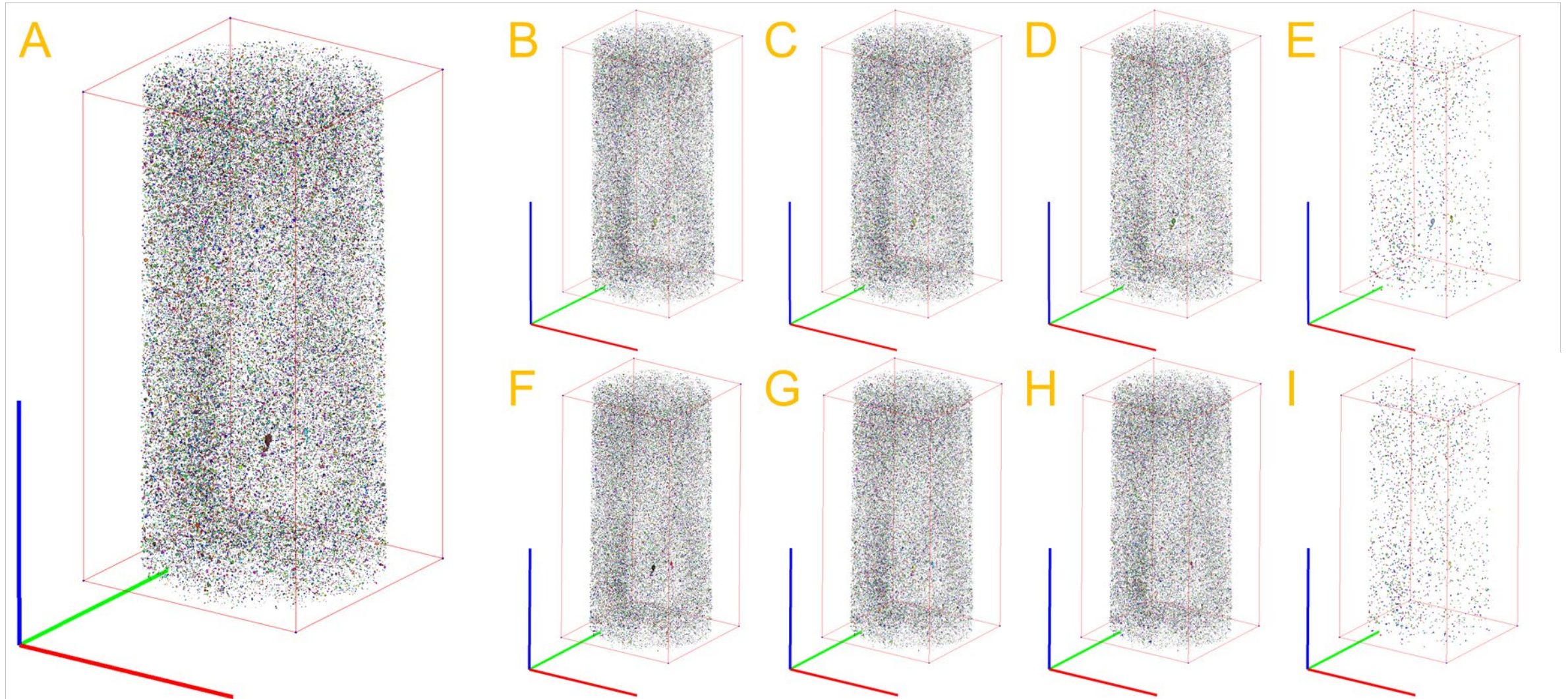
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Specimen Porosity

- Pore count insufficient to represent GP internal structure
- Total porosity was no greater than 2.5%
- Only 4 specimens exhibited porosity > 1.0%
- 16 specimens had a porosity of < 0.5%
- All fall well above the WAC filling level of > 85 vol%
- Note: OSE1 comparable to SSR



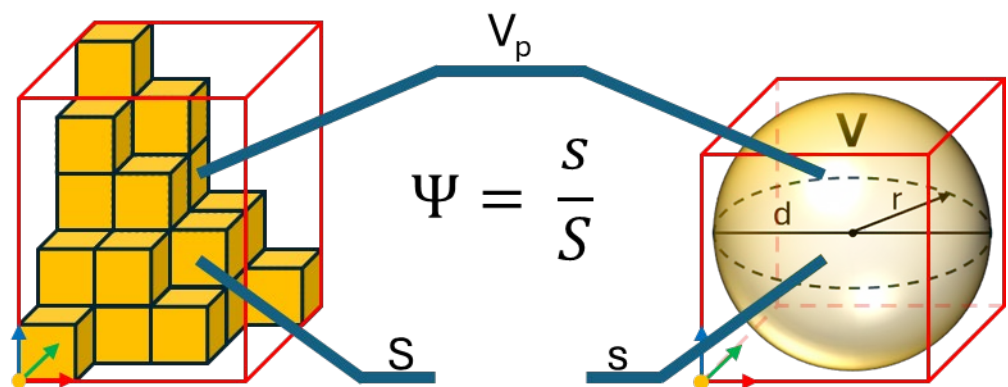
Pore Filtering – X-ray CT Detectability



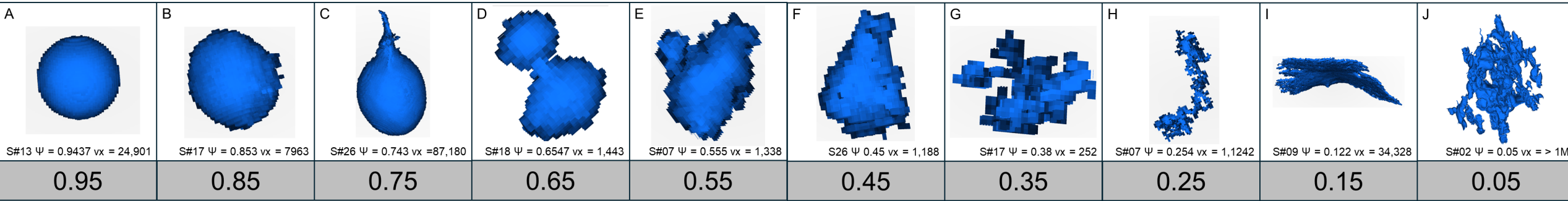
Pore Characterisation – Sphericity (Ψ)

Pore Shape Descriptors

- Pore count & porosity useful regarding extent of pores but provide little to no description of the pore characteristics (e.g. pore vs crack)
- Aspect ratio 2D, while Zingg classification (3D) does not discern between cubes & spheres
- Roundness is a local measure, not global
- **Sphericity describes the relationship between surface area of an object vs. surface area of a sphere with the same volume (Sphere = 1)**



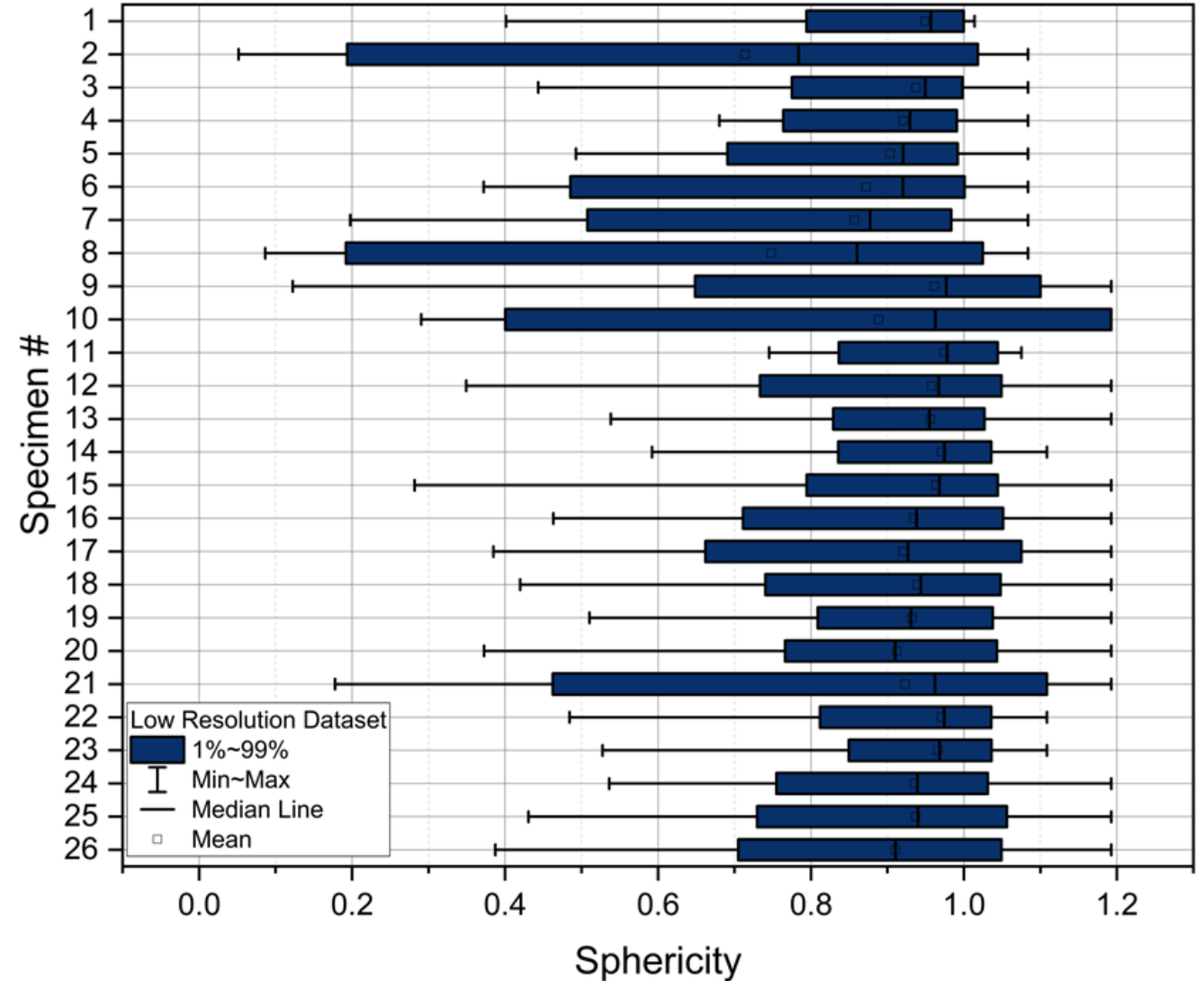
$$\Psi = \frac{\pi^{\frac{1}{3}} (6V_p)^{\frac{2}{3}}}{A_p}$$



Defect Identification & Void Classification

Specimen Pore Sphericity (Threshold: OSE1)

- Median sphericity > 0.8 for 25 of 26 specimens
- Mean sphericity > 0.8 for 24 of 26 specimens
- For 20 specimens 98 % of pore sphericity > 0.6
- Indicates tendency towards spherical shaped pores
- Indicative of air pockets or bubbles



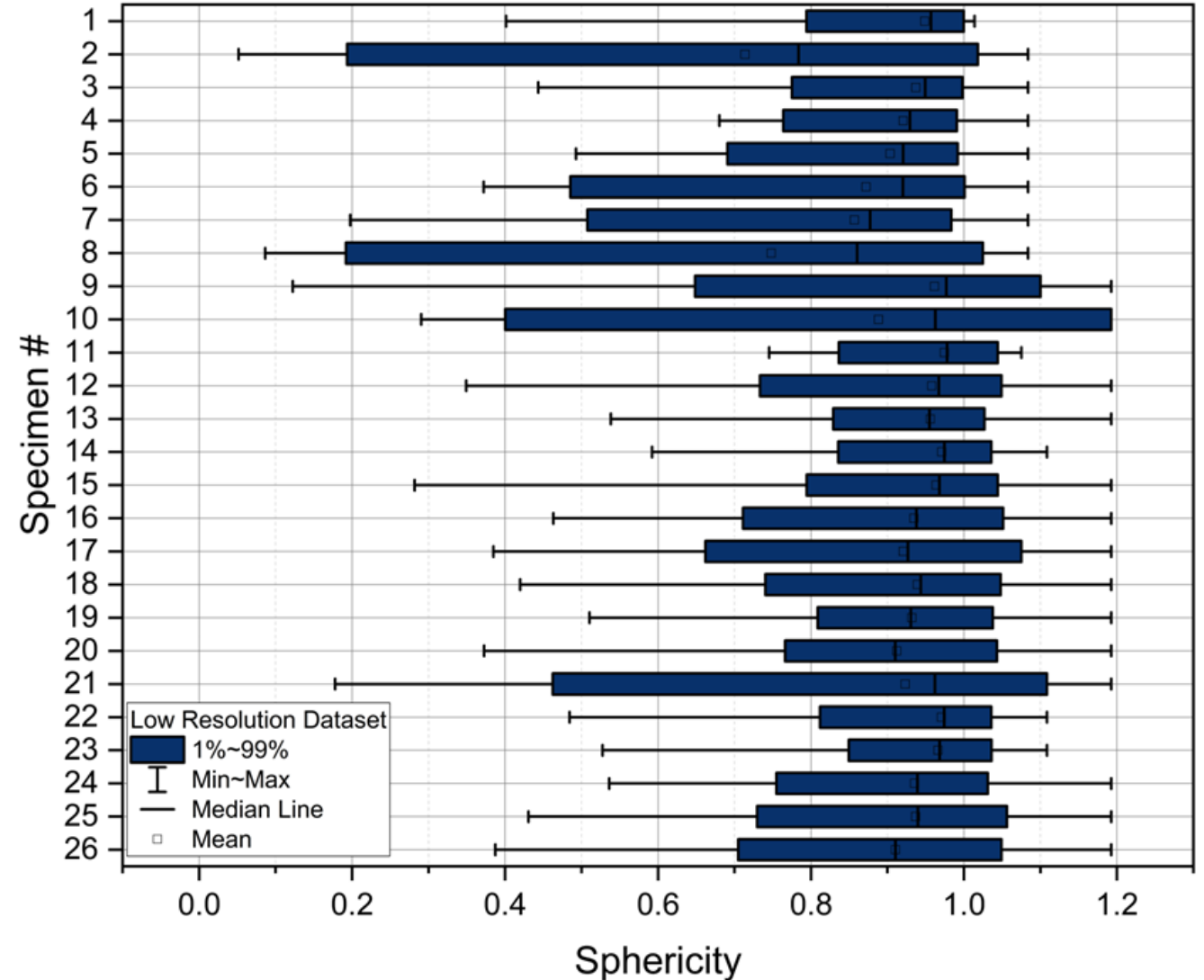
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Sphericity Provides Incomplete Picture

- Half of all specimens contain at least one pore $\Psi < 0.4$
- Indicating a degree of irregularity like cracks
- Major drawback of sphericity is no volume consideration
- Size matters when considering pores & crack formation
- Useful to gauge the potential detrimental impact



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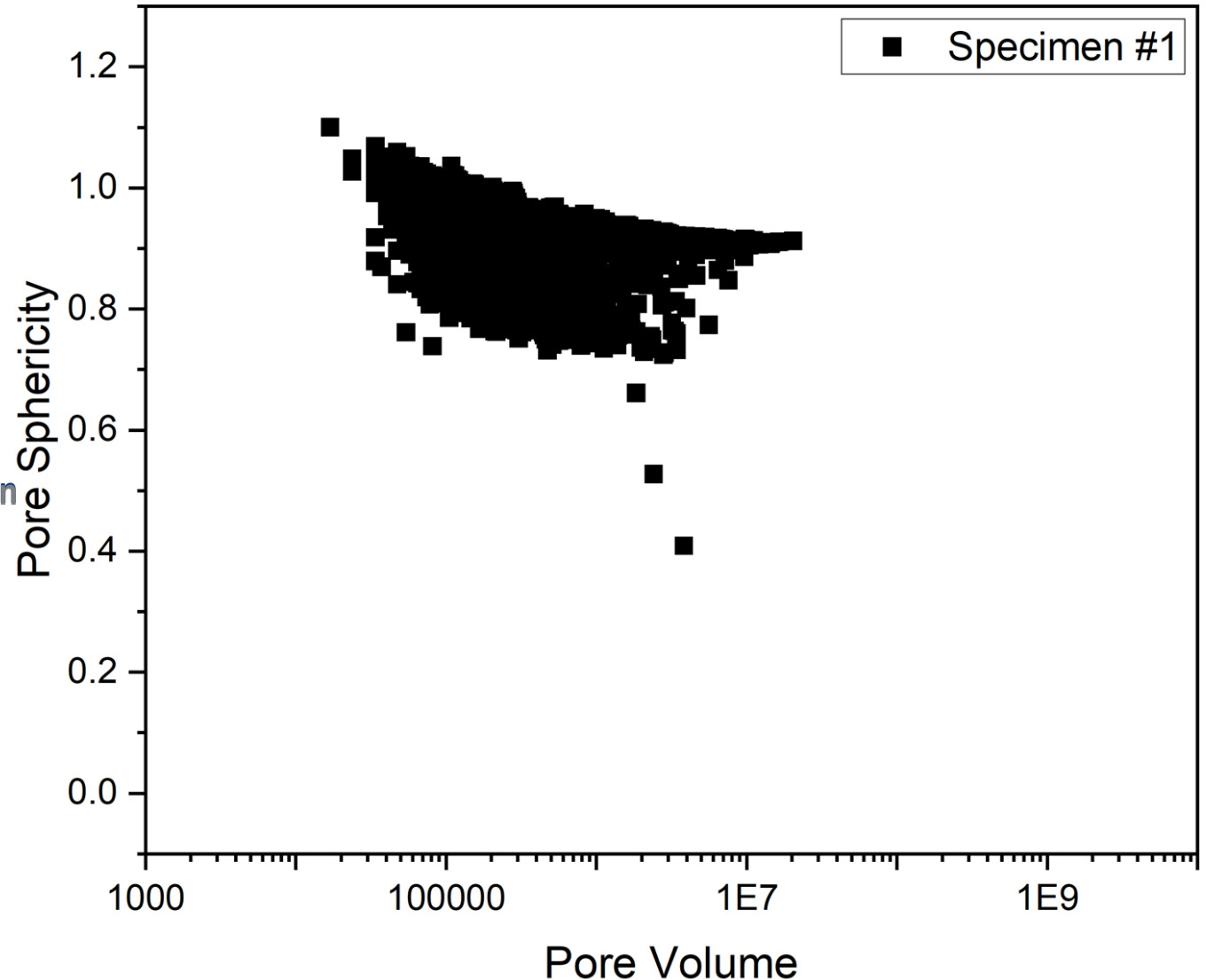
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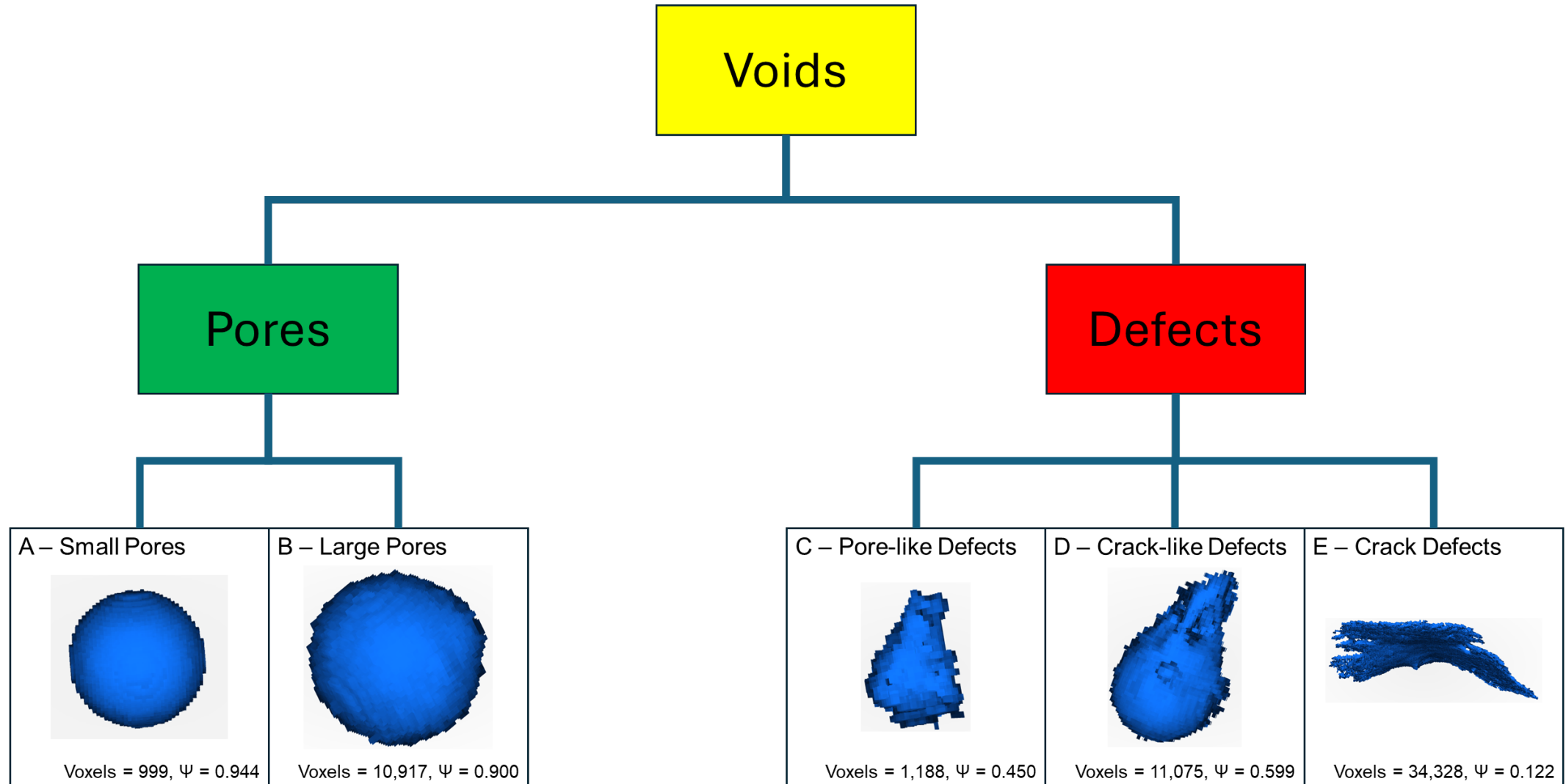
Proposed Classification System

- Provides means of defect identification

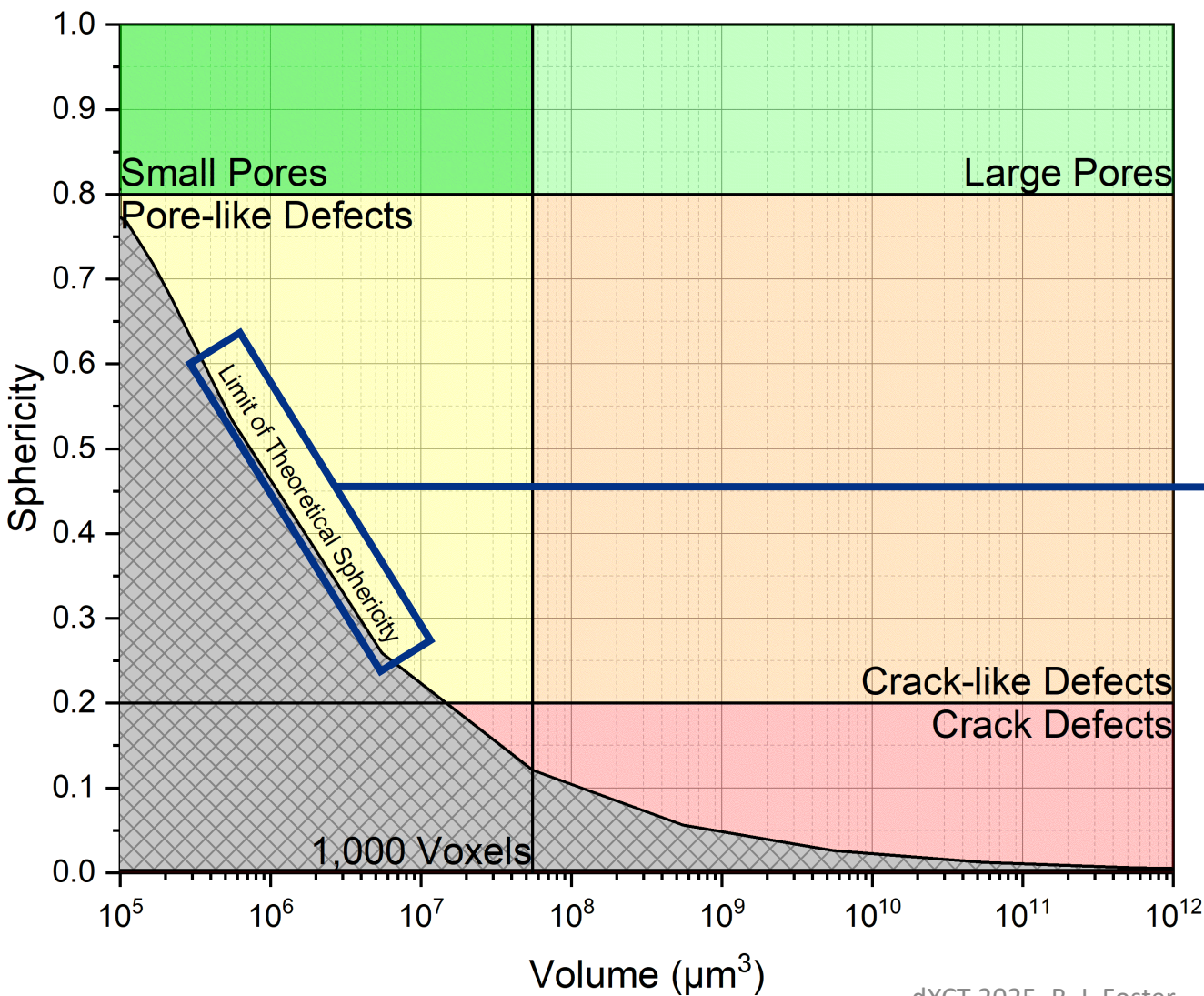
Classification	Category	Volume (vx)	Sphericity
Small Pores	Pore	< 1000	$s \geq 0.8$
Large Pores	Pore	≥ 1000	$s \geq 0.8$
Pore-like Defects	Defect	< 1000	$0.2 \leq s < 0.8$
Crack-like Defects	Defect	≥ 1000	$0.2 \leq s < 0.8$
Crack Defects	Defect	> 1	$s < 0.2$



“When is a Pore Not a Pore, but a Defect” – Voids: Pores vs. Defects



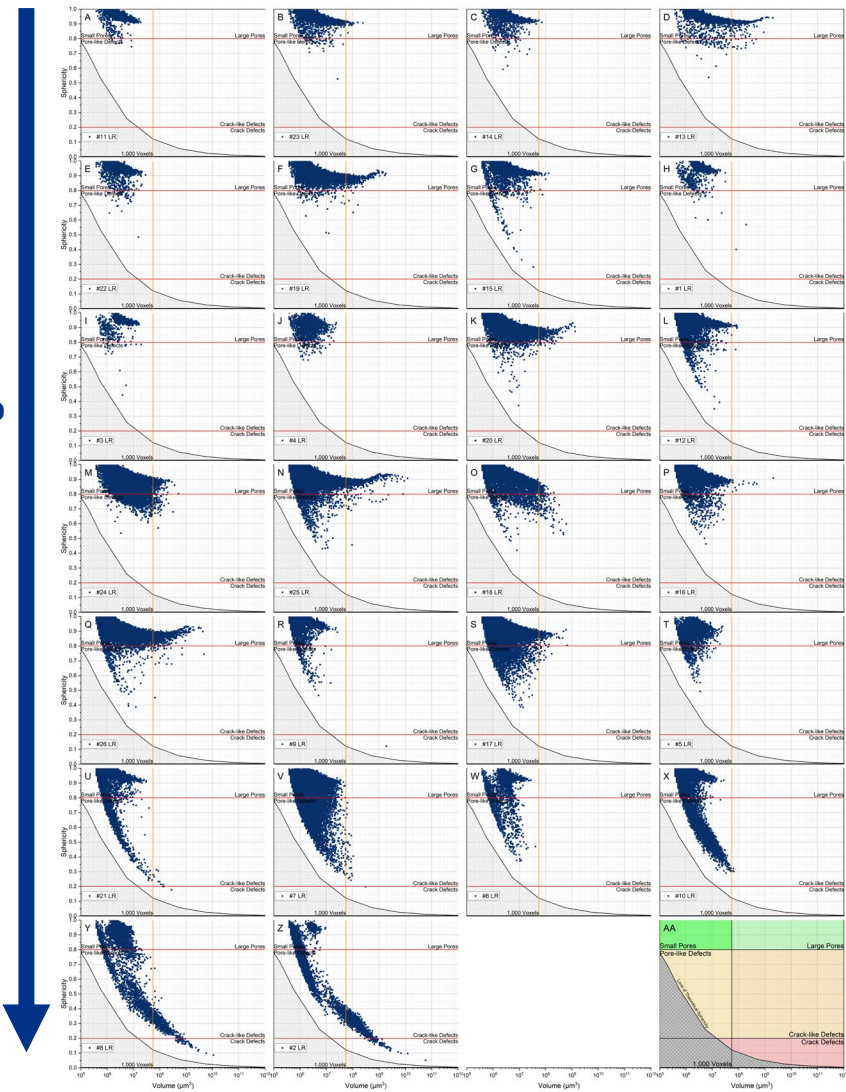
Proposed Classification System



Theoretical Limit of Sphericity				
Voxels	Volume	# of Sides	Area	Sphericity
	1	6	6	0.806
	2	10	10	0.768
	3	14	14	0.719
	4	18	18	0.677
	5	22	22	0.643
	1k	4,002	4,002	0.121
	1M	4E+06	4E+06	0.012
	1B	4E+09	4E+09	0.001

Proposed Classification System – Crack Detection?

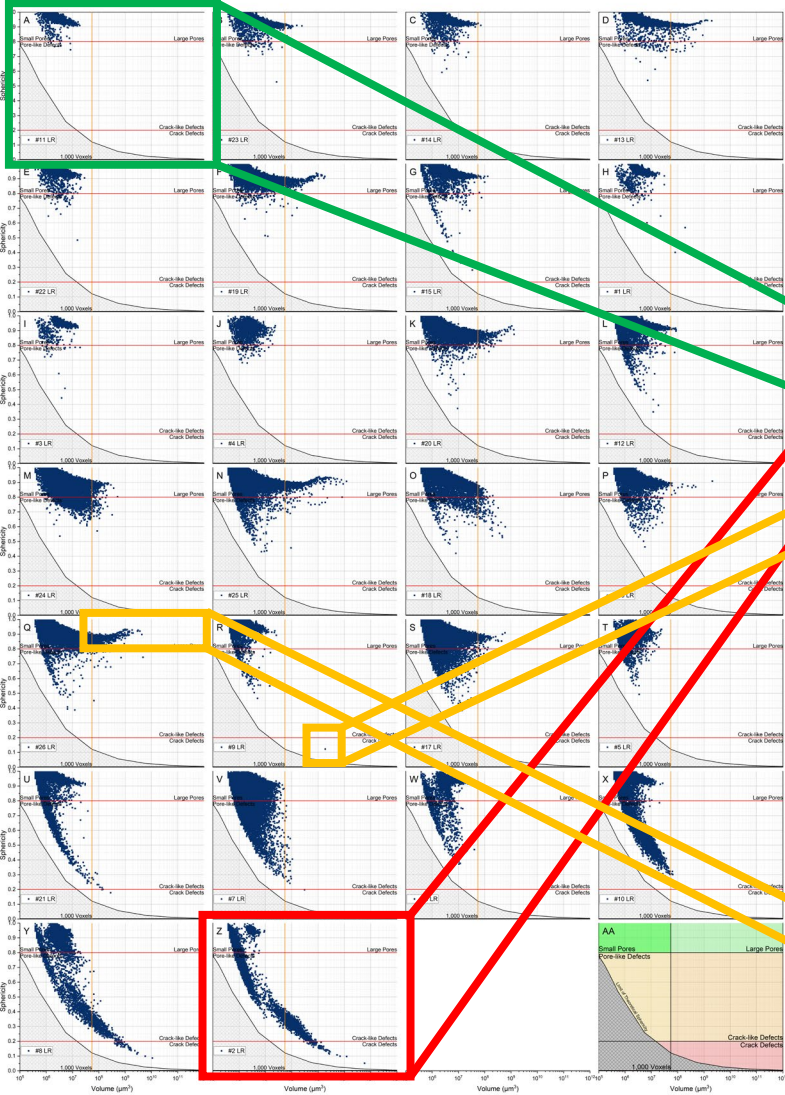
Increasing Defect-to-Pore Ratio



Specimen	Small Pores	Large Pores	Pore-like Defects	Crack-like Defects	Crack Defects	Total Pores	Total Defects
#01	2201	0	23	2	0	2201	25
	98.9%	0.0%	1.0%	0.1%	0.0%	98.9%	1.1%
#02	3155	0	2743	927	79	3155	3749
	45.70%	0.00%	39.73%	13.43%	1.14%	45.7%	54.3%
#03	1076	0	22	0	0	1076	22
	98.00%	0.00%	2.00%	0.00%	0.00%	98.0%	2.0%
#04	2670	0	63	0	0	2670	63
	97.69%	0.00%	2.31%	0.00%	0.00%	97.7%	2.3%
#05	3474	0	278	0	0	3474	278
	92.59%	0.00%	7.41%	0.00%	0.00%	92.6%	7.4%
#06	2407	0	635	0	0	2407	635
	79.13%	0.00%	20.87%	0.00%	0.00%	79.1%	20.9%
#07	25801	0	6650	27	1	25801	6678
	79.44%	0.00%	20.47%	0.08%	0.00%	79.4%	20.6%
#08	2627	0	1212	445	49	2627	1706
	60.63%	0.00%	27.97%	10.27%	1.13%	60.6%	39.4%
#09	4292	0	177	0	1	4292	178
	96.02%	0.00%	3.96%	0.00%	0.02%	96.0%	4.0%
#10	8517	0	2469	3	0	8517	2472
	77.50%	0.00%	22.47%	0.03%	0.00%	77.5%	22.5%
#11	3340	0	9	0	0	3340	9
	99.73%	0.00%	0.27%	0.00%	0.00%	99.7%	0.3%
#12	14663	8	378	1	0	14671	379
	97.43%	0.05%	2.51%	0.01%	0.00%	97.5%	2.5%
#13	15468	525	82	15	0	15993	97
	96.13%	3.26%	0.51%	0.09%	0.00%	99.4%	0.6%
#14	9596	2	36	0	0	9598	36
	99.61%	0.02%	0.37%	0.00%	0.00%	99.6%	0.4%
#15	14005	11	157	1	0	14016	158
	98.81%	0.08%	1.11%	0.01%	0.00%	98.9%	1.1%
#16	10786	14	387	0	0	10800	387
	96.42%	0.13%	3.46%	0.00%	0.00%	96.5%	3.5%
#17	26003	147	1777	17	0	26150	1794
	93.05%	0.53%	6.36%	0.06%	0.00%	93.6%	6.4%
#18	25190	70	621	97	0	25260	718
	96.97%	0.27%	2.39%	0.37%	0.00%	97.2%	2.8%
#19	10154	363	85	5	0	10517	90
	95.73%	3.42%	0.80%	0.05%	0.00%	99.2%	0.8%
#20	9668	240	233	13	0	9908	246
	95.21%	2.36%	2.29%	0.13%	0.00%	97.6%	2.4%
#21	9280	0	1457	9	2	9280	1468
	86.34%	0.00%	13.56%	0.08%	0.02%	86.3%	13.7%
#22	7398	0	53	0	0	7398	53
	99.29%	0.00%	0.71%	0.00%	0.00%	99.3%	0.7%
#23	14835	27	49	0	0	14862	49
	99.5%	0.2%	0.3%	0.0%	0.0%	99.7%	0.3%
#24	41140	232	1058	73	0	41372	1131
	96.8%	0.5%	2.5%	0.2%	0.0%	97.3%	2.7%
#25	28619	685	784	32	0	29304	816
	95.0%	2.3%	2.6%	0.1%	0.0%	97.3%	2.7%
#26	10590	643	409	30	0	11233	439
	90.7%	5.5%	3.5%	0.3%	0.0%	96.2%	3.8%

Proposed Classification System – Crack Detection?

Increasing Defect-to-Pore Ratio



Specimen	Small Pores	Large Pores	Pore-like Defects	Crack-like Defects	Crack Defects	Total Pores	Total Defects
#01	2201	0	23	2	0	2201	25
#02	3155	0	2743	927	79	3155	3749
#03	1076	0	22	0	0	1076	22
#04	2670	0	63	0	0	2670	63
#05	3474	0	278	0	0	3474	278
#06	2407	0	635	0	0	2407	635
#07	25801	0	6650	27	1	25801	6678
#08	2627	0	1212	445	49	2627	1706
#09	4292	0	177	0	1	4292	178
#10	8517	0	2469	3	0	8517	2472
#11	3340	0	9	0	0	3340	9
#12	14663	8	378	1	0	14671	379
#13	15468	525	82	15	0	15993	97
#14	9596	2	36	0	0	9598	36
#15	14005	11	157	1	0	14016	158
#16	10786	14	387	0	0	10800	387
#17	26003	147	1777	17	0	26150	1794
#18	25190	70	621	97	0	25260	718
#19	10154	363	85	5	0	10517	90
#20	9668	240	233	13	0	9908	246
#21	9280	0	1457	9	2	9280	1468
#22	7398	0	53	0	0	7398	53
#23	14835	27	49	0	0	14862	49
#24	41140	232	1058	73	0	41372	1131
#25	28619	685	784	32	0	29304	816
#26	10590	643	409	30	0	11233	439

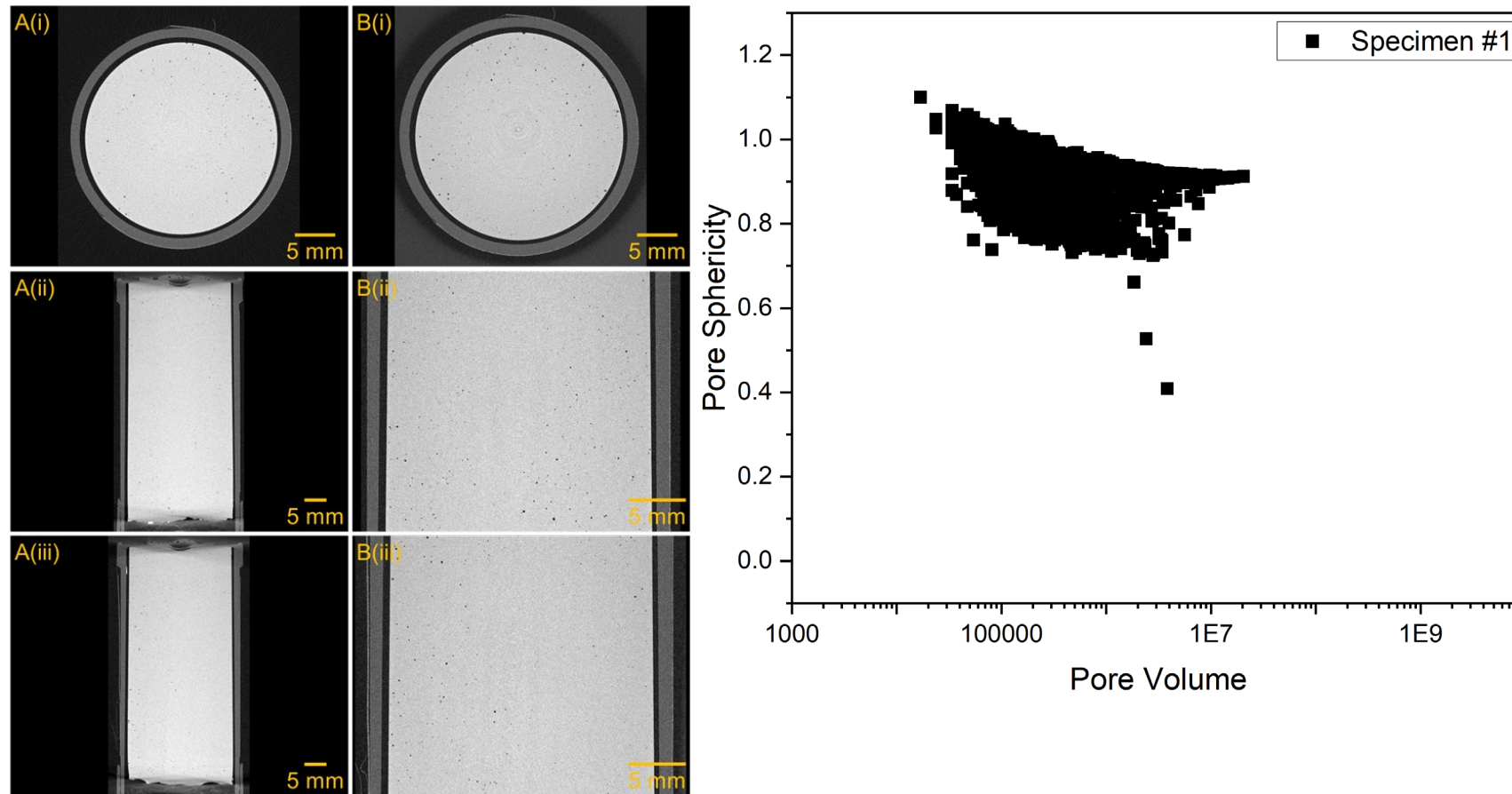
Majority Defects

Single Large Defect

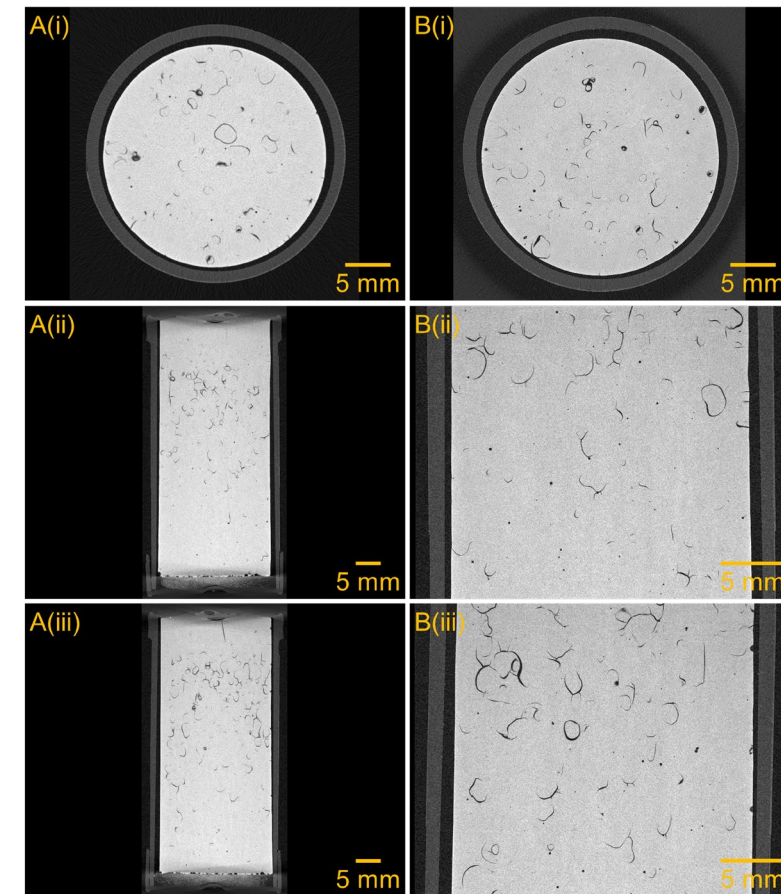
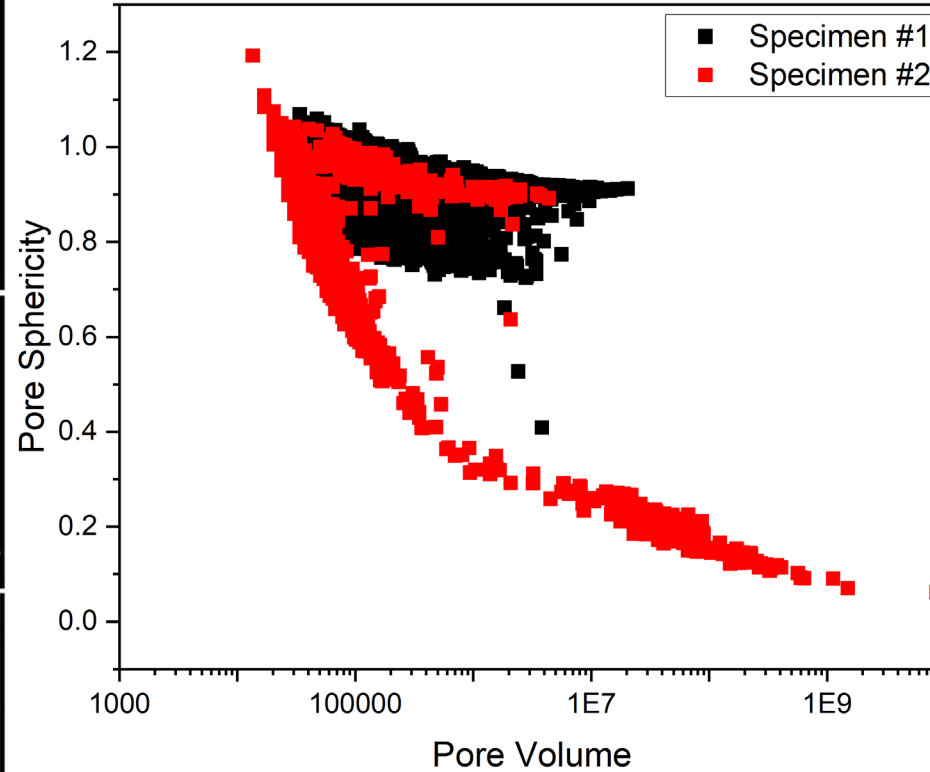
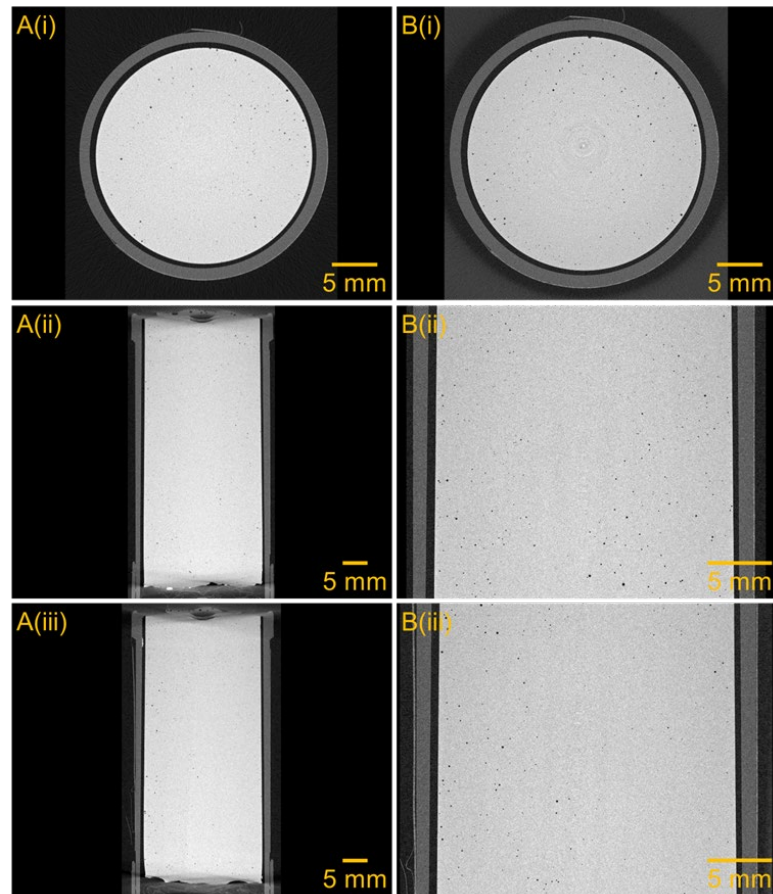
Majority Small Pores

Significant Large Pores

X-ray CT Data Processing – Crack Detection?



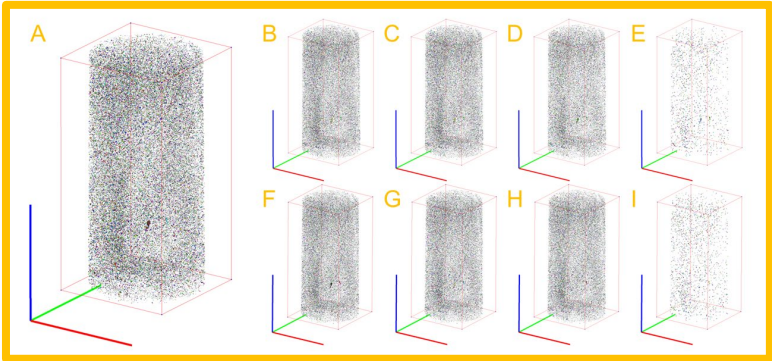
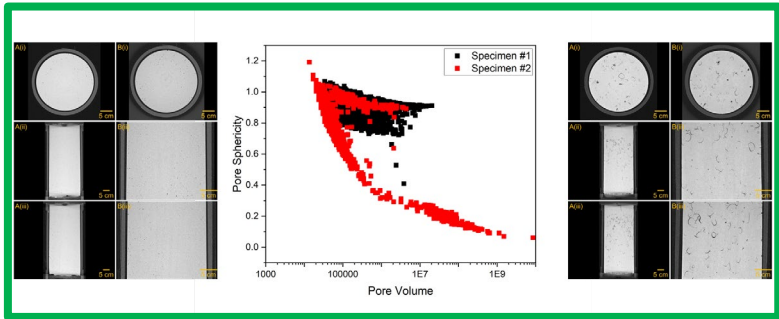
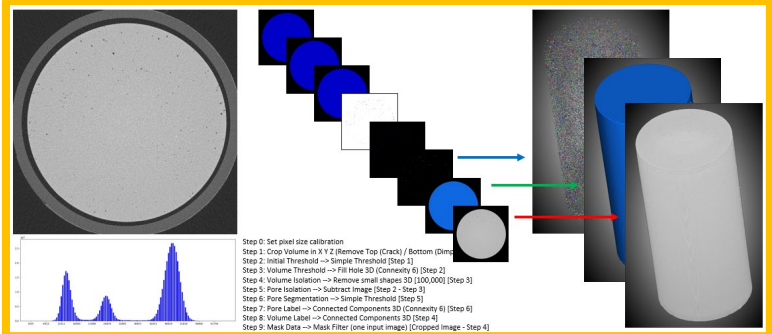
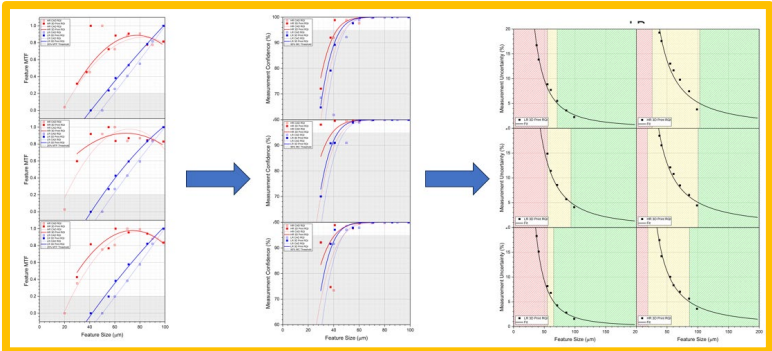
X-ray CT Data Processing – Crack Detection?



CONTENTS

- 01 Project Preface
- 02 Spatial Resolution Determination
- 03 Geopolymer Specimen Scan Results
- 04 Conclusions**

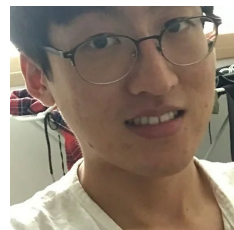
Conclusions – Implications for Geopolymer Wasteform Inspection



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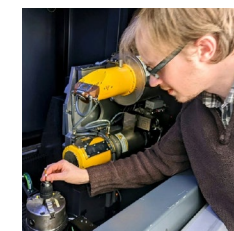
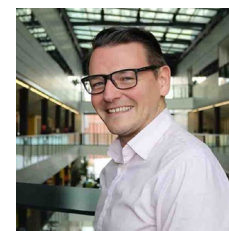


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