CONFLUENT

Volume weighted probabilistic methods for nitinol lifetime prediction

Craig Bonsignore

Karthikeyan Senthilnathan

Ali Shamimi

Confluent Medical Technologies | Fremont California

> **Introduction**

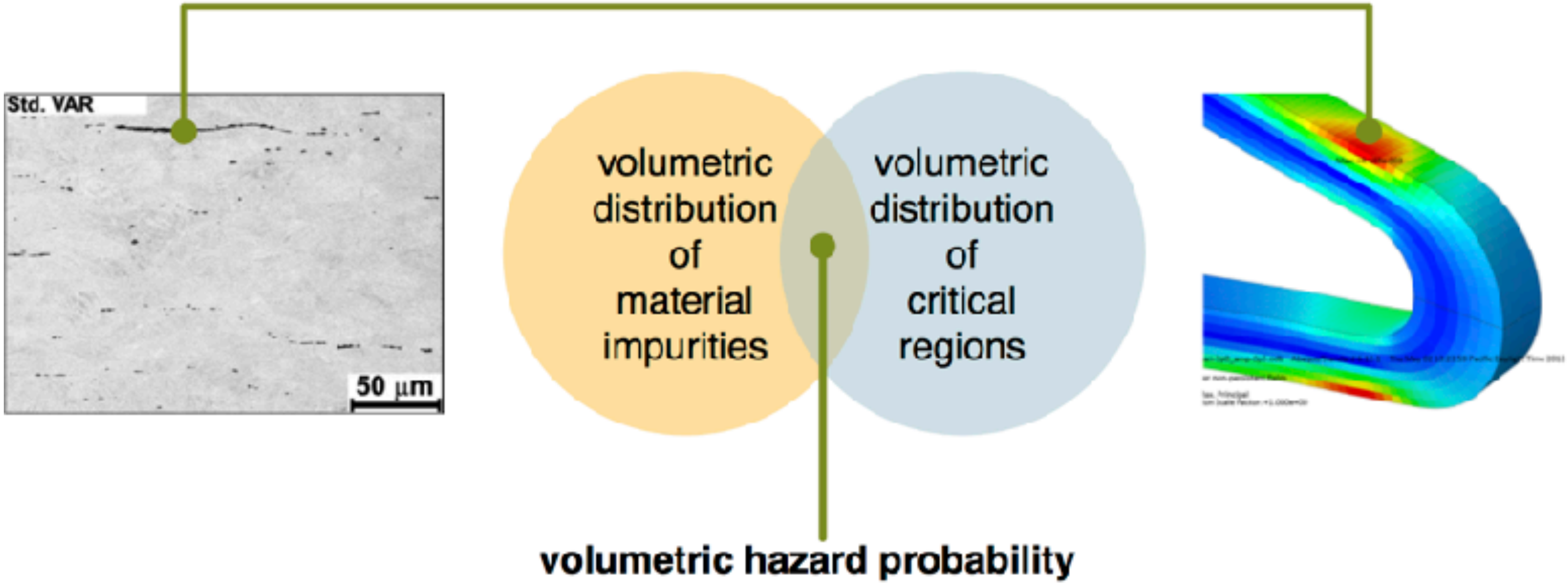
Volumetric FEA methods

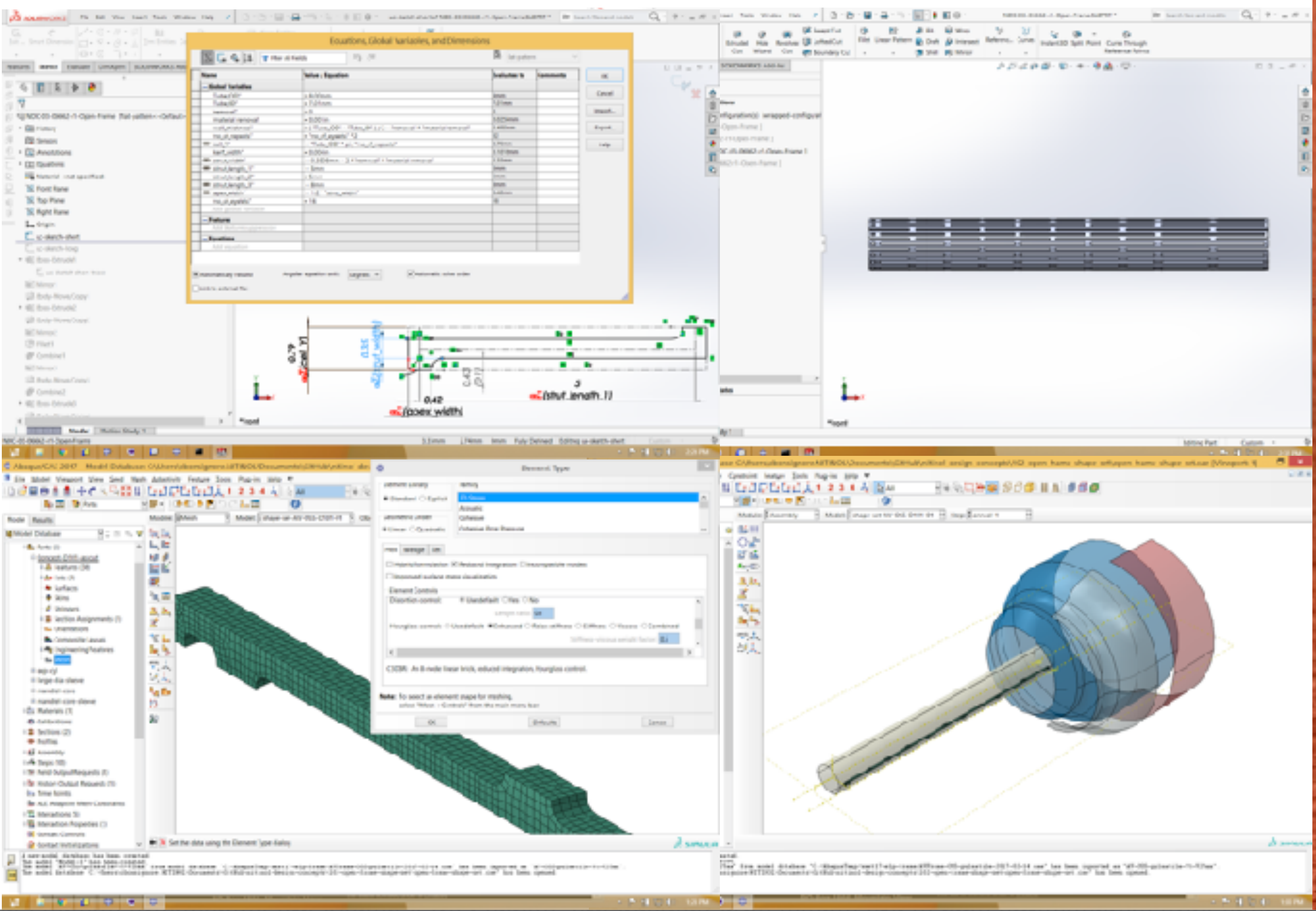
Sub-µm x-ray computed tomography

Monte-Carlo risk assessment

Resources

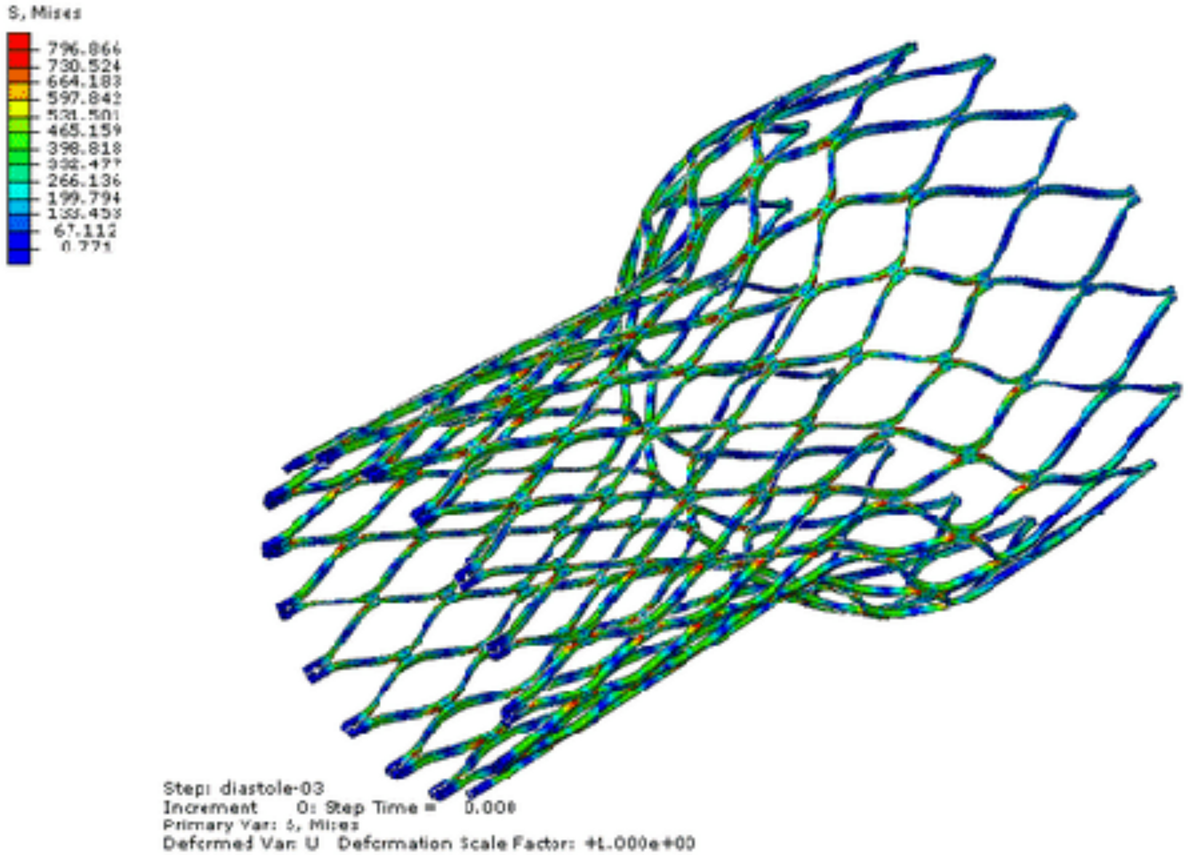
Motivation


Std. VAR
50 μm
volumetric distribution of material impurities
volumetric distribution of critical regions
volumetric hazard probability


Equations, Global Variables, and Dimensions
0.42
(apex_width)
(strut_length_1)

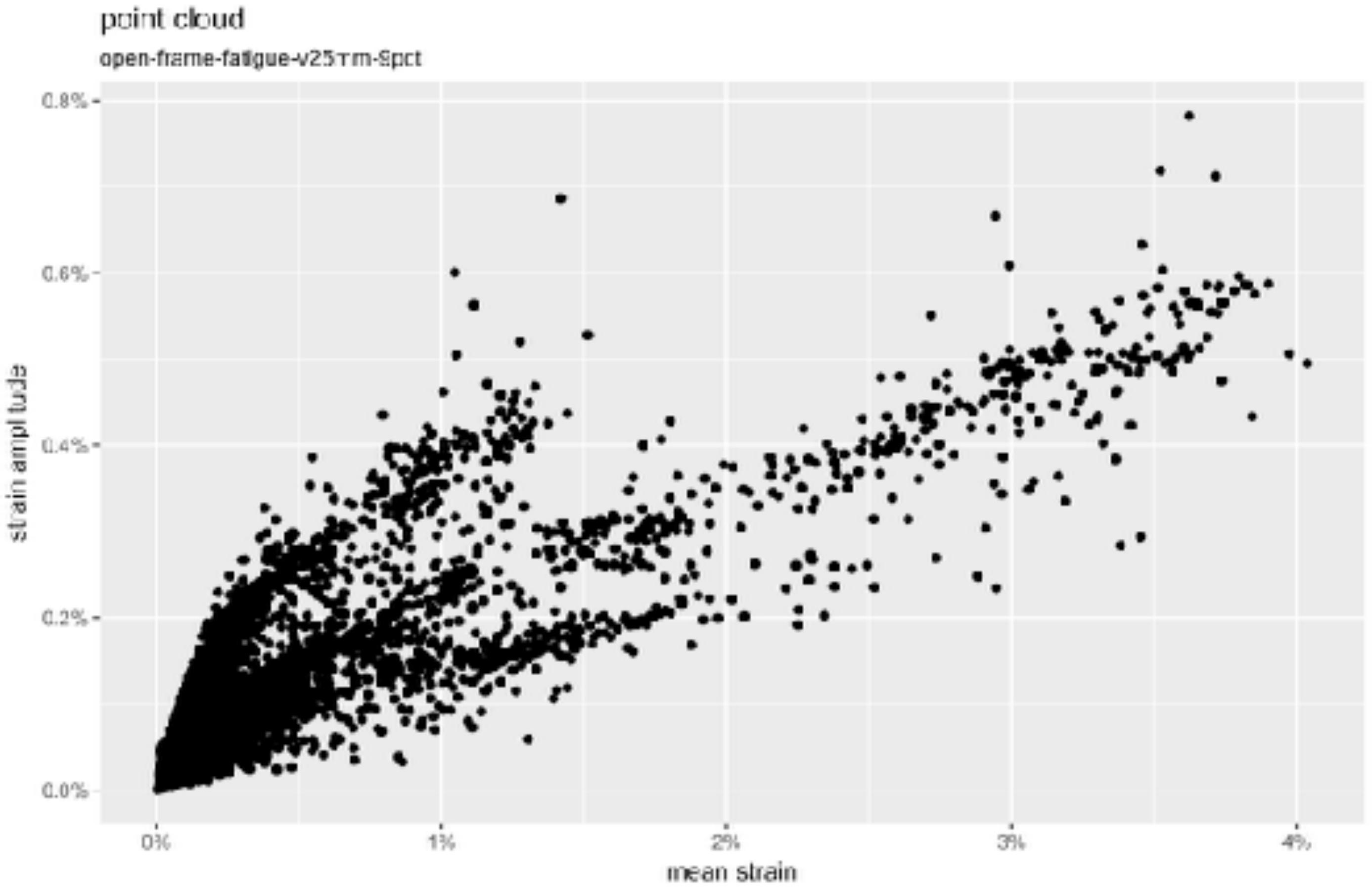
cyclic fatigue condition

9% cyclic change in diameter



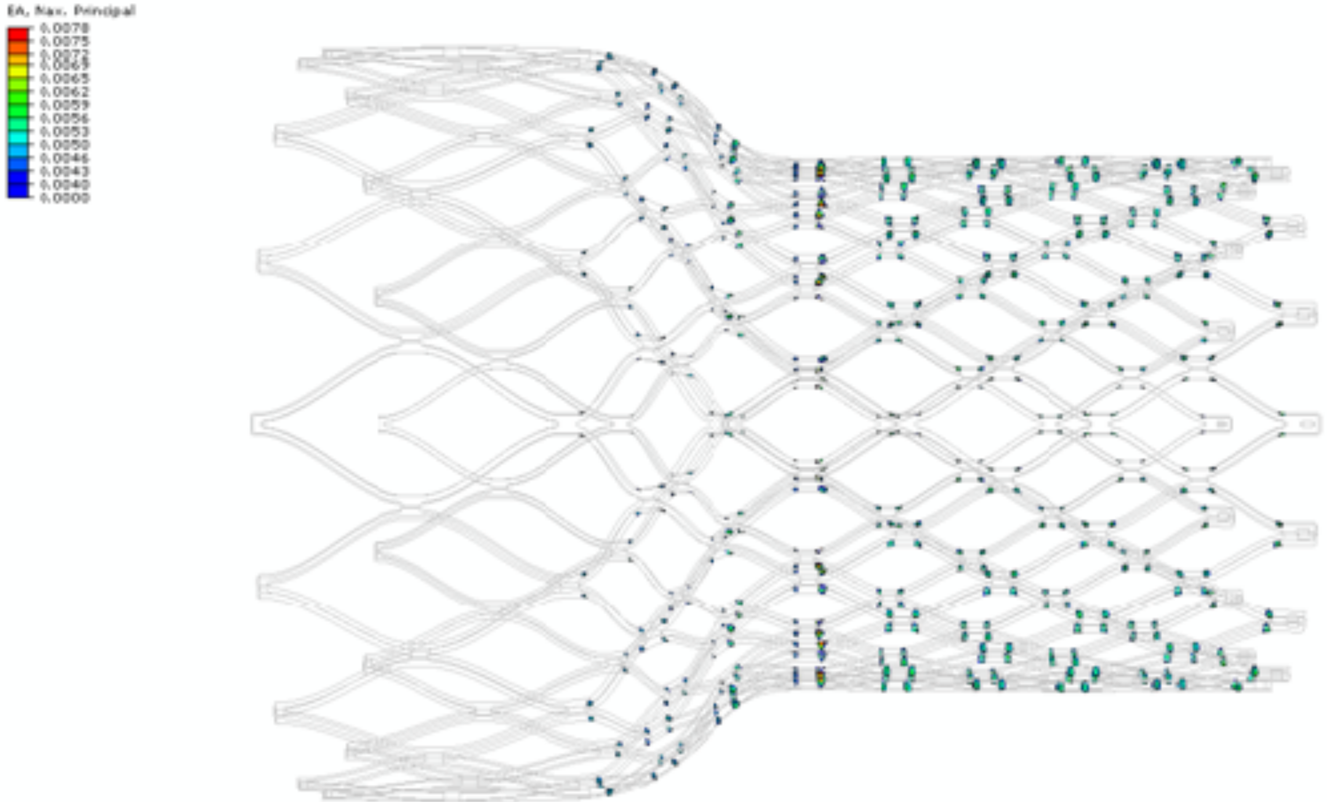
typical point cloud

9% cyclic change in diameter



critical volumes

a small proportion of the volume exceeds a critical limit of strain amplitude.



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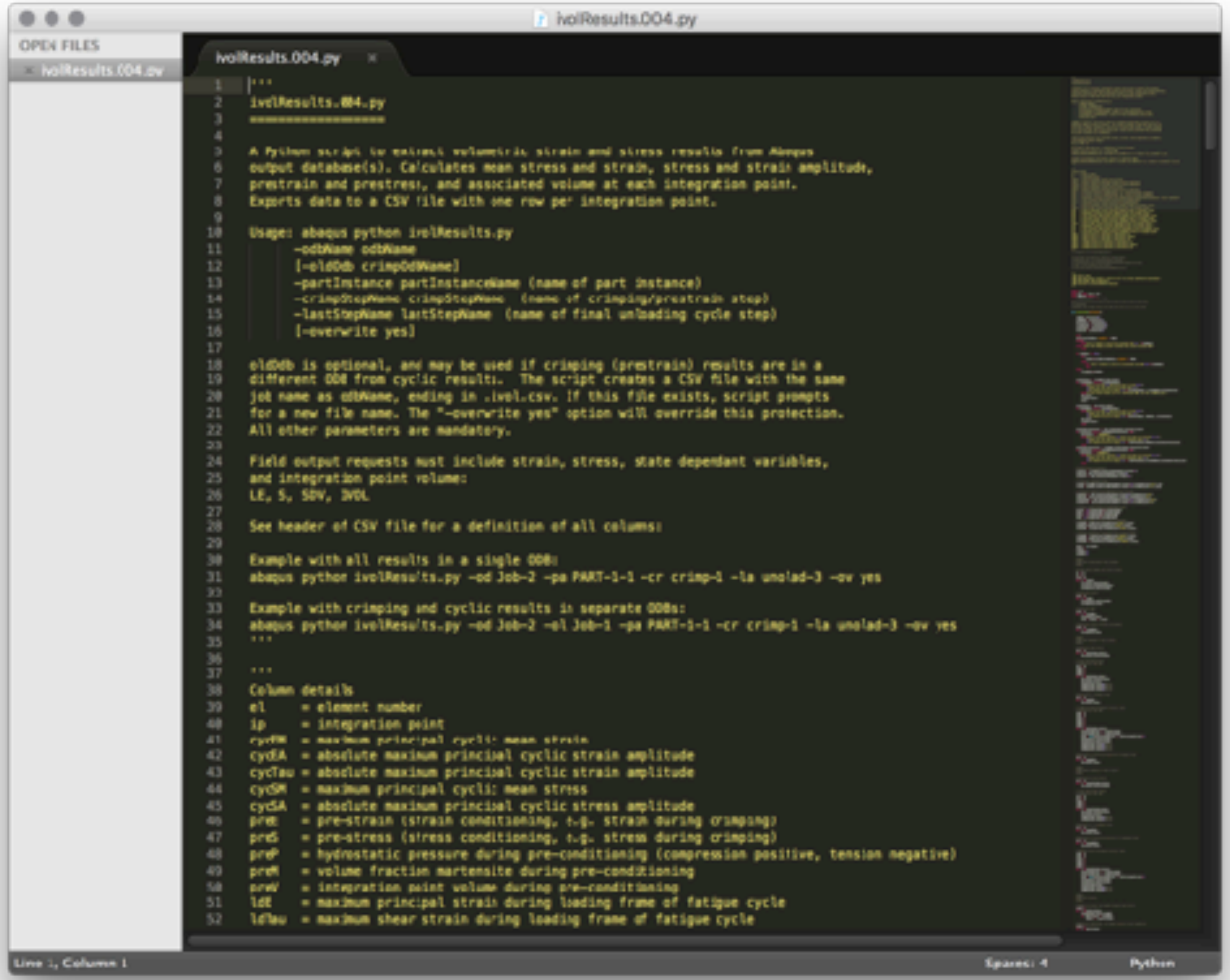
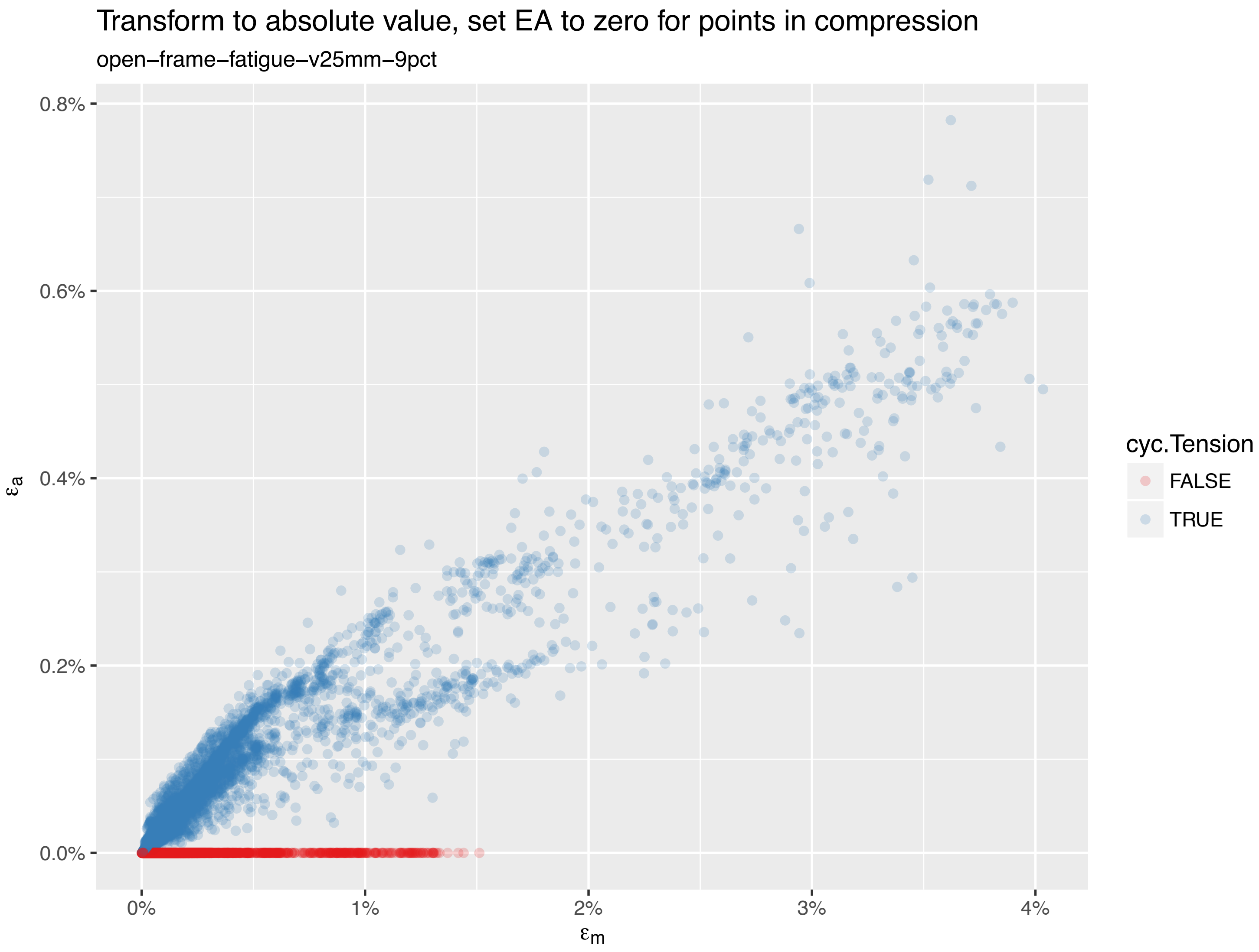
Tools to extract volume data and more

- integration point volume
- strain, stress at crimping step (pre-strain)
- hydrostatic pressure (tension vs. compression)
- volume fraction of martensite
- mean stress/strain
- stress/strain amplitude
- stress and strain components



Typical point cloud

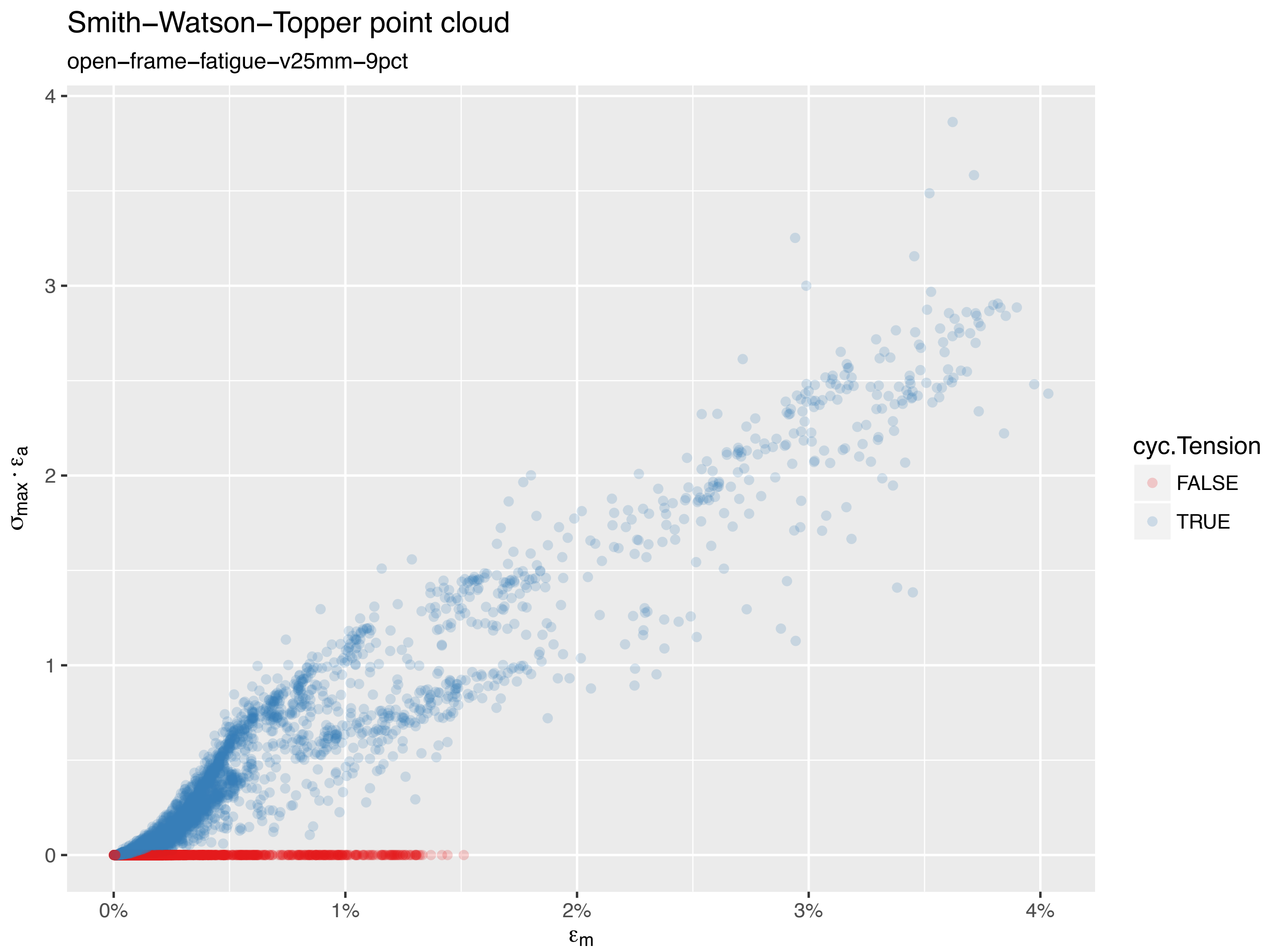
strain amplitude vs. mean strain



SWT point cloud

Smith-Watson-Topper

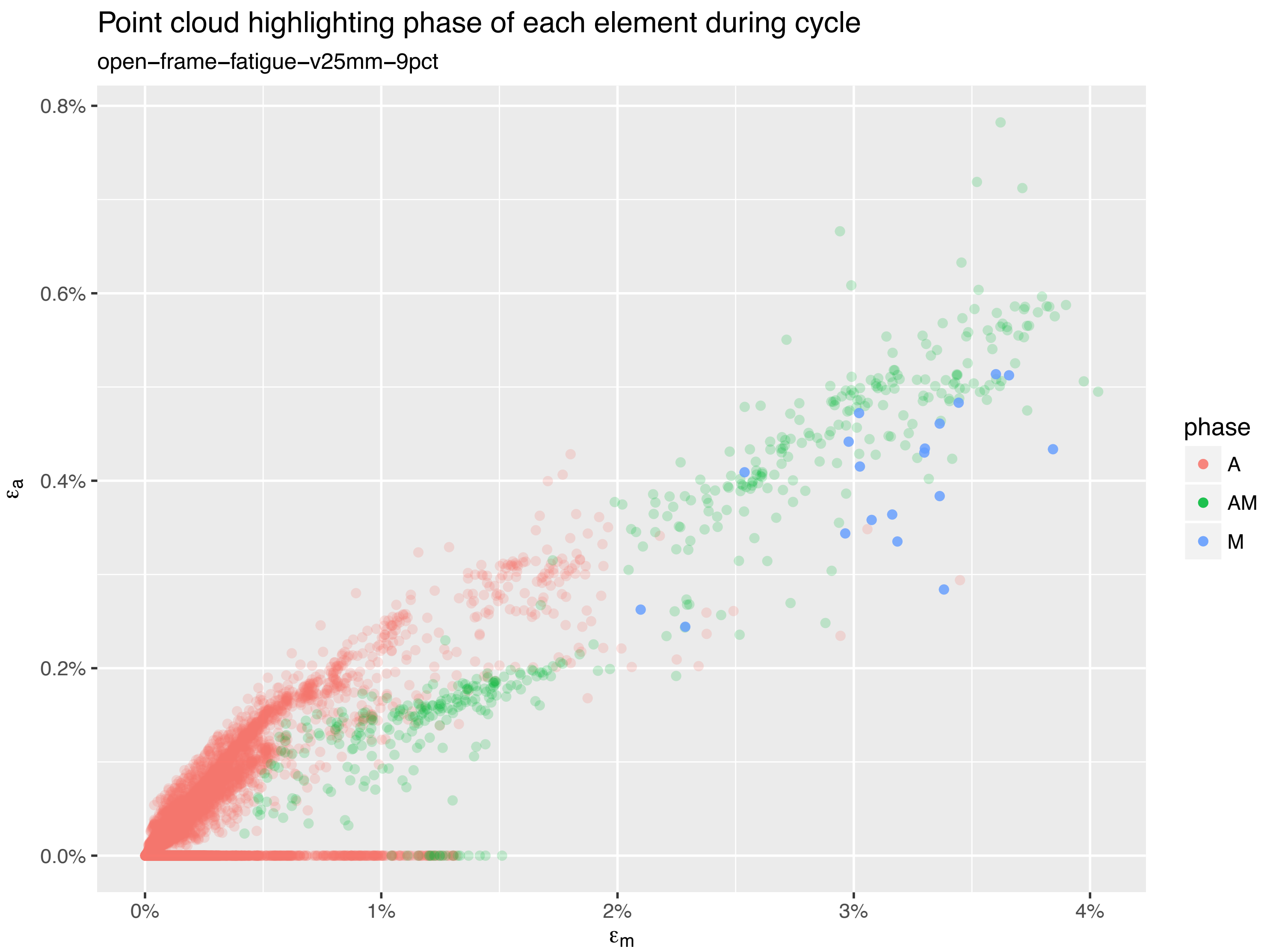
(maximum stress)·(strain amplitude)



Phase map

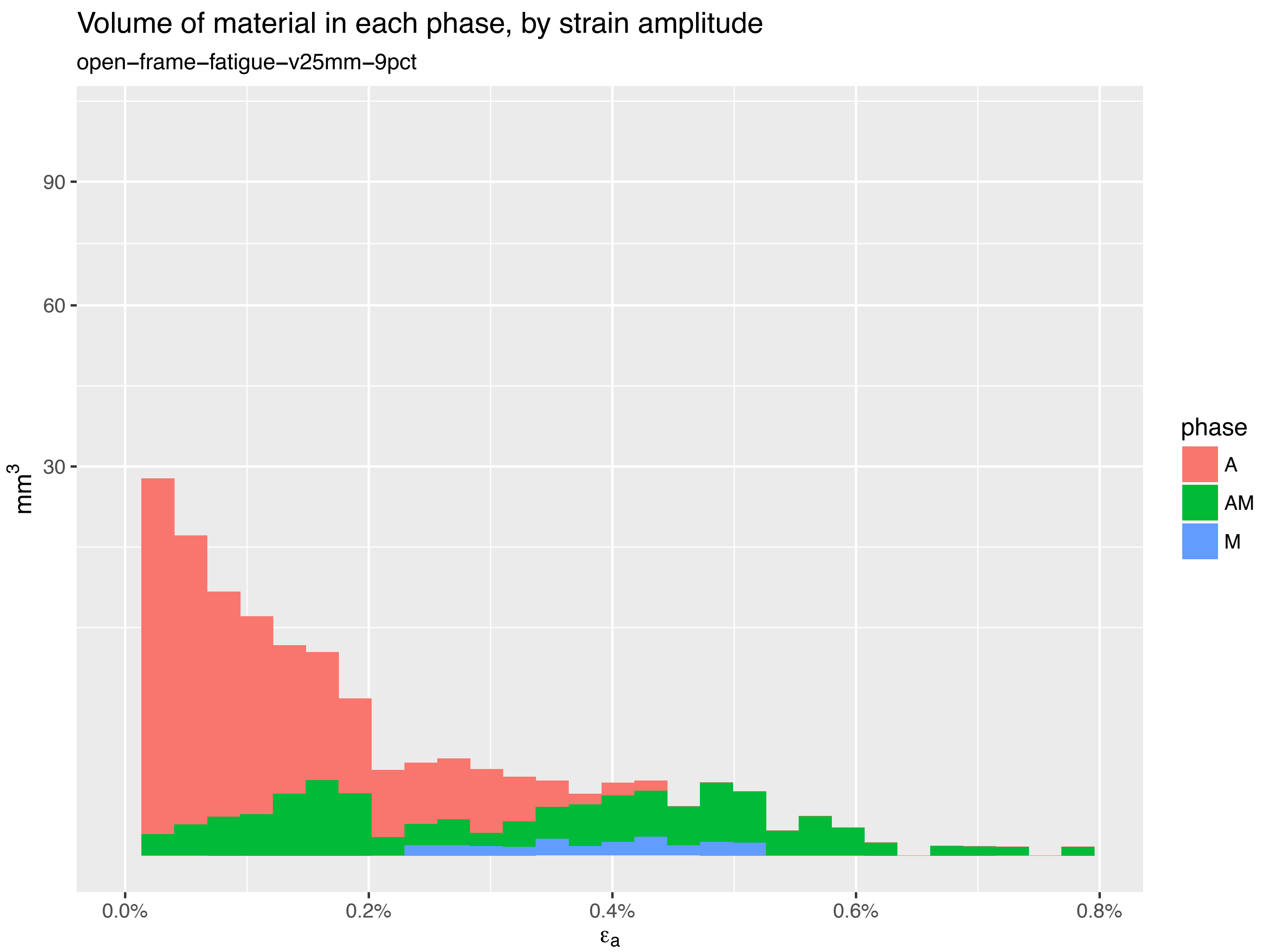
During the fatigue cycle, elements may:

- Remain austenite throughout
- Remain martensite throughout
- Alternate A/M during cycle



Volumetric histogram

Measure the total volume of material in each phase, according to strain amplitude (or SWT, or any other criterion)



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Standard VAR (SE508)

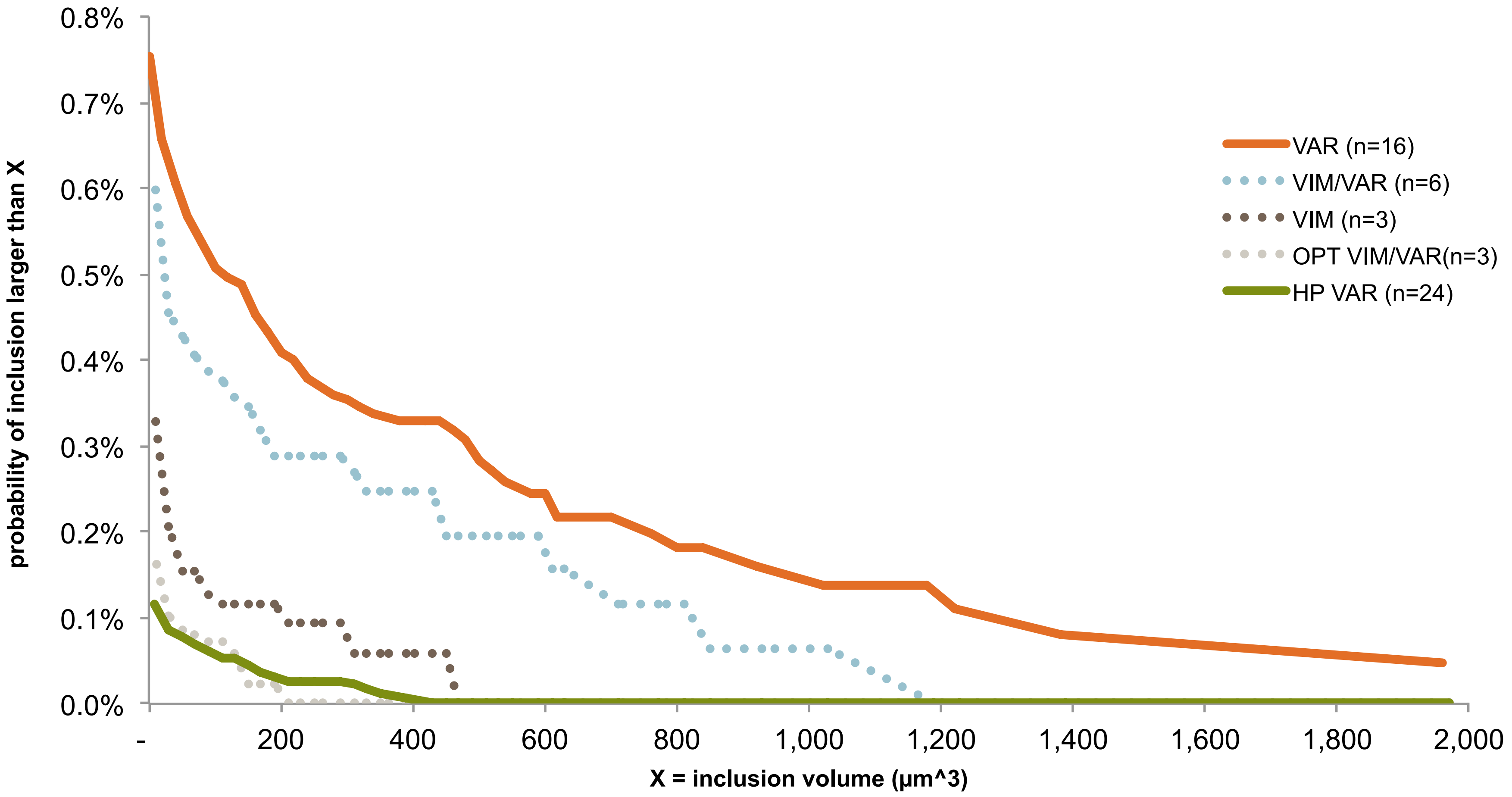
264.46x198.35 µm (1280x960); 8-bit; 1.2MB

High Purity VAR (SE508-ELI)

264.46x198.35 µm (1280x960); 8-bit; 1.2MB

SMST 2014: Strain Amplitude Volume Fraction Method for Evaluation of Nitinol Fatigue Durability

Approximation of inclusion volumetric probability



SMST 2013: Strain Amplitude Volume Fraction Method for Evaluation of Nitinol Fatigue Durability

Durability performance benefit of high purity material

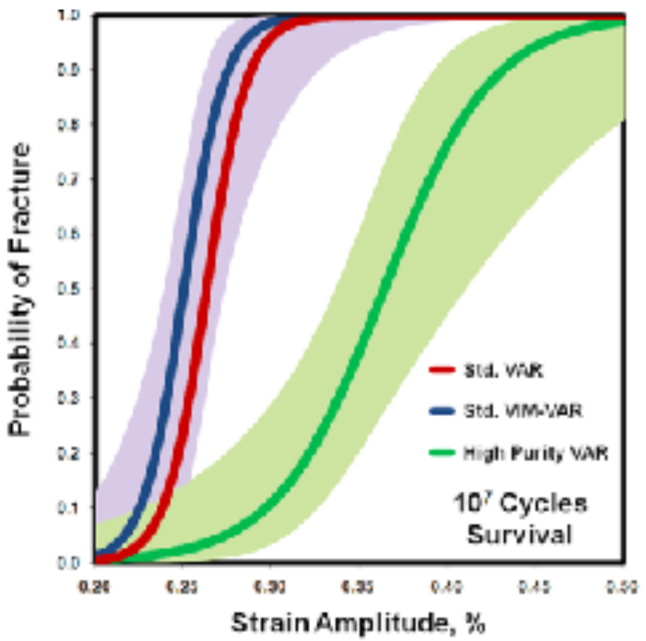


Fig. 8 – Probability of Nitinol wire fracture versus strain amplitude plots with the curve fit line shown bracketed by the 95th percentile upper and lower confidence interval bands.

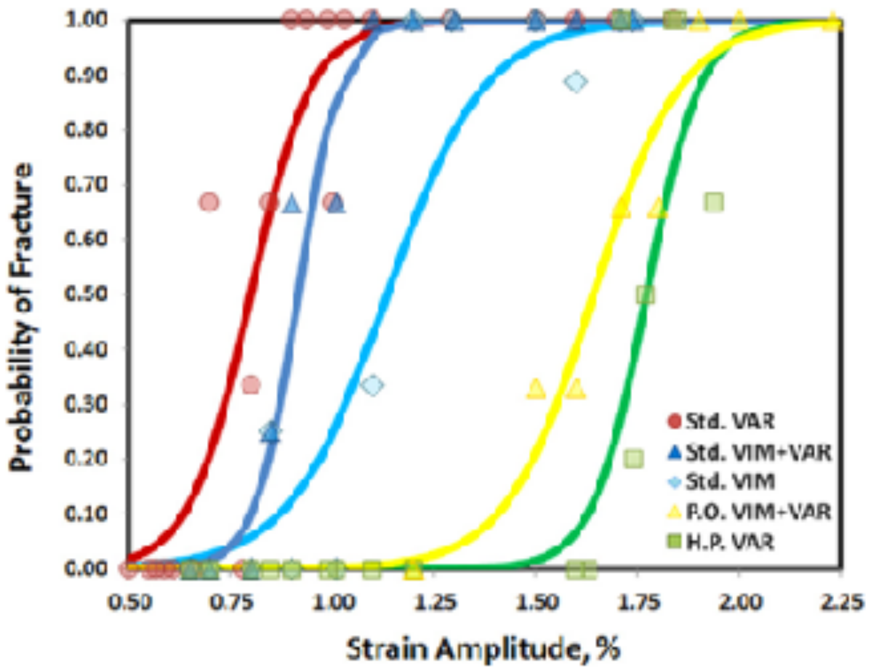


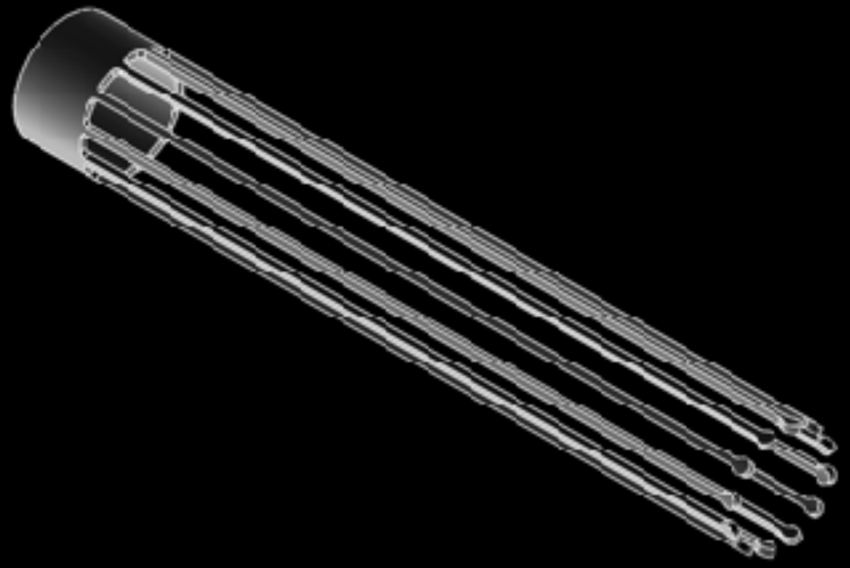
Fig. 9 – Probability of Nitinol diamond fracture at 10^7 cycles versus strain amplitude plots with a logit sigmoidal curve fit line for each data set.

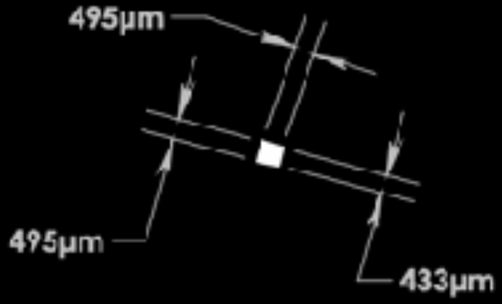
Robertson, S. W. et al. A statistical approach to understand the role of inclusions on the fatigue resistance of superelastic Nitinol wire and tubing. J. Mech. Behav. Biomed. Mater. 51, 119–131 (2015).

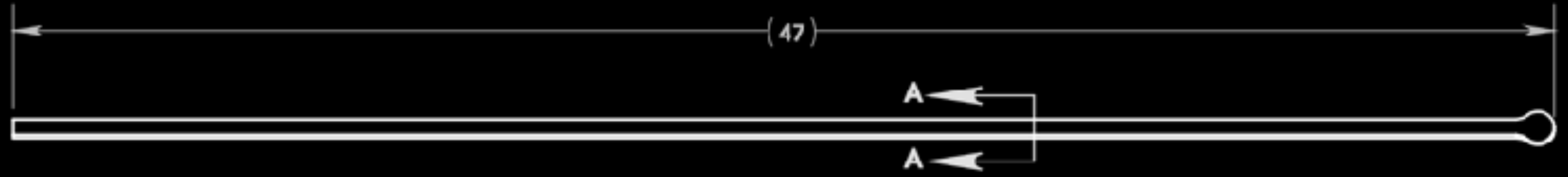
X-ray computed tomography (XCT) test specimens

8.00x7.01 superelastic nitinol tubing
0.5mm x 0.5mm x 50mm laser cut “matchstick” samples

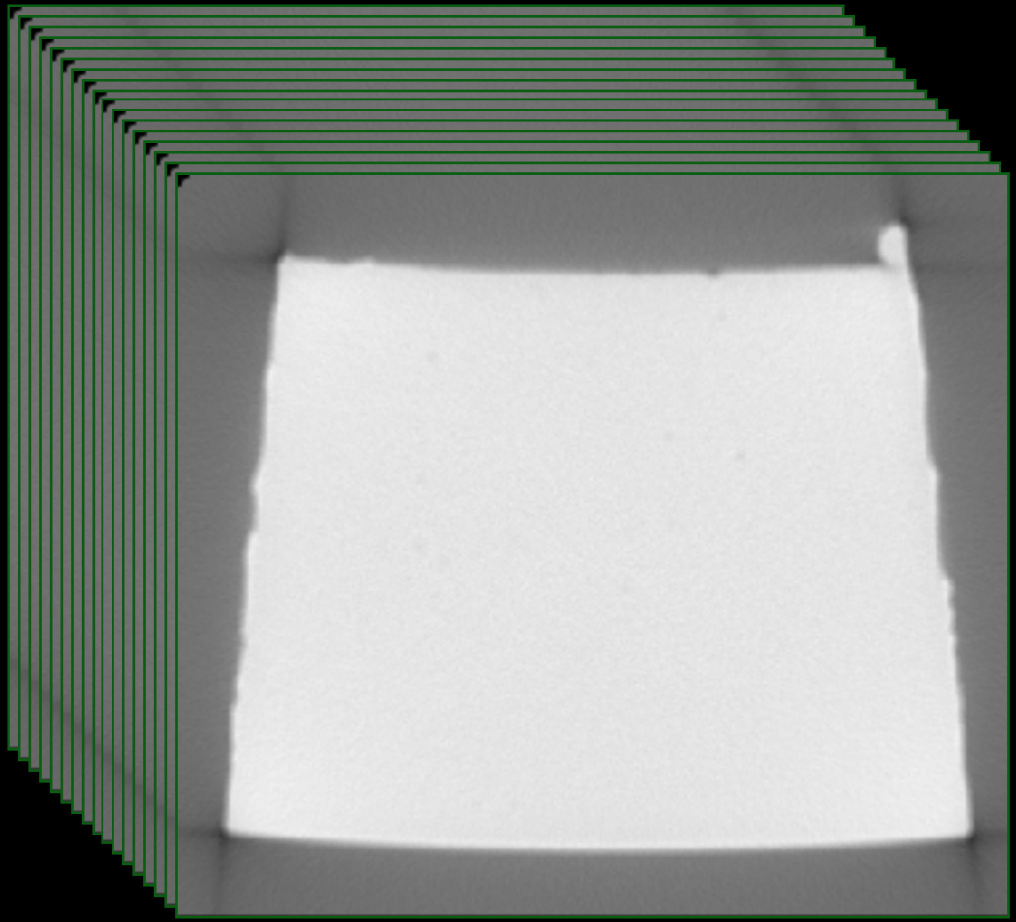
scan01: SE508
scan02: SE508ELI
scan03: SE508ELI







XCT scan output: 1,994 16-bit images (0.50µm^3 voxel)



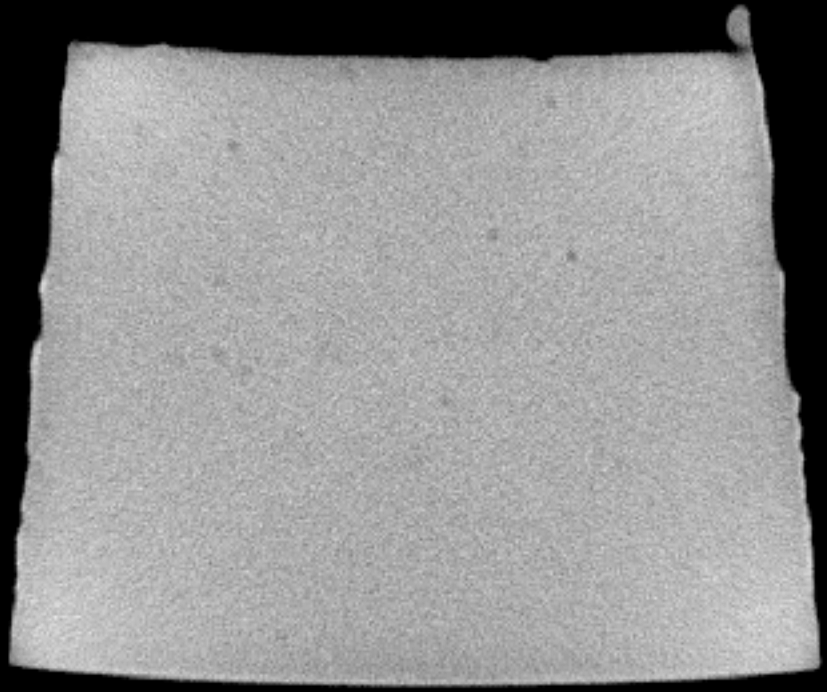
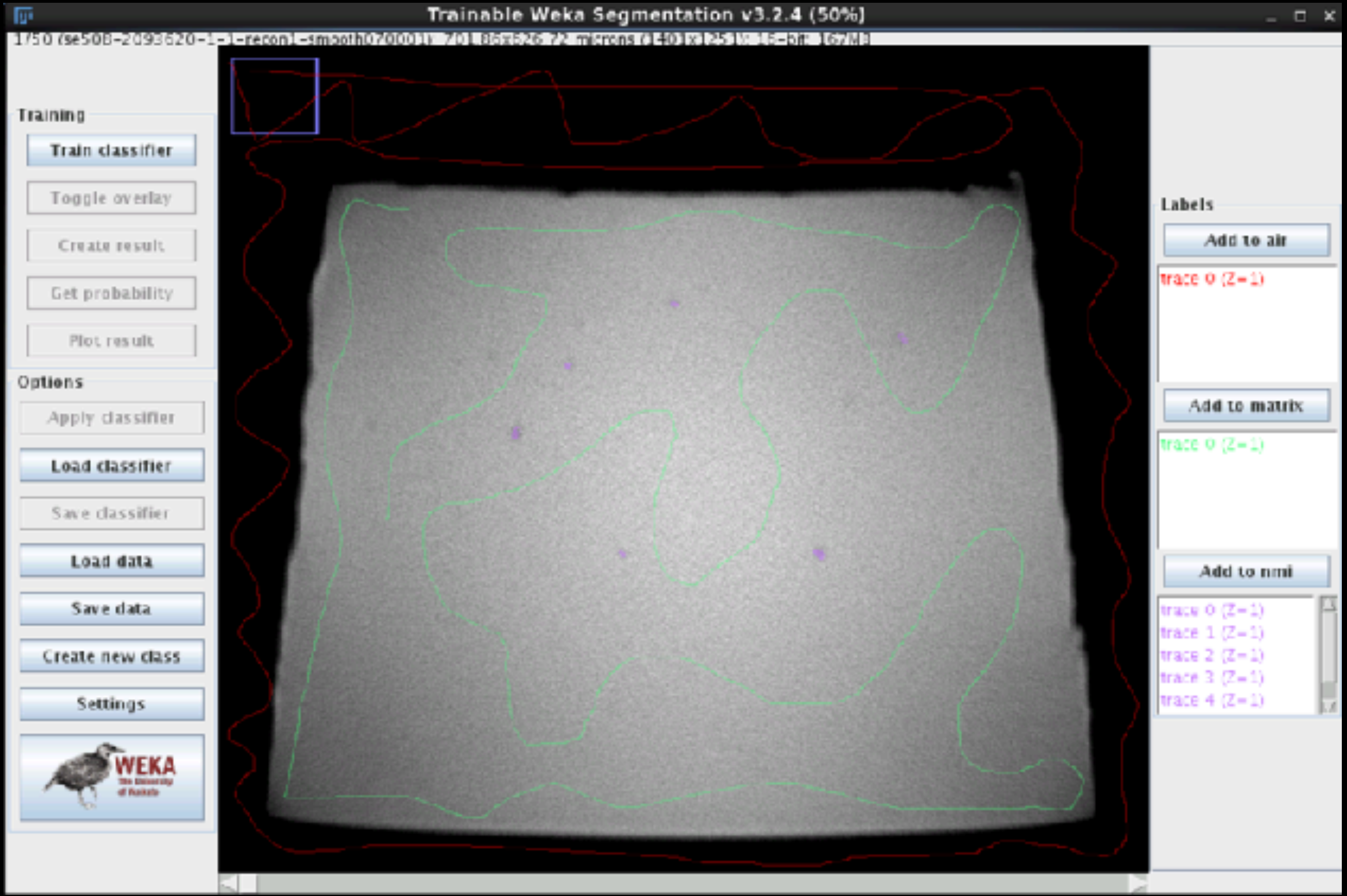


Image segmentation by machine learning

Fiji [1] is just ImageJ [2]

Trainable Weka Segmentation [3]

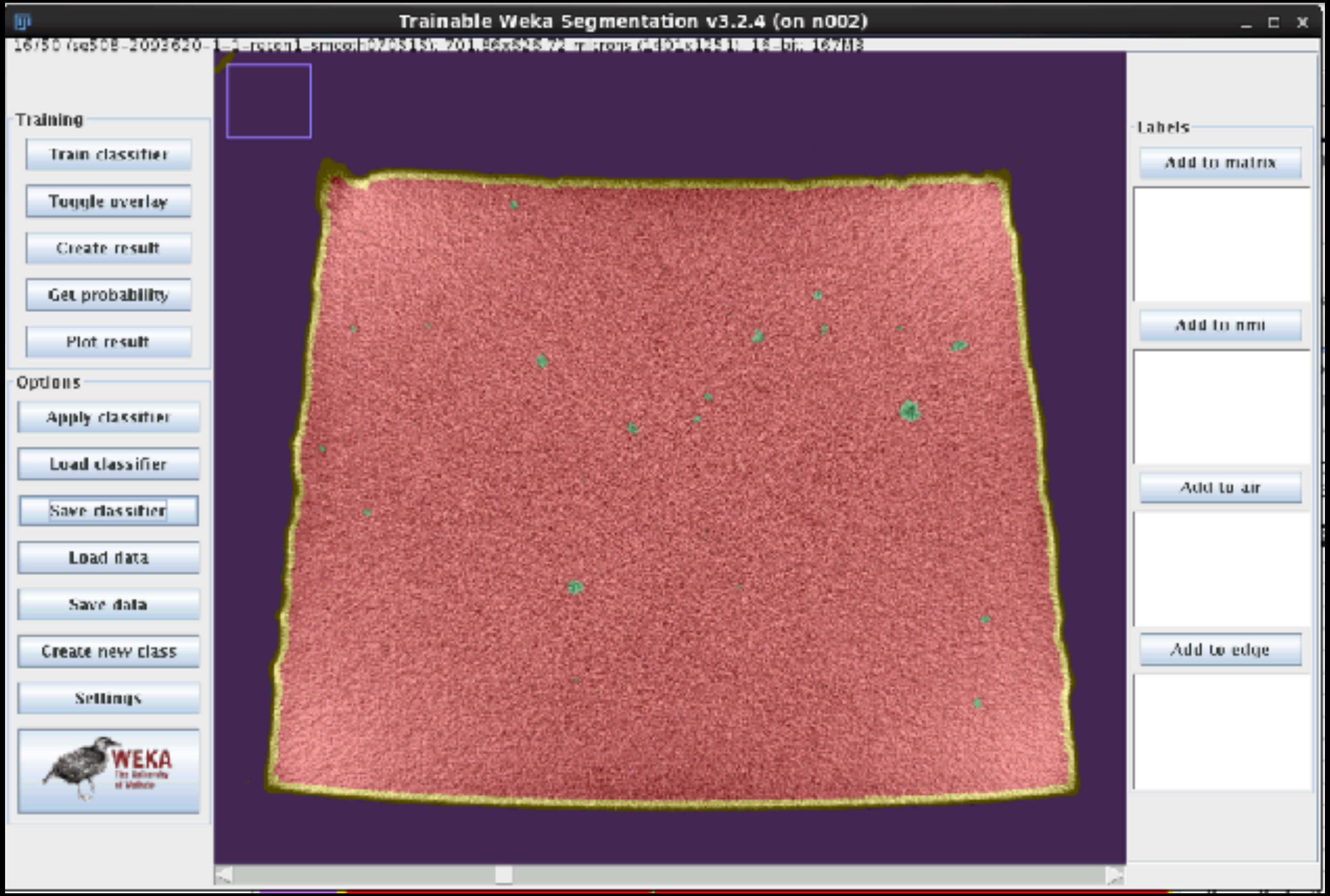


[1] J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, C. Rueden, S. Saalfeld, B. Schmid, J.-Y. Tinevez, D.J. White, V. Hartenstein, K. Eliceiri, P. Tomancak, A. Cardona, Fiji: an open-source platform for biological-image analysis., Nat. Methods. 9 (2012) 676–82. doi:10.1038/nmeth.2019.
[2] M.D. Abràmoff, P.J. Magalhães, S.J. Ram, Image processing with imageJ, Biophotonics Int. 11 (2004) 36–41. doi:10.1117/1.3589100.

Voxel Classification

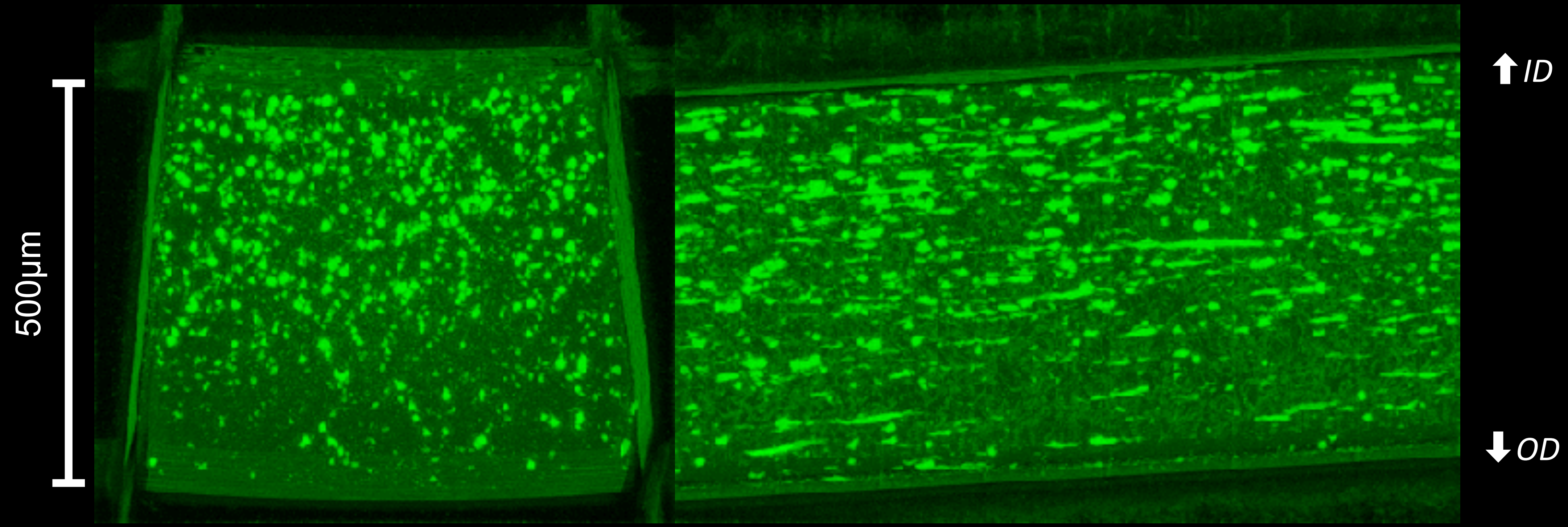
Train classifier to identify probability of each voxel as:

- matrix
- nmi (inclusion/void)
- air
- edge



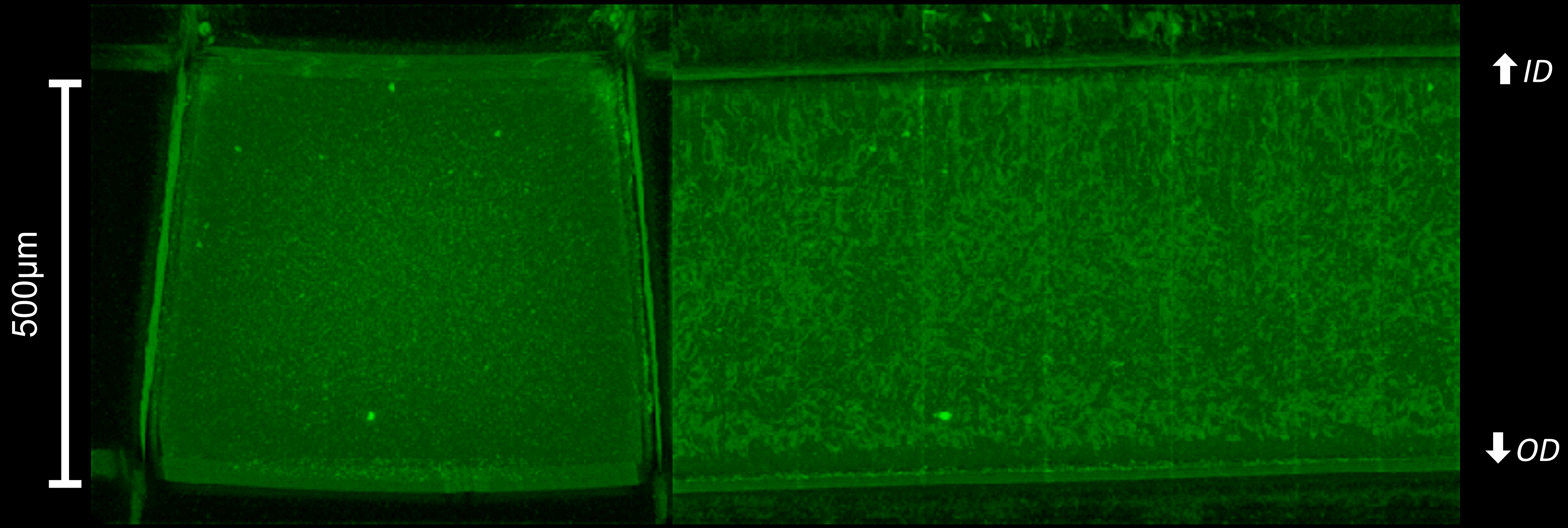
[3] I. Arganda-Carreras, V. Kaynig, J. Schindelin, A. Cardona, H.S. Seung, Trainable Weka Segmentation: A Machine Learning Tool for Microscopy Image Segmentation, Neurosci. 2014 Short Course 2 - Adv. Brain-Scale, Autom. Anat. Tech. Neuronal Reconstr. Tract Tracing, Atlasing. (2014) 73--80.

SE508 maximum intensity projection of inclusion probability



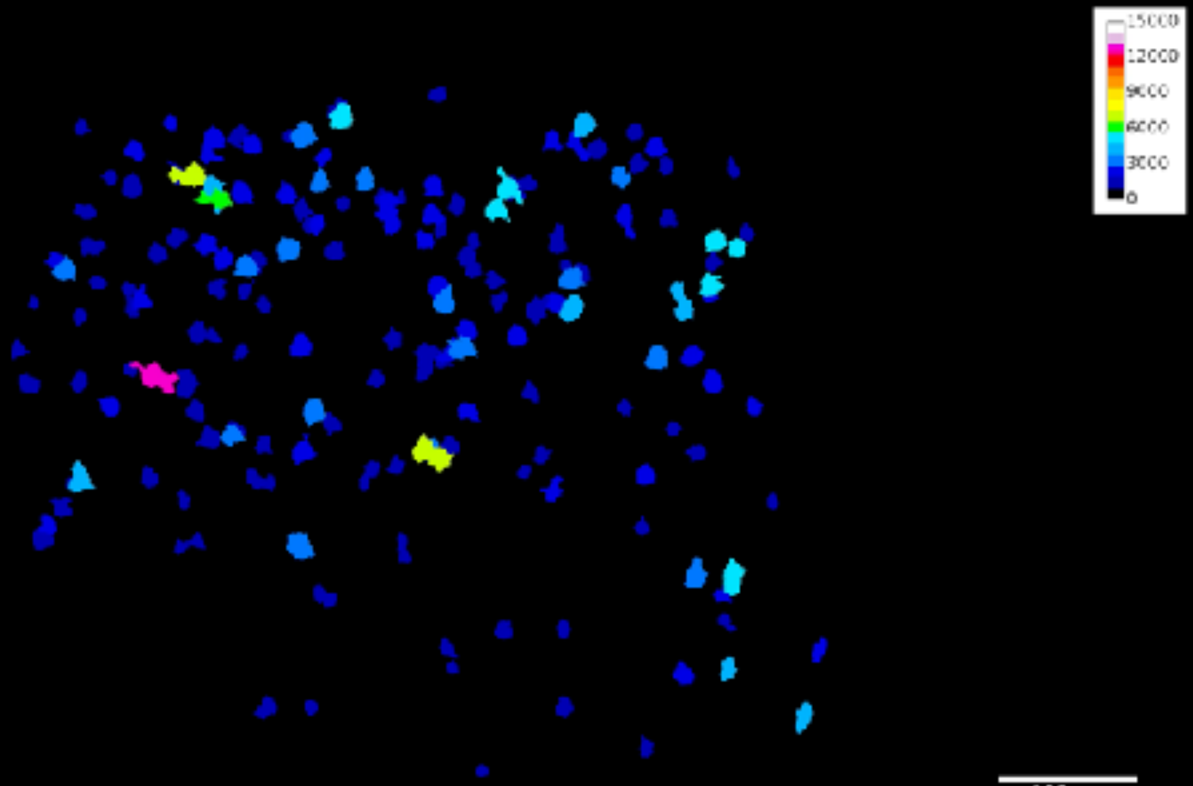
visualization superimposes all inclusions through 500µm thickness

SE508-ELI maximum intensity projection of inclusion probability



visualization superimposes all inclusions through 500μm thickness

SE508 inclusion segmentation colored by volume

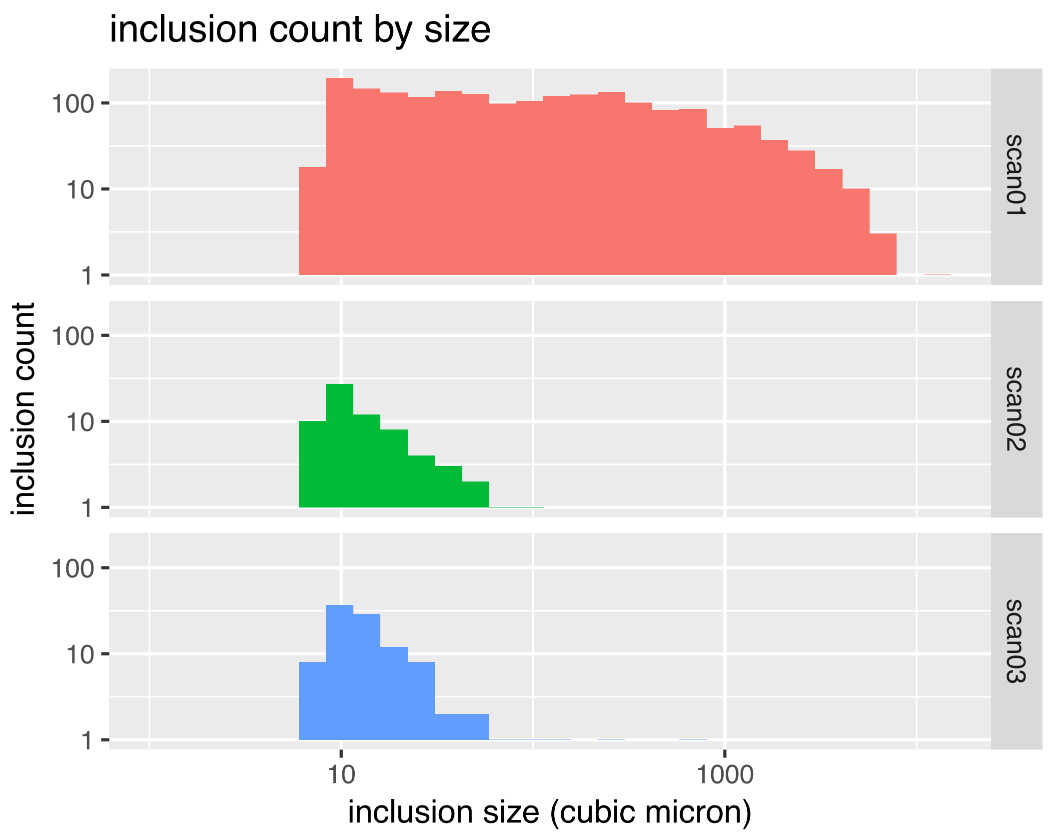


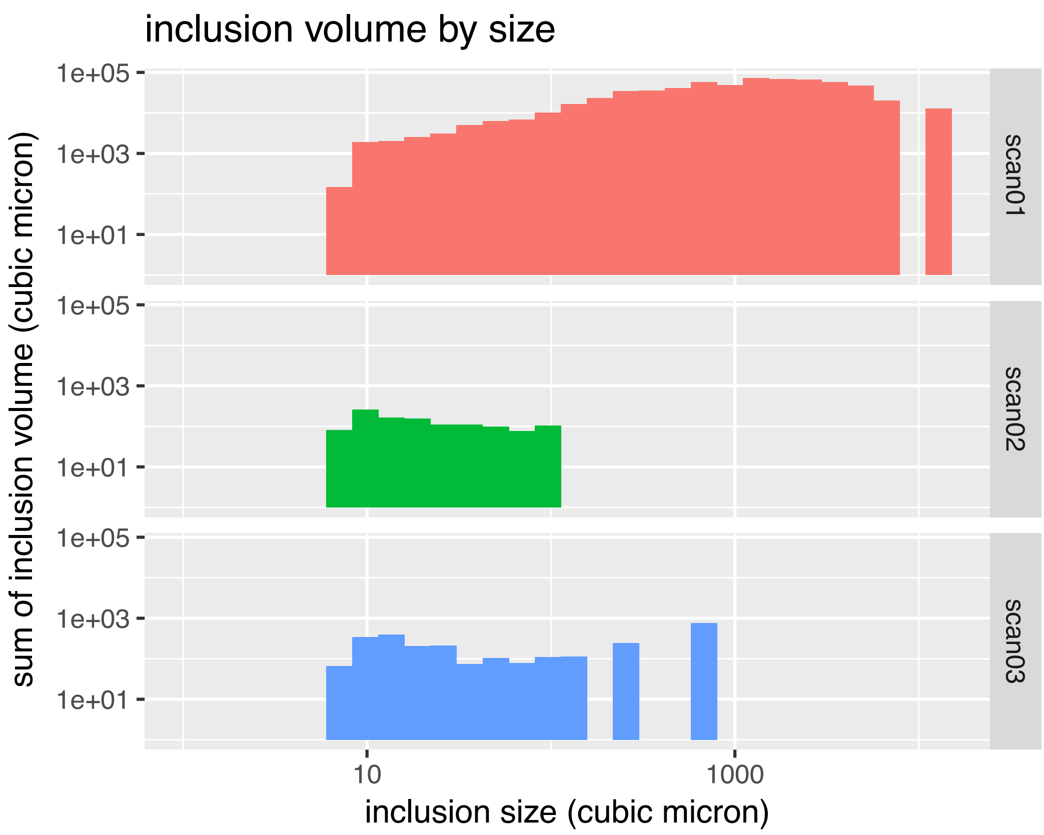
[1] D. Legland, I. Arganda-Carreras, P. Andrey, MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, Bioinformatics. (2016) btw413. doi:10.1093/bioinformatics/btw413.

SE508-ELI inclusion segmentation colored by volume

[1] D. Legland, I. Arganda-Carreras, P. Andrey, MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, Bioinformatics. (2016) btw413. doi:10.1093/bioinformatics/btw413.

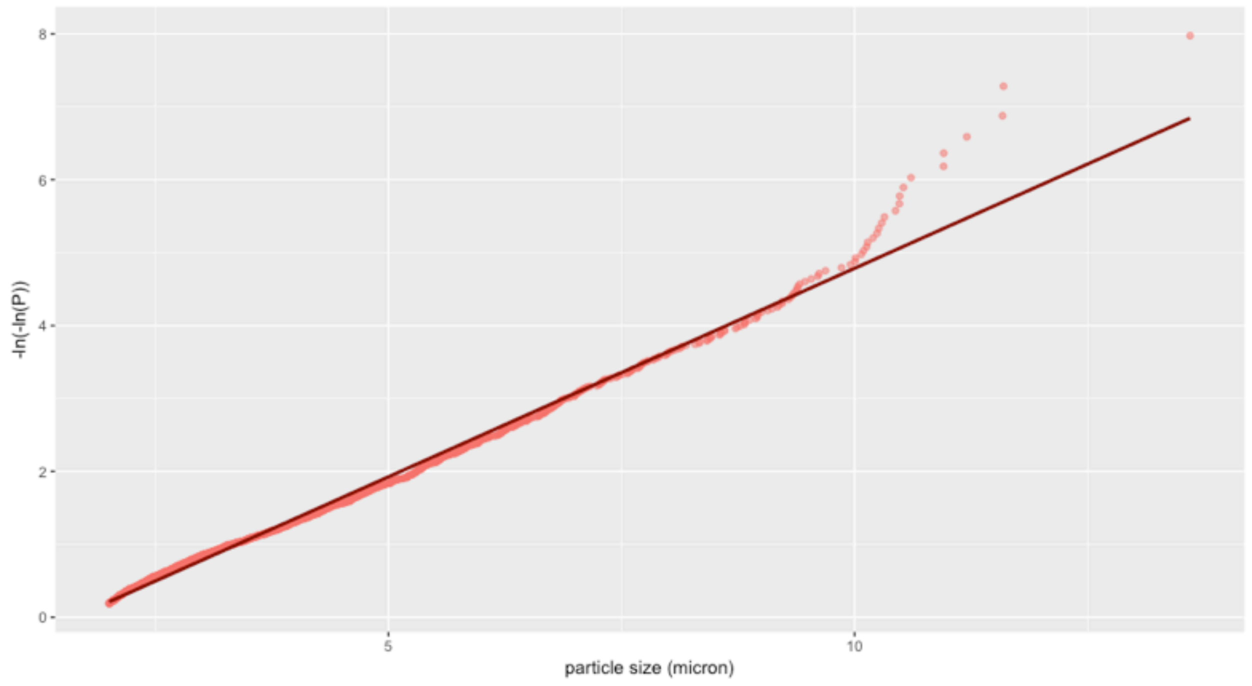
Volumetric distribution of inclusions

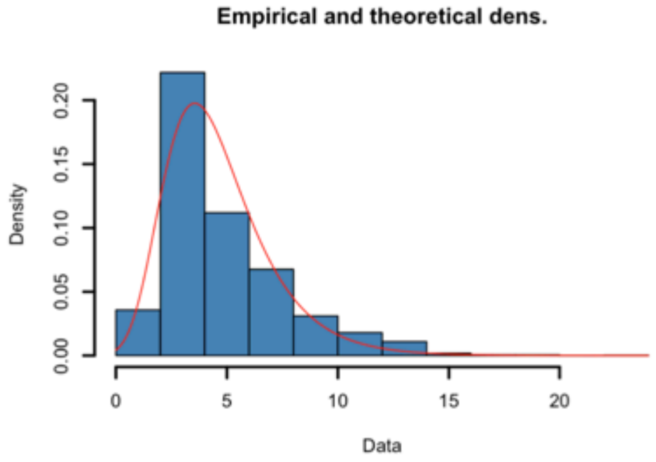


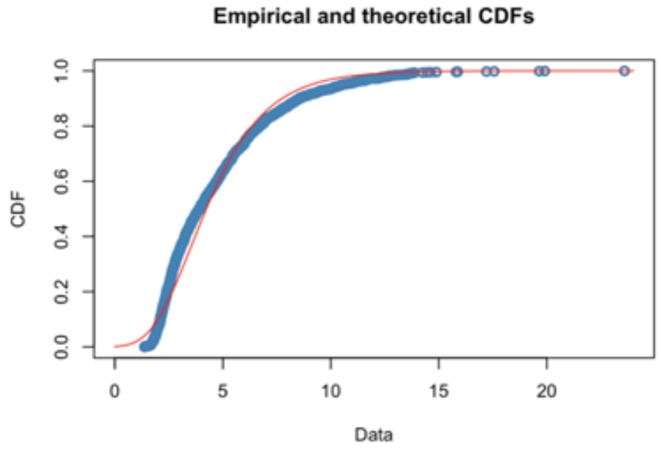


* *note log-log scales*

√Area fit to Extreme Value Distribution per Urbano[1]







[1] M.F. Urbano, A. Cadelli, F. Sczerzenie, P. Luccarelli, S. Beretta, A. Coda, Inclusions Size-based Fatigue Life Prediction Model of NiTi Alloy for Biomedical Applications, Shape Mem. Superelasticity. 1 (2015) 1–12.

Inclusion density, Gumbel location and scaling parameters

SE508 Inclusion Distribution Parameters

plane	cutoff (μm^3)	inclusion density ($1/mm^3$)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	7,475	2.84	1.36
yz (longitudinal)	8	7,475	3.59	1.96
xz (longitudinal)	8	7,475	3.55	1.86

ELI Inclusion Distribution Parameters

plane	cutoff (μm^3)	inclusion density ($1/mm^3$)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	340	1.77	0.40
yz (longitudinal)	8	340	2.06	0.40
xz (longitudinal)	8	340	2.27	0.45

Fingerprint by Mitchell Eva, from the Noun Project

Introduction
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Resources

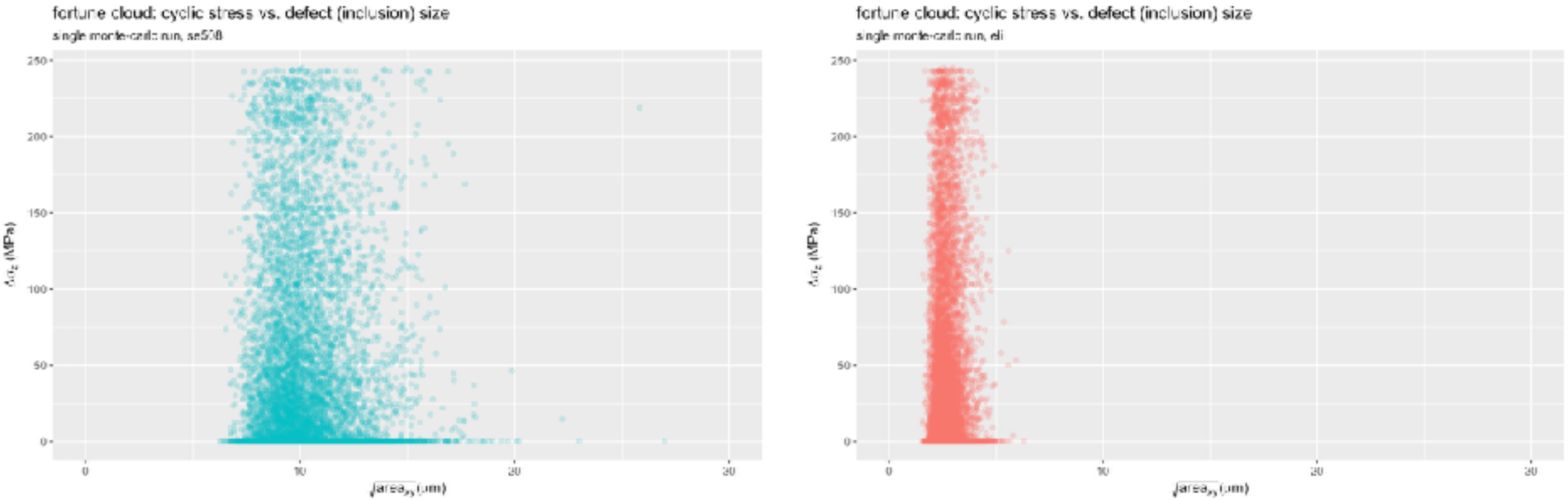
Quantile function: *calculate random defects with sizes following the Gumbel distribution for each material*

$$Q(p) = \mu - \sigma \ \ln[-\ln(p)]$$

$Q(U)$ has a Gumbel distribution
for random values of U drawn from
a uniform distribution on the interval (0,1)

Dice by b farias, from the Noun Project

“Fortune cloud”: Δσ vs. √area (single run SE508, ELI)



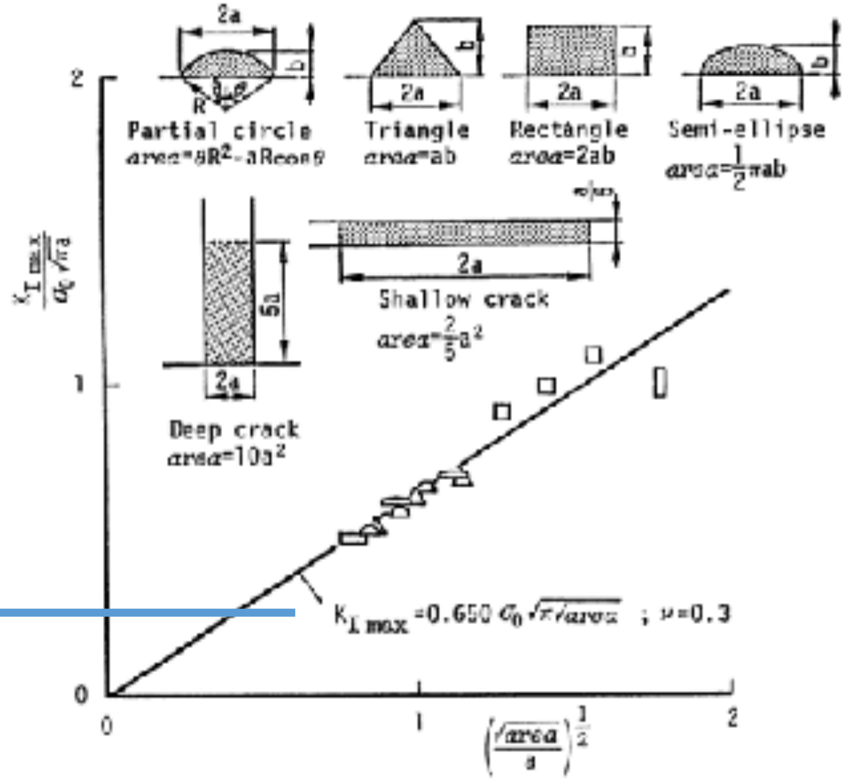
Estimating stress intensity factor K by Murakami's √area

FEA

XCT, Gumbel Parameters

$$K\left(\sigma,\sqrt{area}\right) = 0.65 \cdot \sigma\sqrt{\pi \cdot \sqrt{area}}$$

Figure 7 shows the relationship between the maximum stress intensity factor K_{Imax} and $\sqrt{area}$ for surface cracks (elastic analysis) (24)(25). (See also (20)(66).)



Murakami Y, Endo M (1986) Effect of hardness and crack geometries on ΔK_{th} of small cracks emanating from small defects, In: The Behavior of Short Fatigue Cracks, EGF Pub. 1, pp 275–293

K and ΔK in each plane, at each integration point

$$K_x = 0.65 \cdot \sqrt{\sigma_x \cdot \sqrt{area_{yz}}}$$

$$K_y = 0.65 \cdot \sqrt{\sigma_y \cdot \sqrt{area_{xz}}}$$

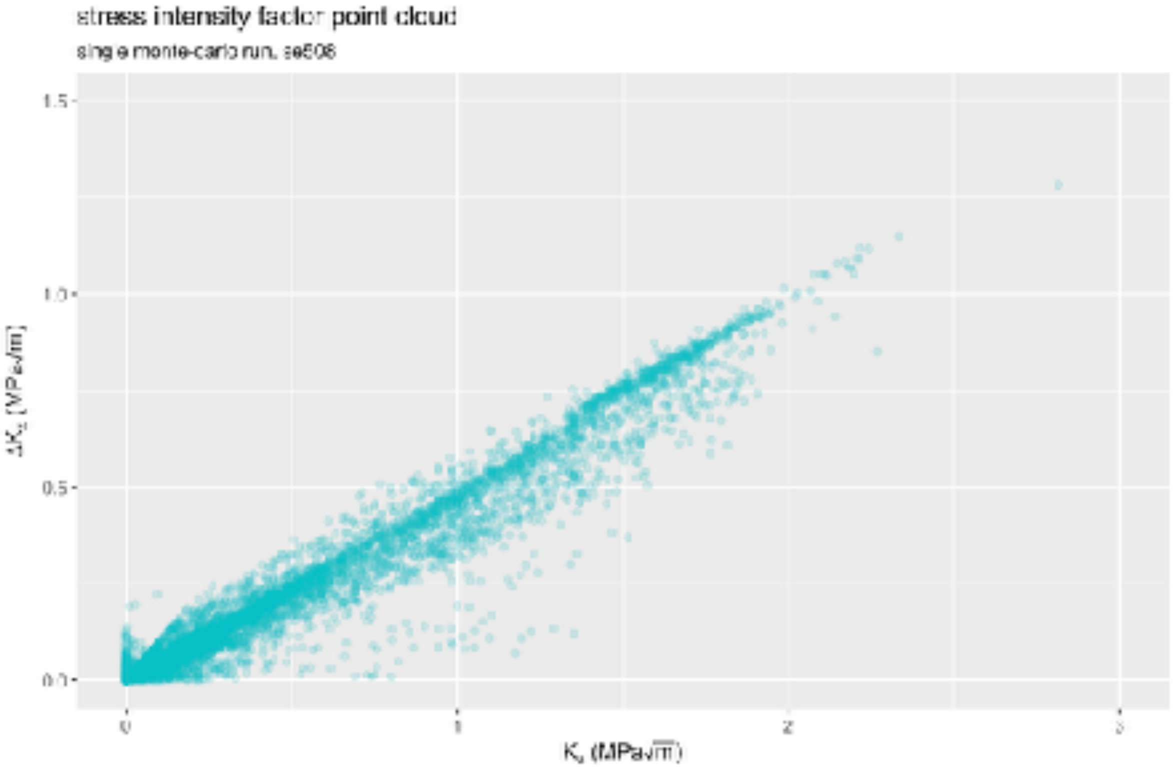
$$K_z = 0.65 \cdot \sqrt{\sigma_z \cdot \sqrt{area_{xy}}}$$

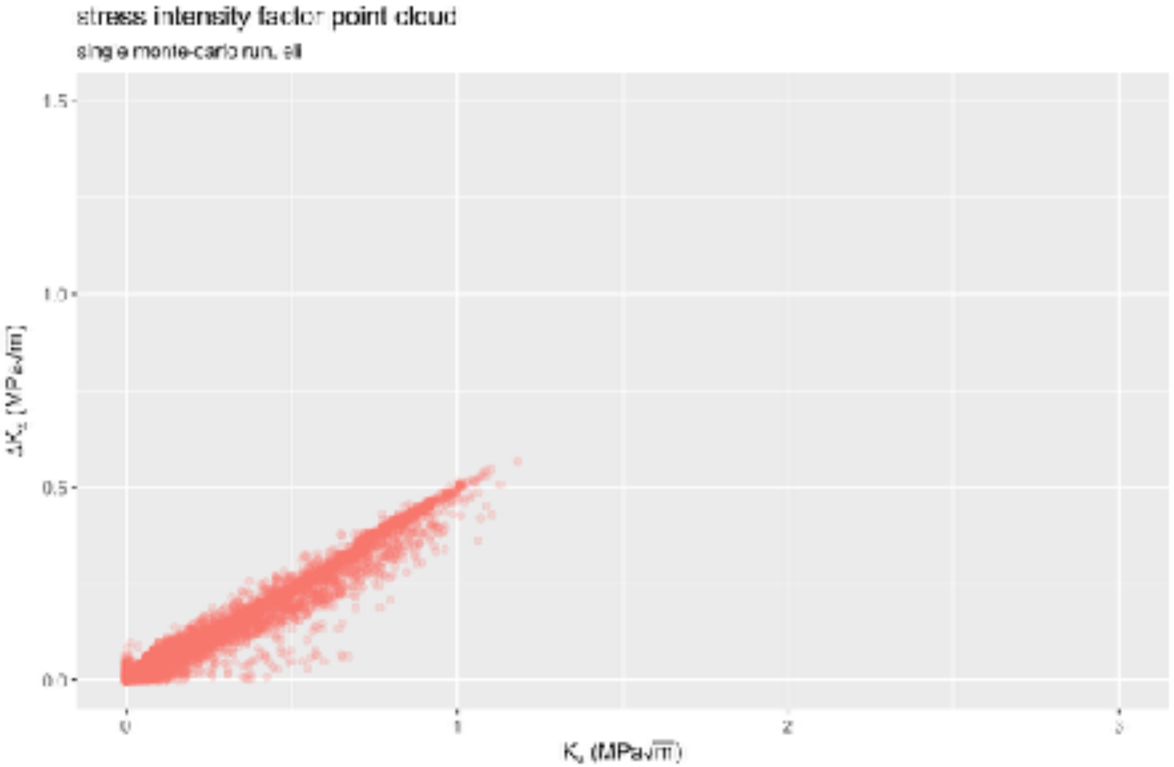
$$\Delta K_x = 0.65 \cdot \sqrt{\Delta\sigma_x \cdot \sqrt{area_{yz}}}$$

$$\Delta K_y = 0.65 \cdot \sqrt{\Delta\sigma_y \cdot \sqrt{area_{xz}}}$$

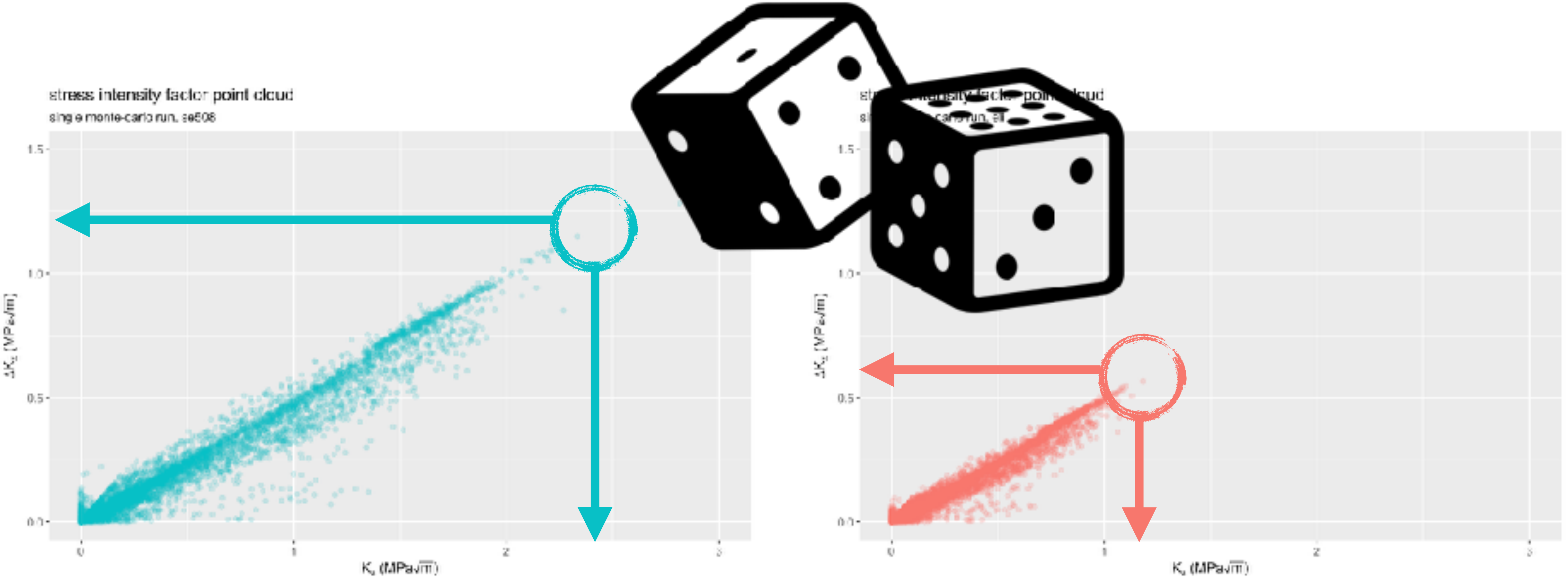
$$\Delta K_z = 0.65 \cdot \sqrt{\Delta\sigma_z \cdot \sqrt{area_{xy}}}$$

“K point cloud” (single run SE508, ELI)

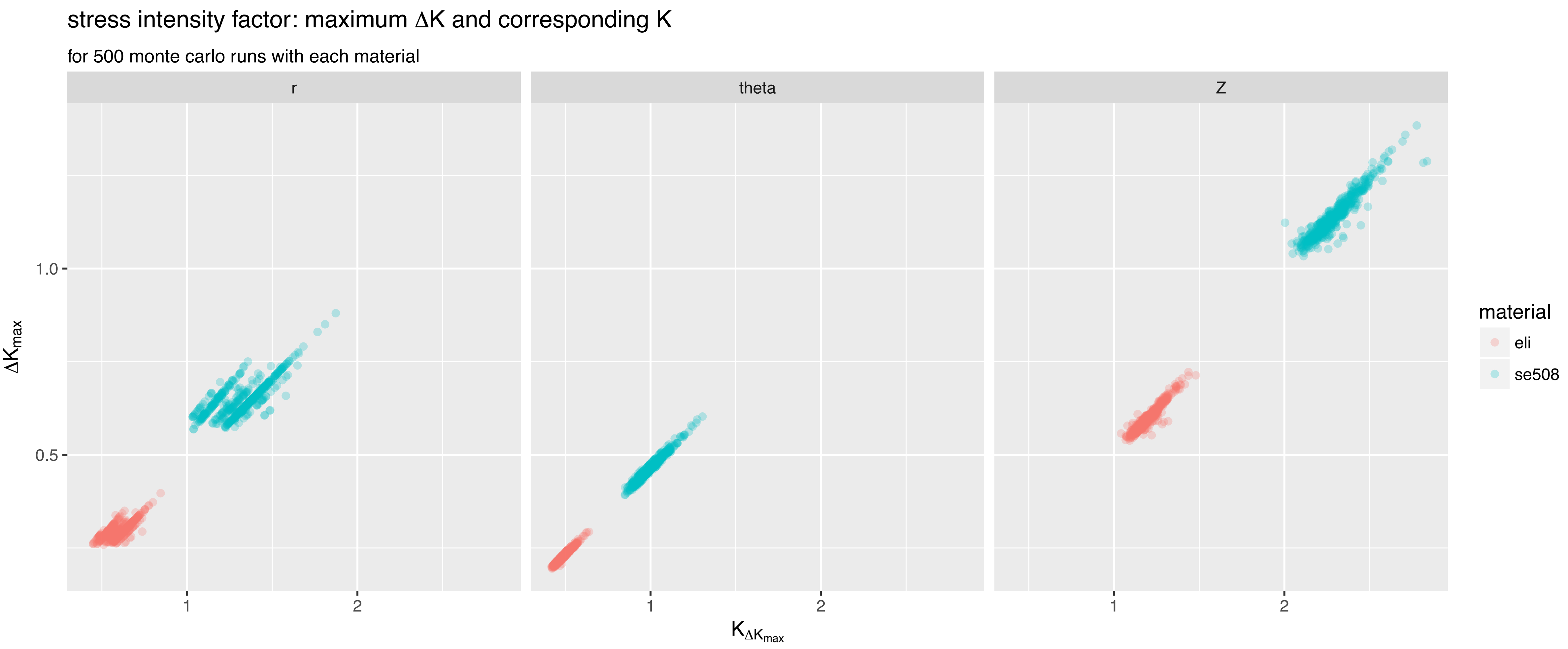




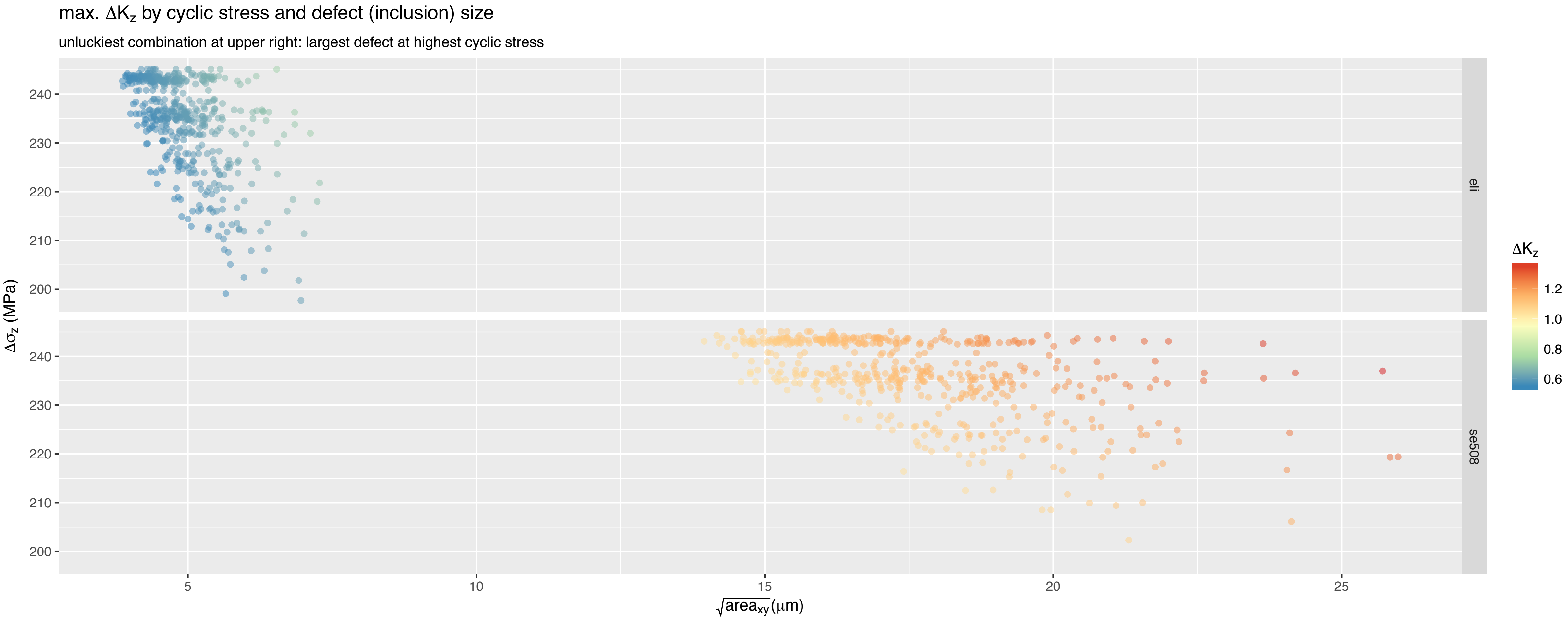
Next: repeat many times, record ΔK_{max} and K



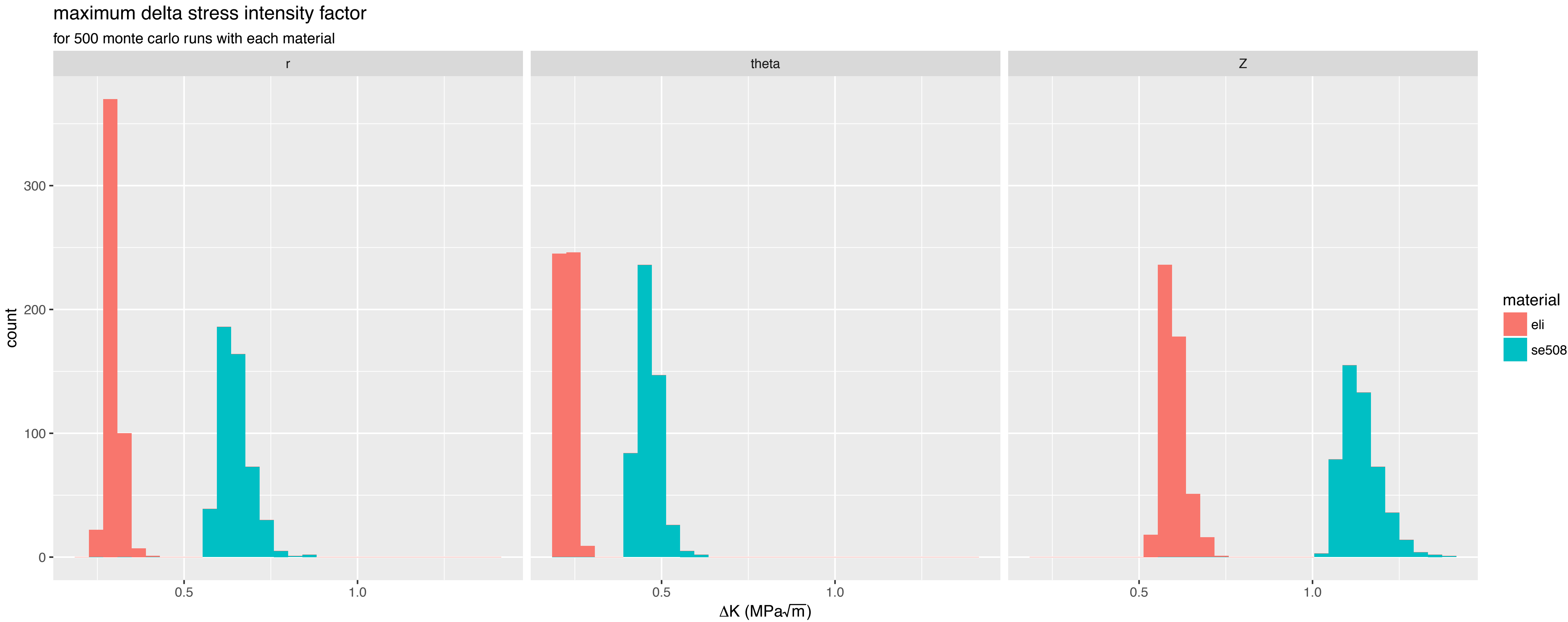
Maximum stress intensity factors for 500+500 runs



“Fortune plot” for 500+500 runs



ΔK_{max} for 500+500 runs



Limitations

- XCT results are currently limited to a single tubing configuration, and three sample volumes
- Resolution limit for XCT unconfirmed; comparison with conventional 2D analysis TBD
- K, ΔK are based on linear elastic fracture mechanics
- Muramaki 0.65 factor does not account for defect depth from surface
- No experimental confirmation completed (yet)
- Material properties for example FEA are unverified
- Code is all new and probably full of mistakes!

- Critical review and feedback will be greatly appreciated!

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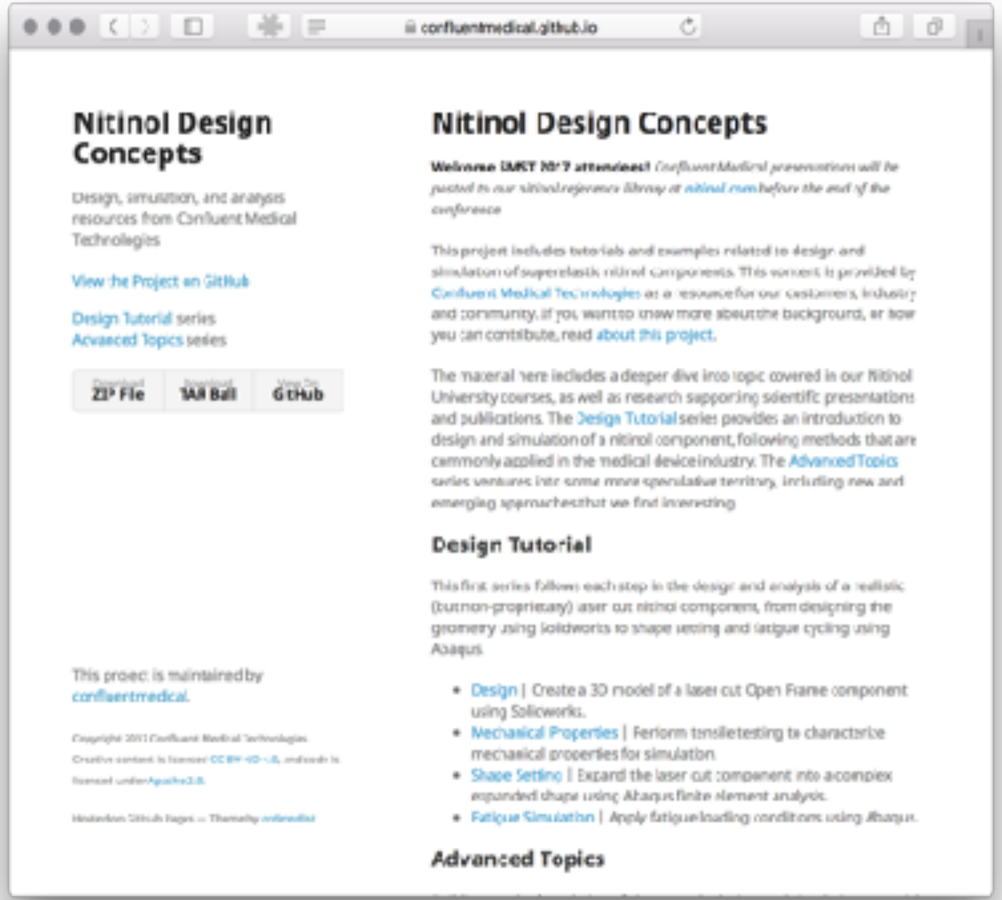
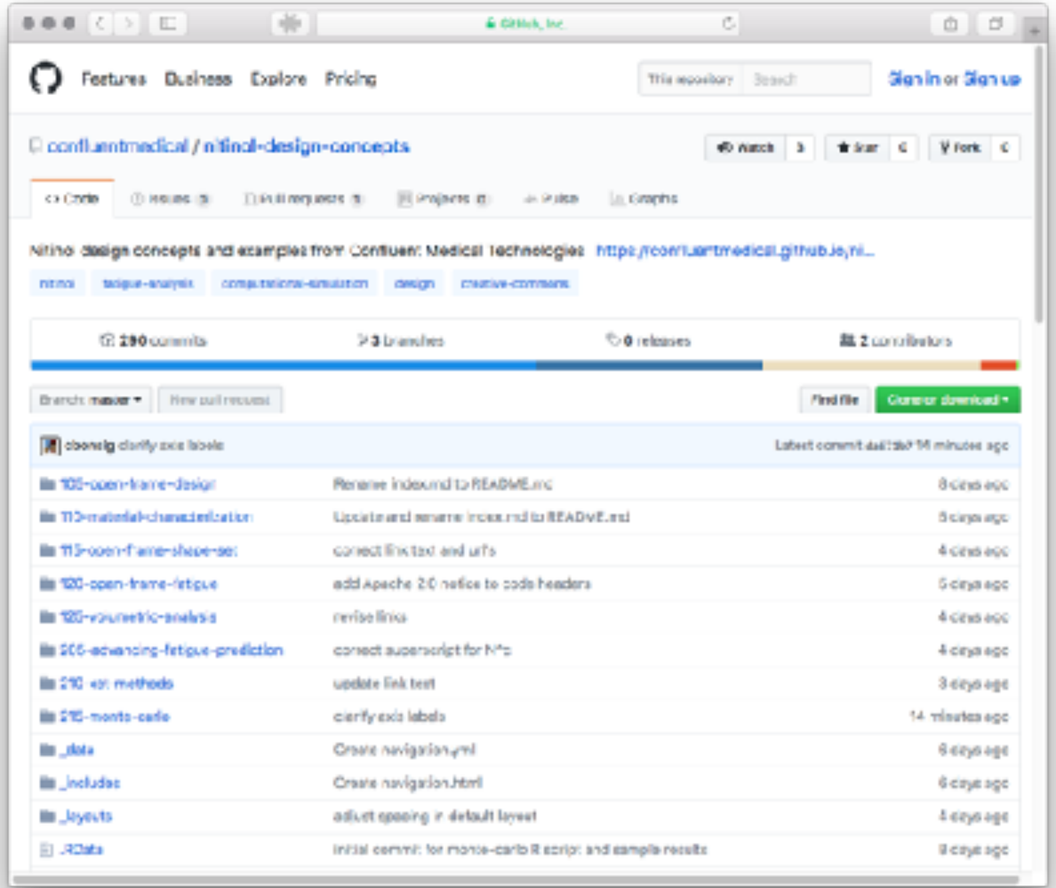
More resources online: Nitinol Design Concepts





bit.ly/smst17ndc

Craig Bonsignore
Confluent Medical Technologies

craig.bonsignore@confluentmedical.com
@cbonsig