In-Situ CO2 Imaging in Laboratory EOR Research

Arne Graue

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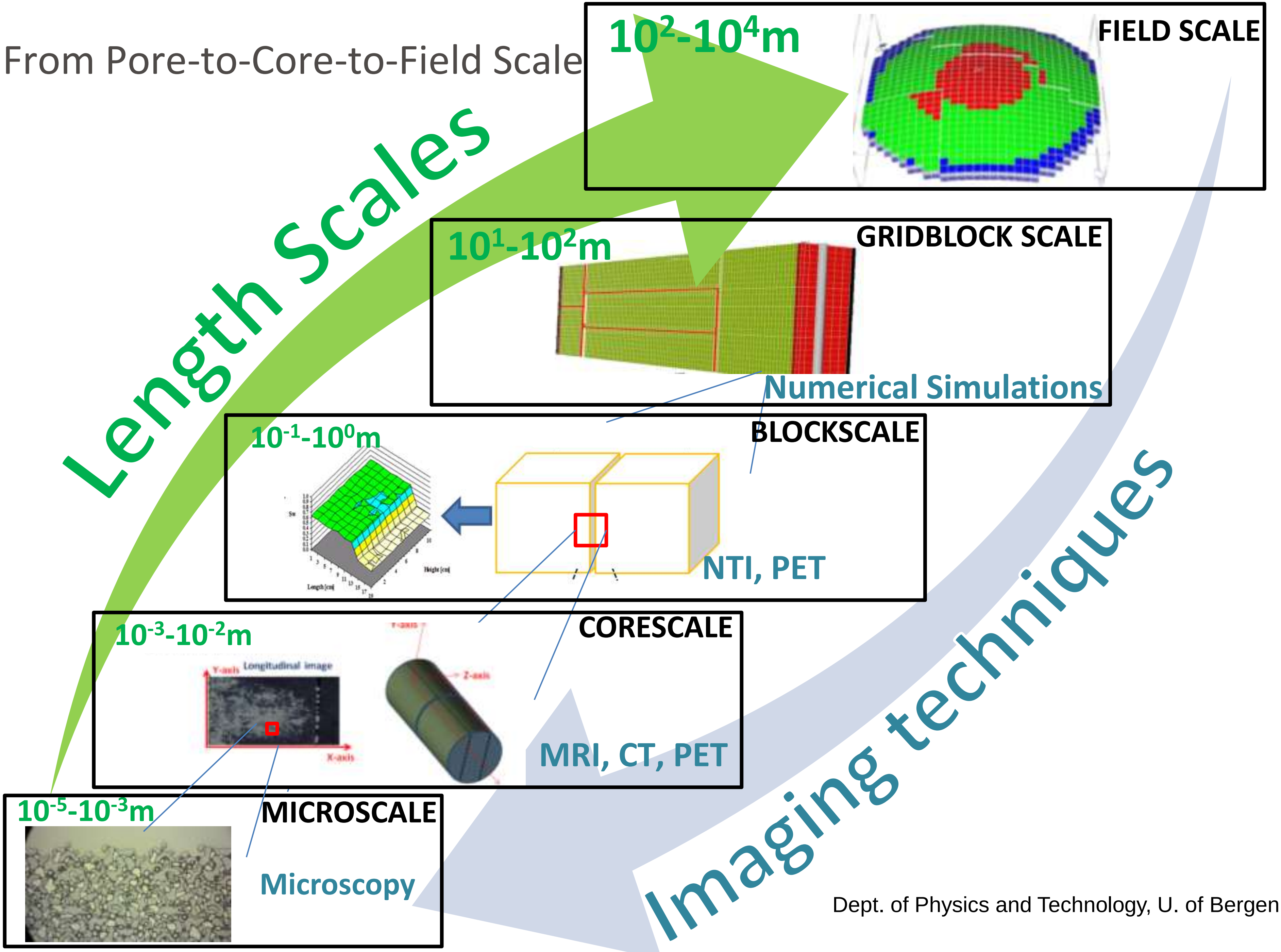
University of Bergen



From Pore-to-Core-to-Field Scale
Length Scales
Imaging techniques
10^2-10^4m
FIELD SCALE
10^1-10^2m
GRIDBLOCK SCALE
Numerical Simulations
10^{-1}-10^0m
BLOCKSCALE
NTI, PET
10^{-3}-10^{-2}m
CORESCALE
Longitudinal image
Y-axis
X-axis
Z-axis
MRI, CT, PET
10^{-5}-10^{-3}m
MICROSCALE
Microscopy
Dept. of Physics and Technology, U. of Bergen

Way Forward

Core analysis:

- Micromodels
- Core plugs
- Blocks
- Numerical simulations

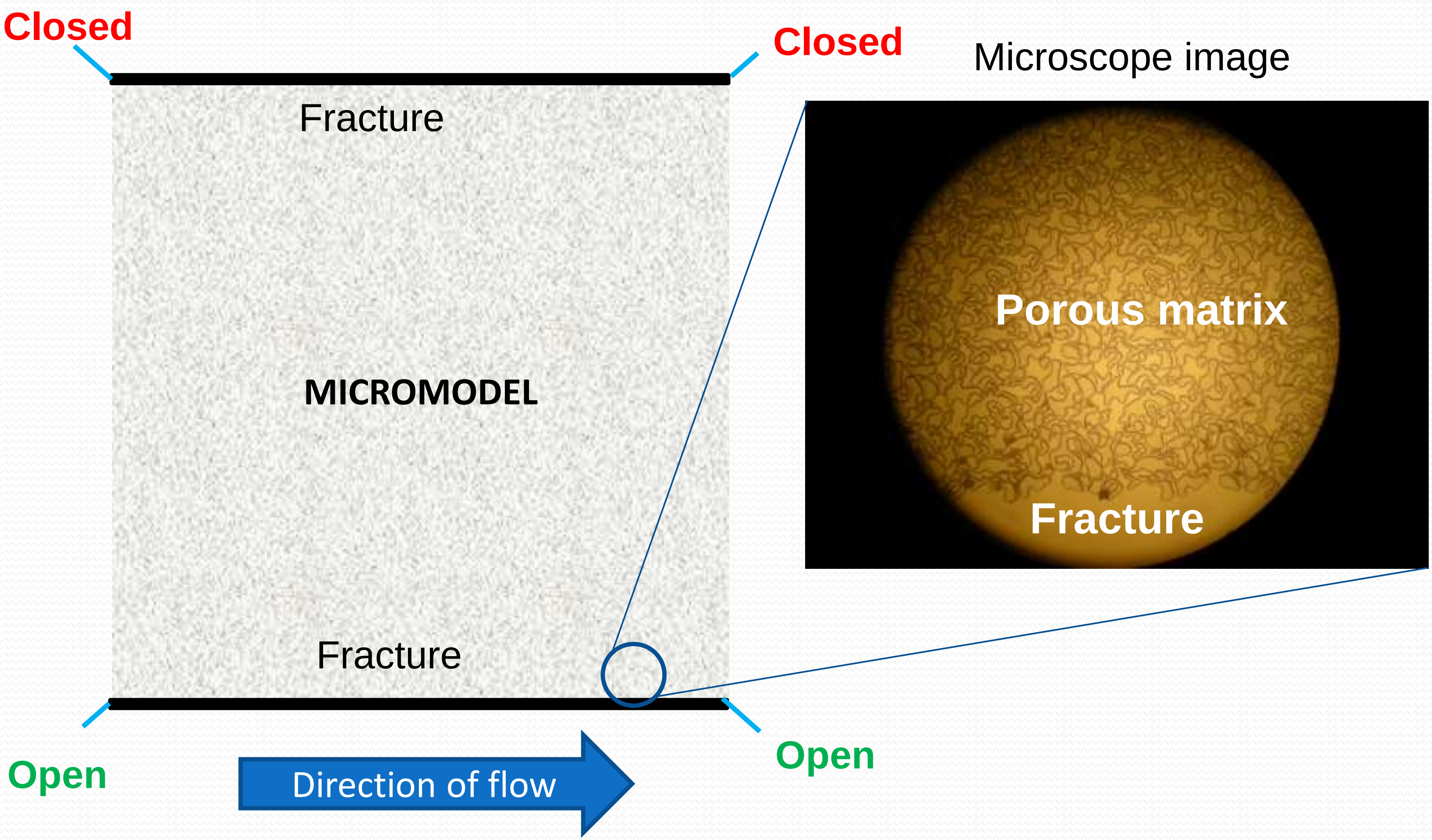
Upscaling:

- Numerical modelling on pore scale
- Numerical modelling on field scale

Pilot field tests:

- Texas (Operator: Tabula Rasa)
- Ekofisk (between close horizontal wells)

Experimental setup micro model experiments

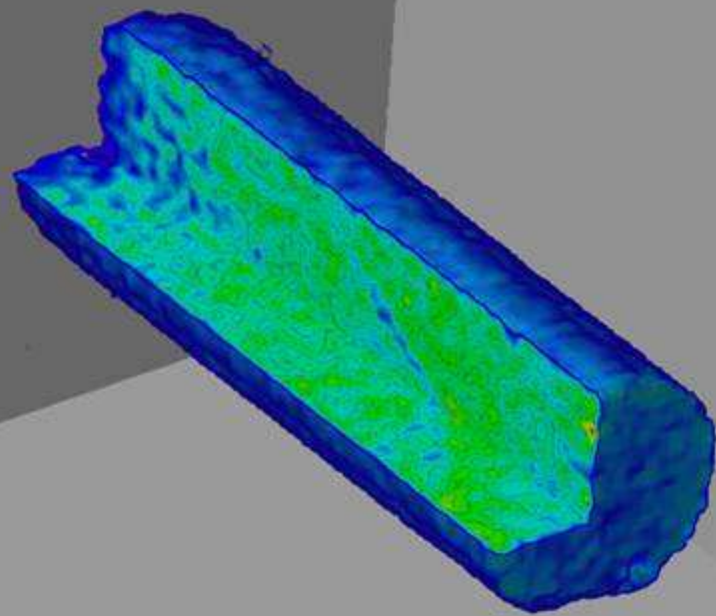


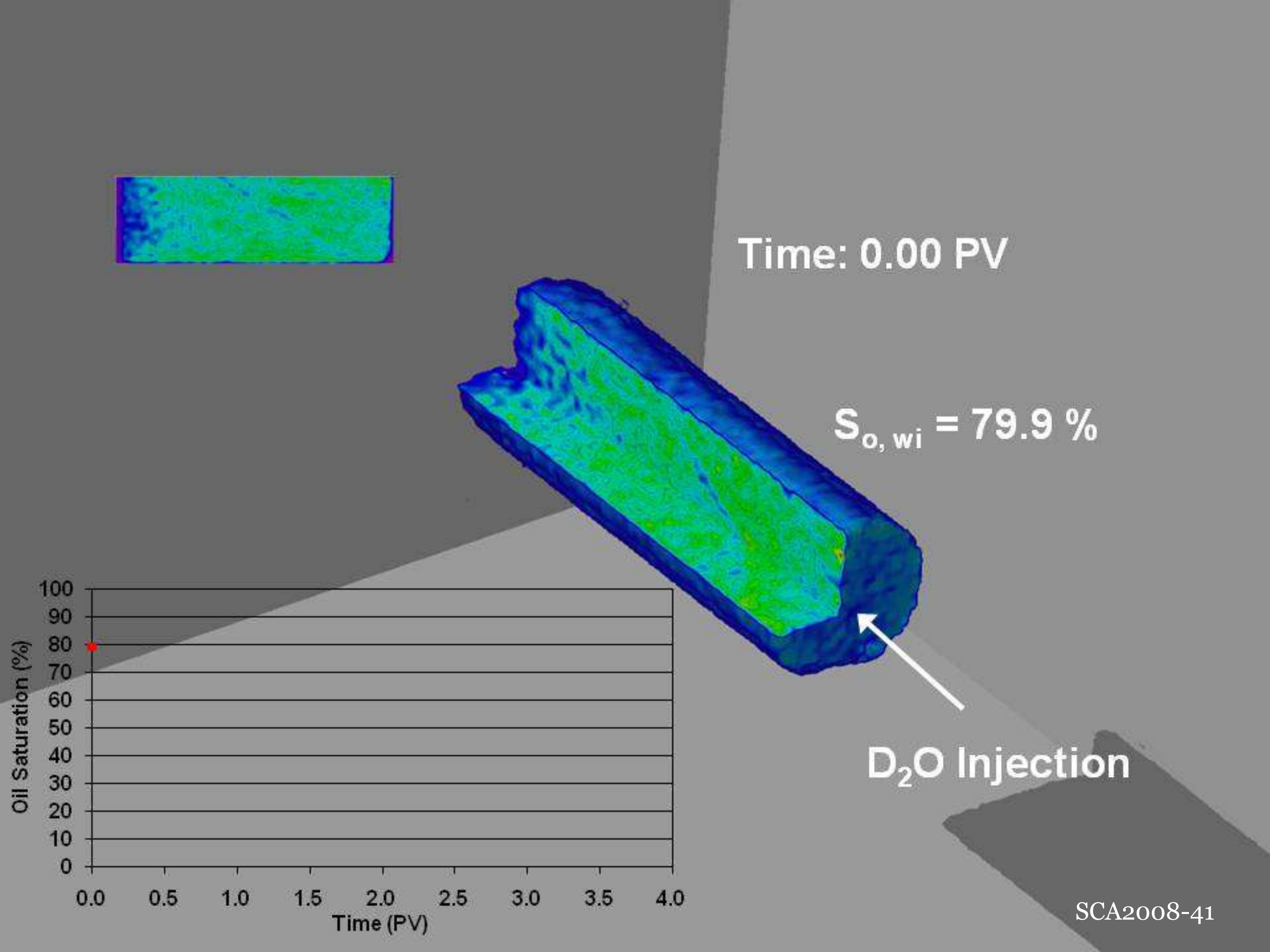
In-Situ Fluid Saturations by Magnetic Resonance Imaging (MRI)

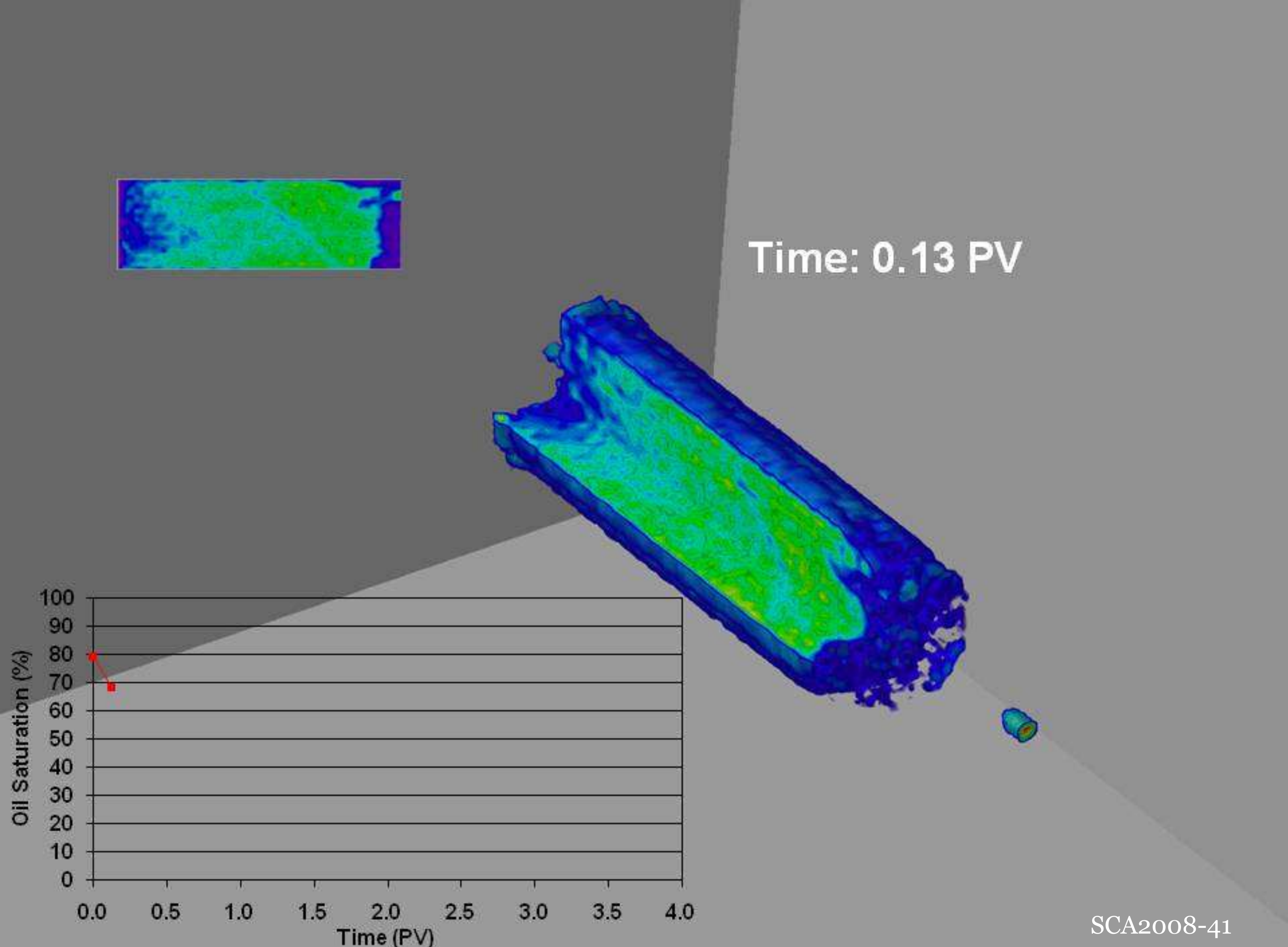
Tertiary CO_2 Injection of Neutral-Wet Chalk

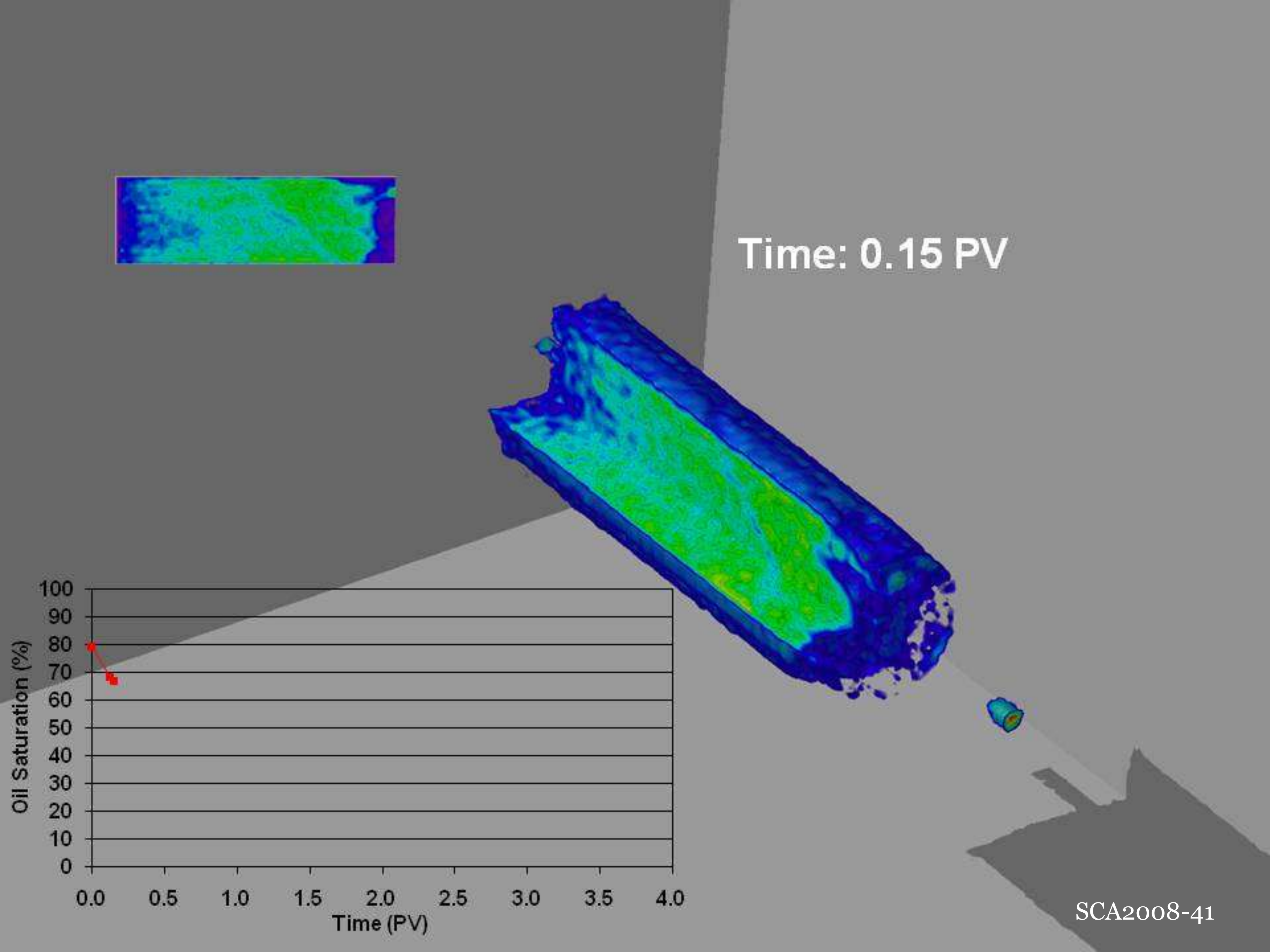
Temp.: 20^0C

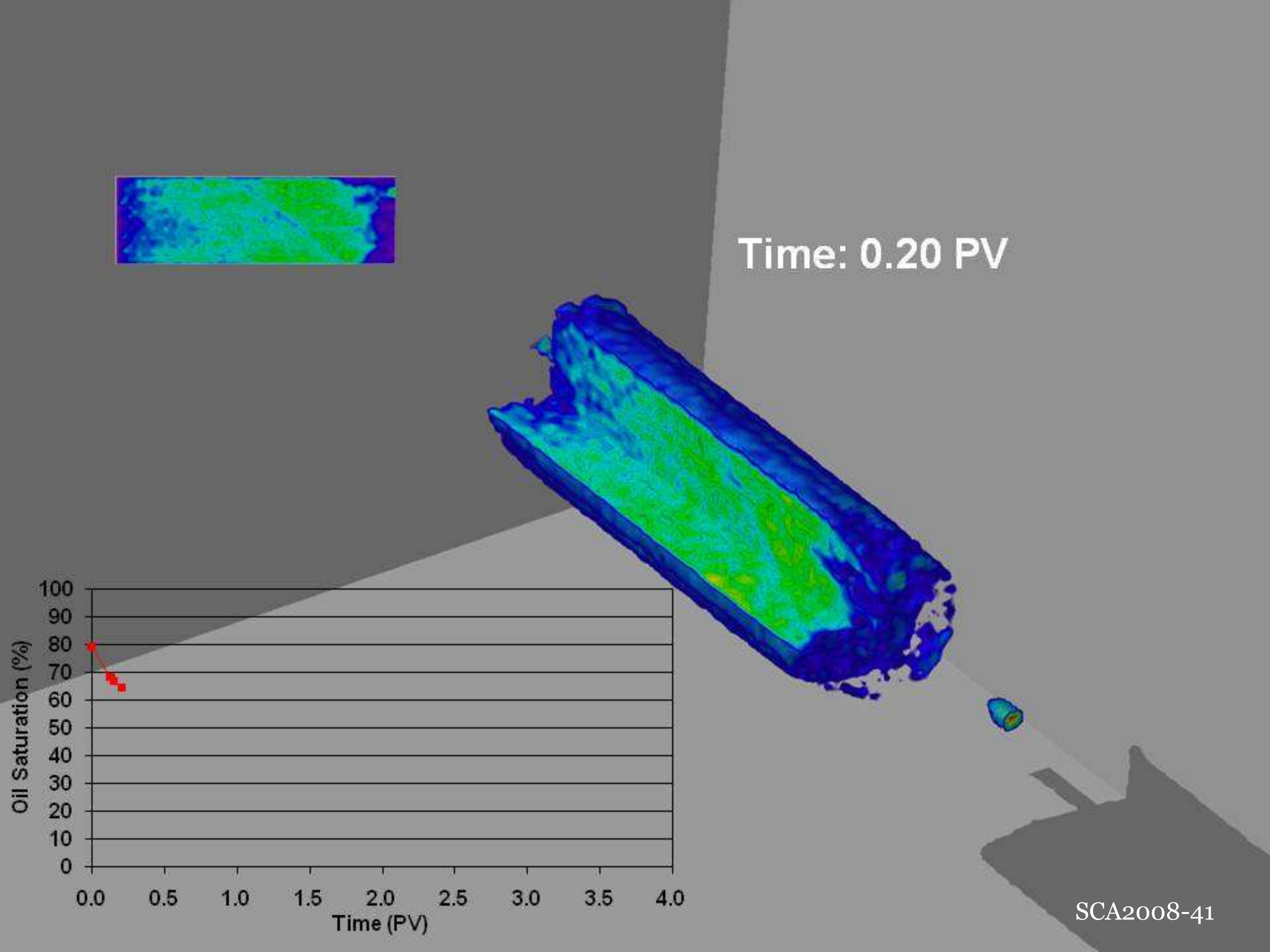
Amott Index 0.15

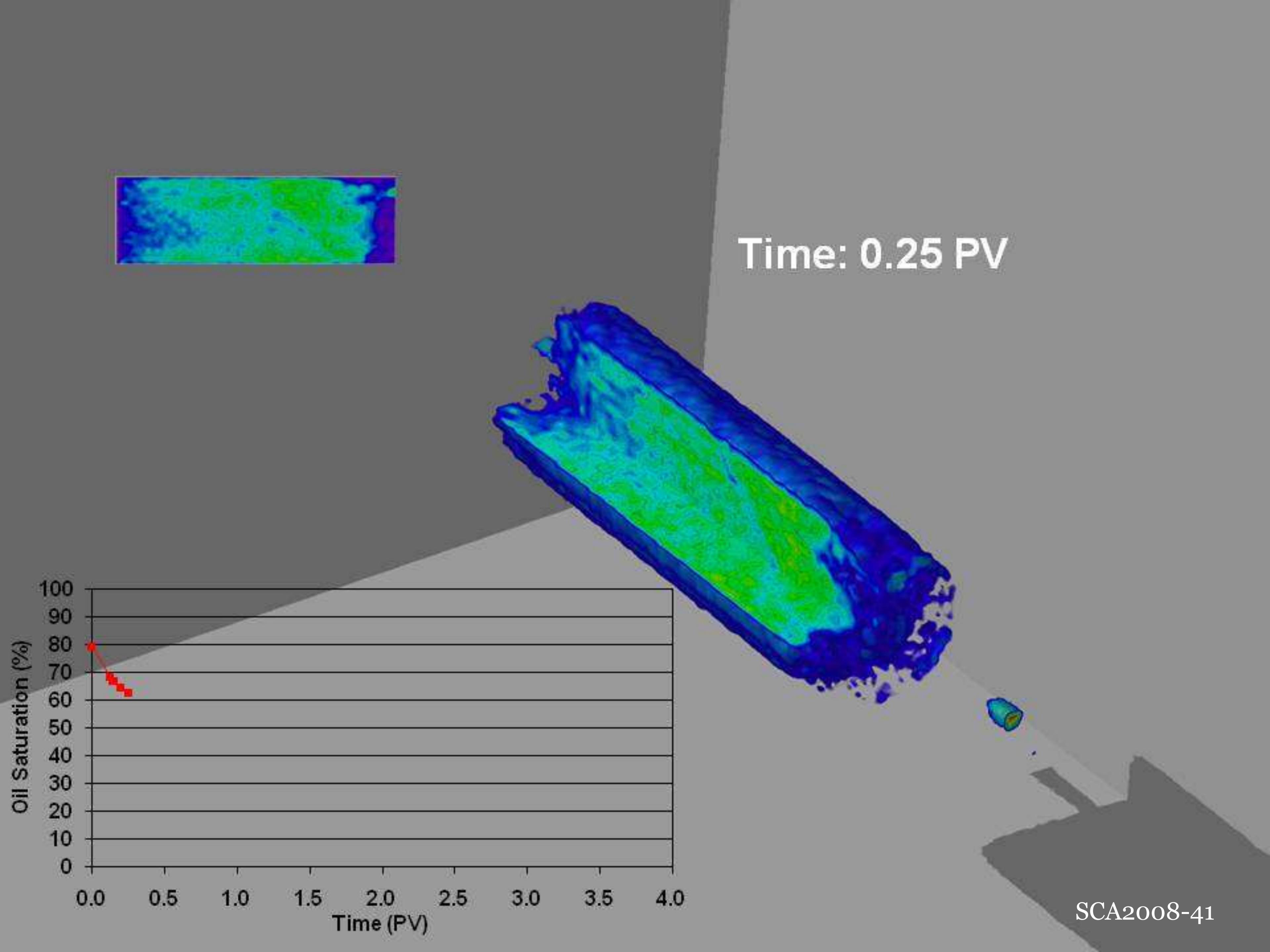


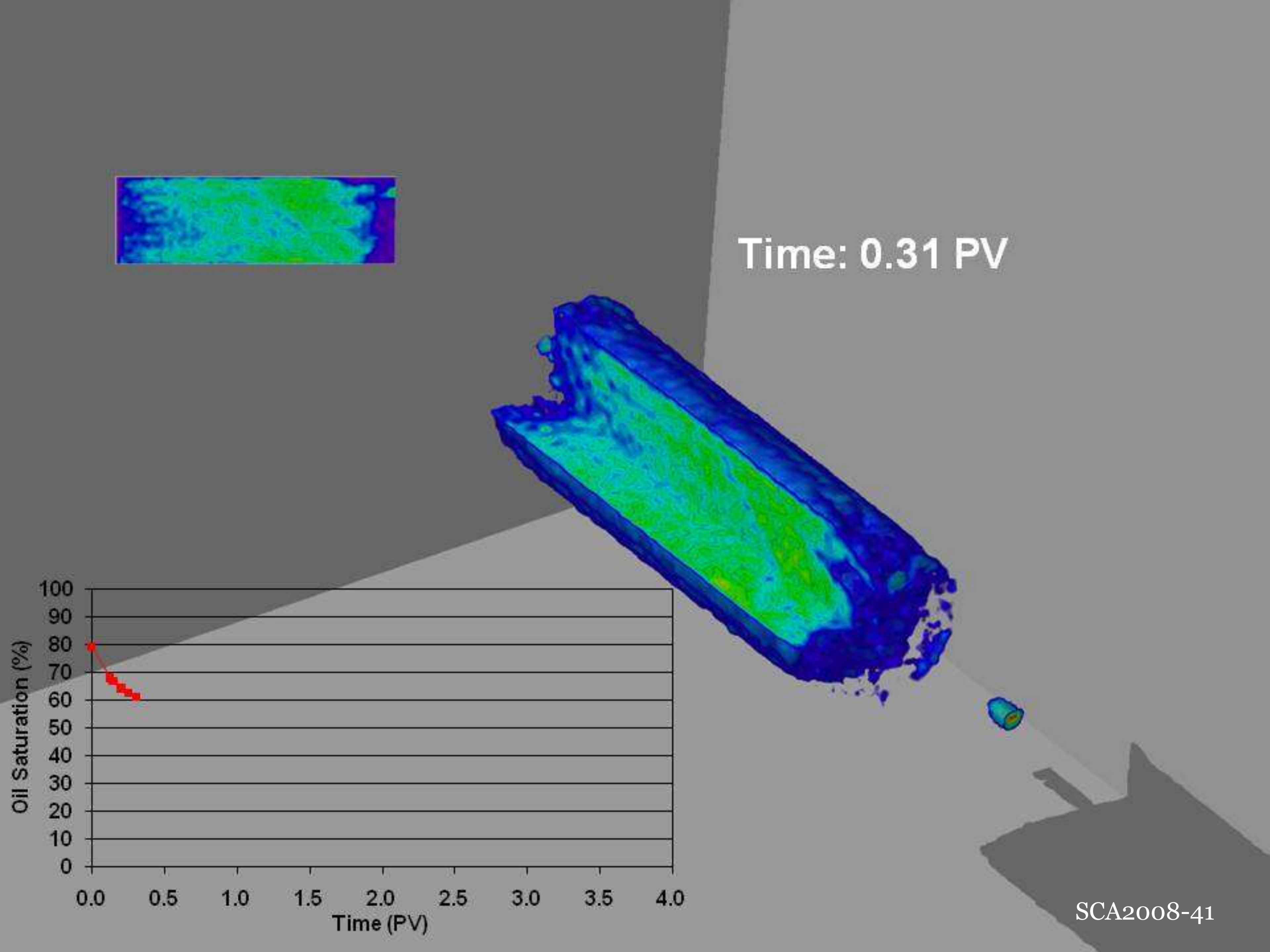

Time: 0.00 PV
$S_{o, wi}$ = 79.9 %
D_2O Injection
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 0.13 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

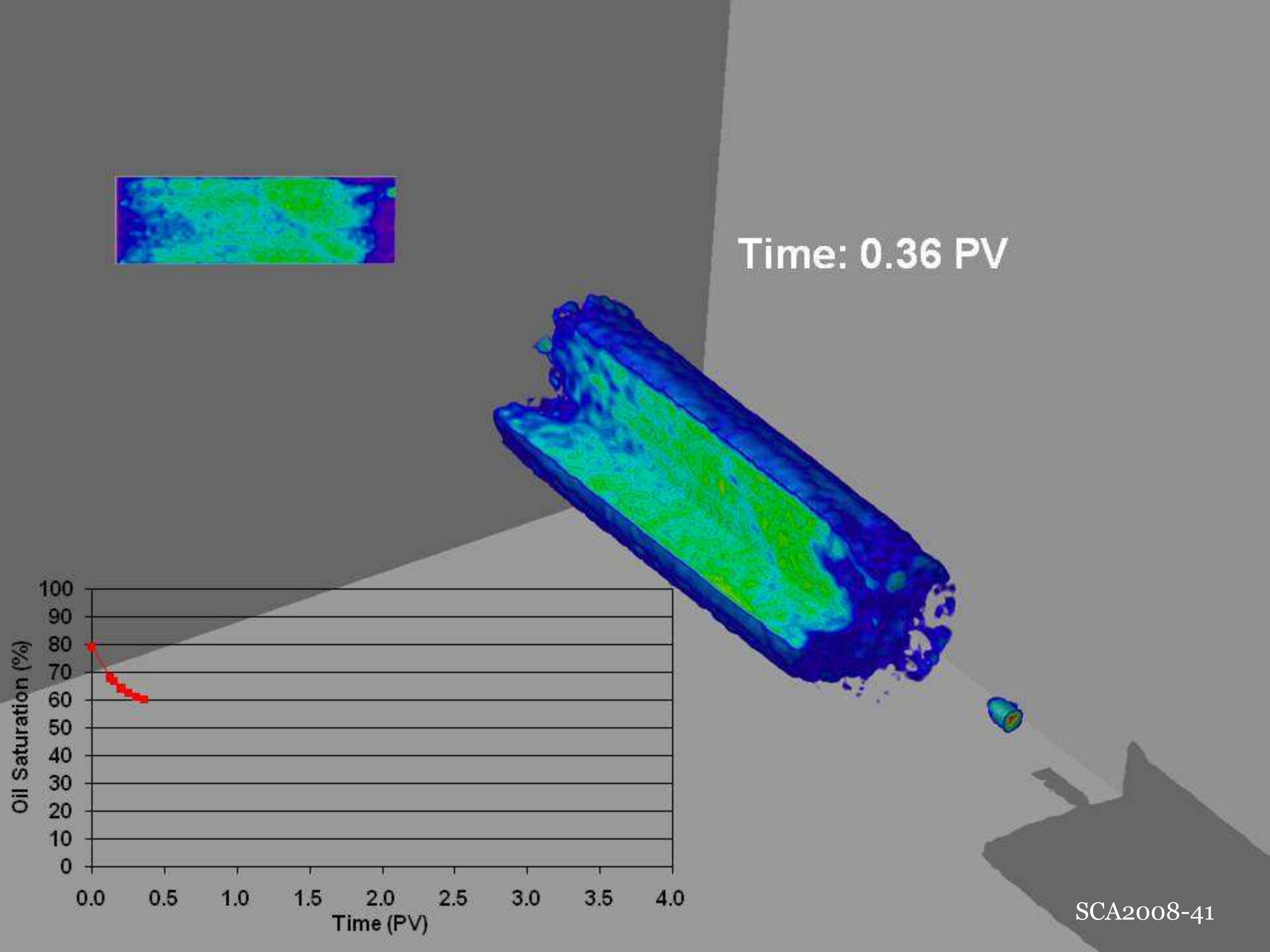

Time: 0.15 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 0.20 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

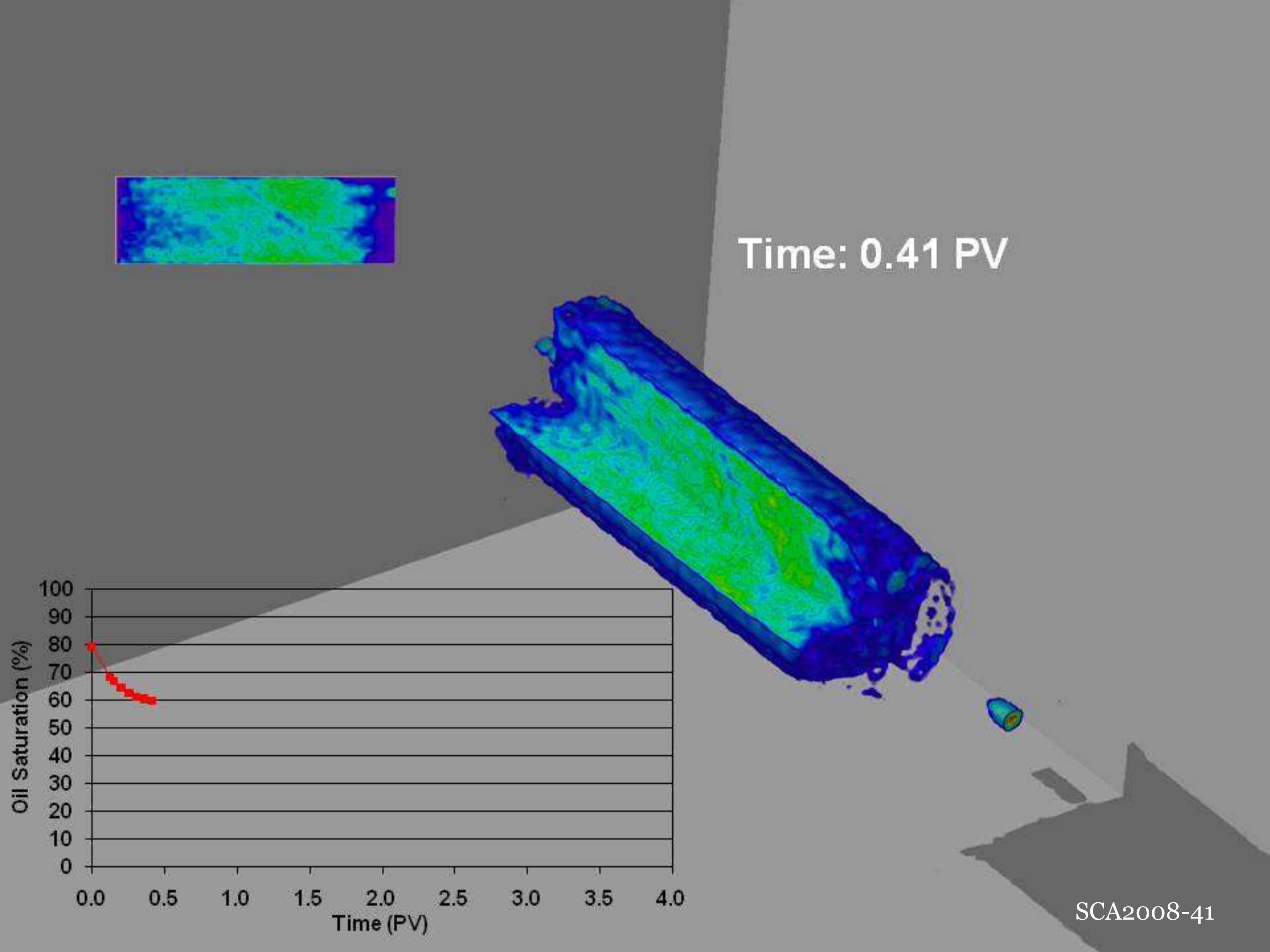

Time: 0.25 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

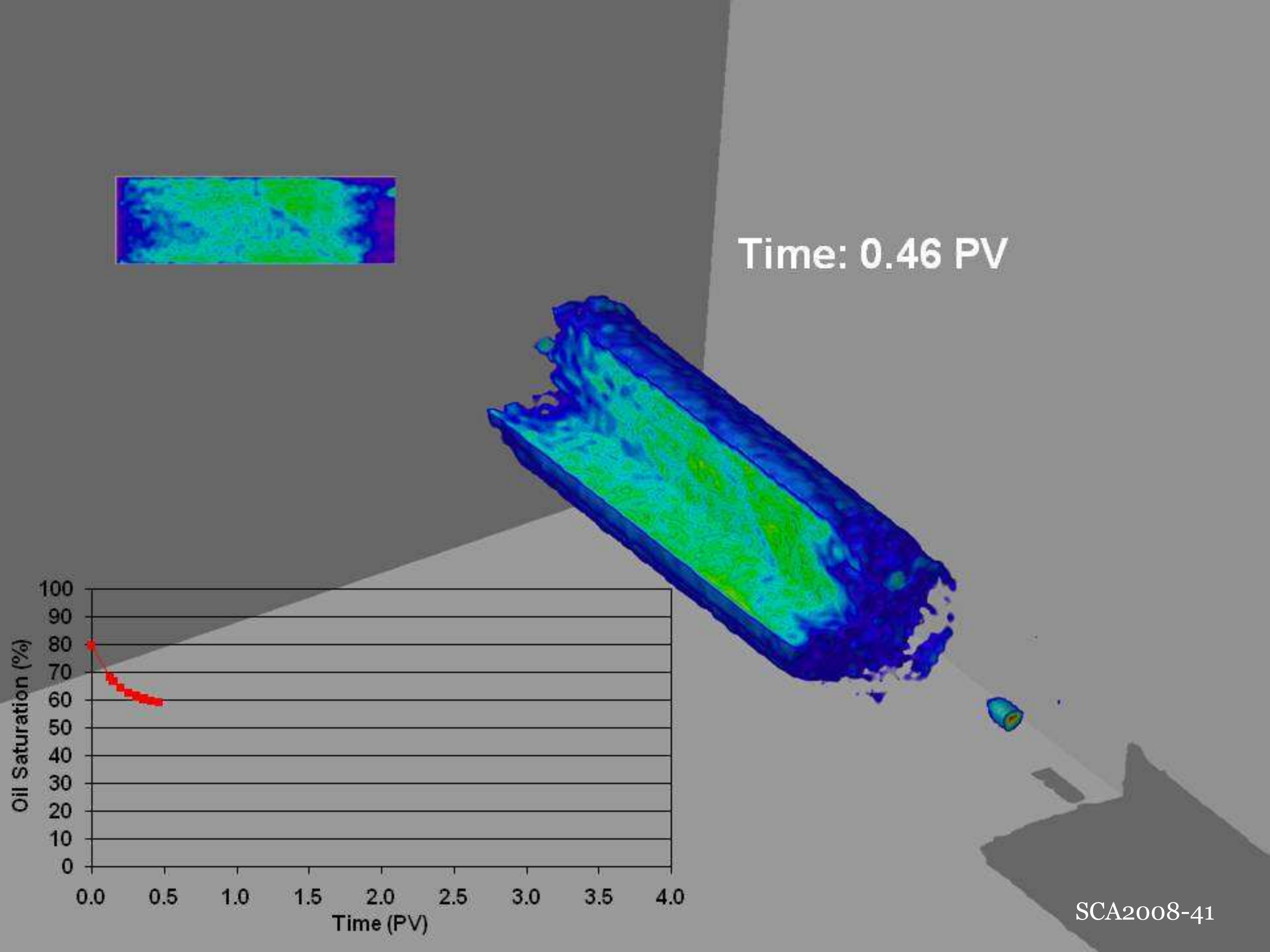


Time: 0.31 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

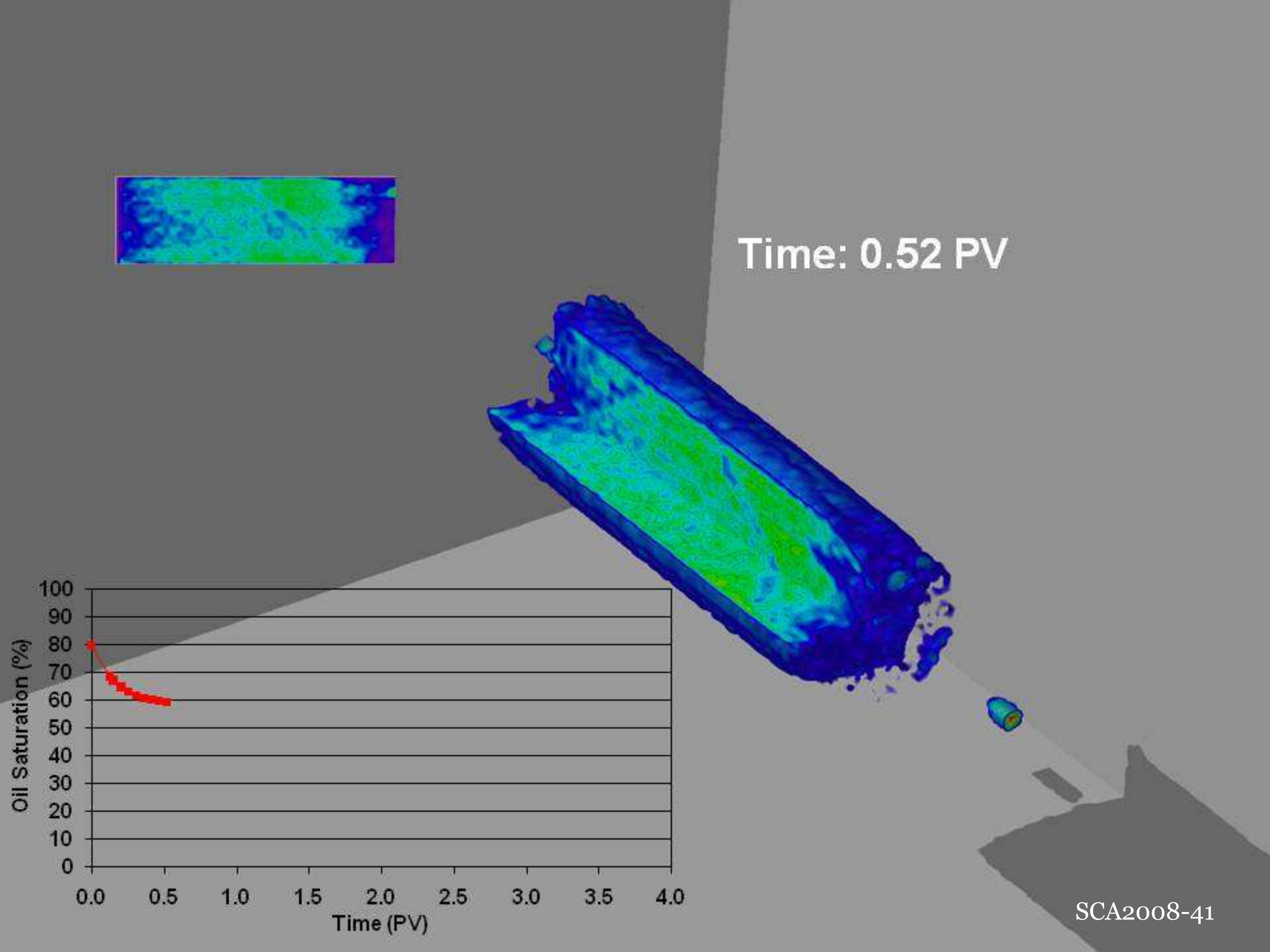


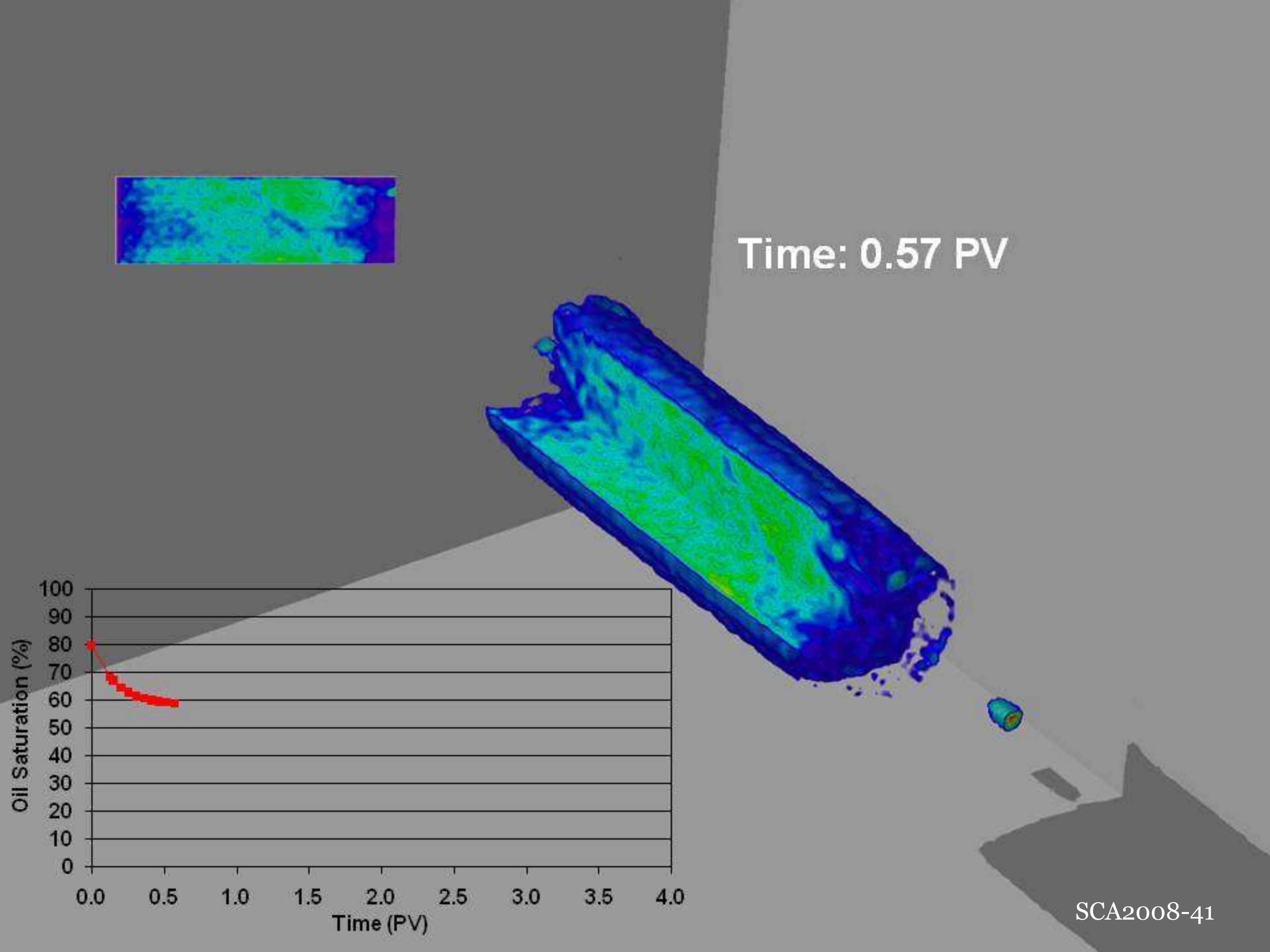
Time: 0.36 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 0.41 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

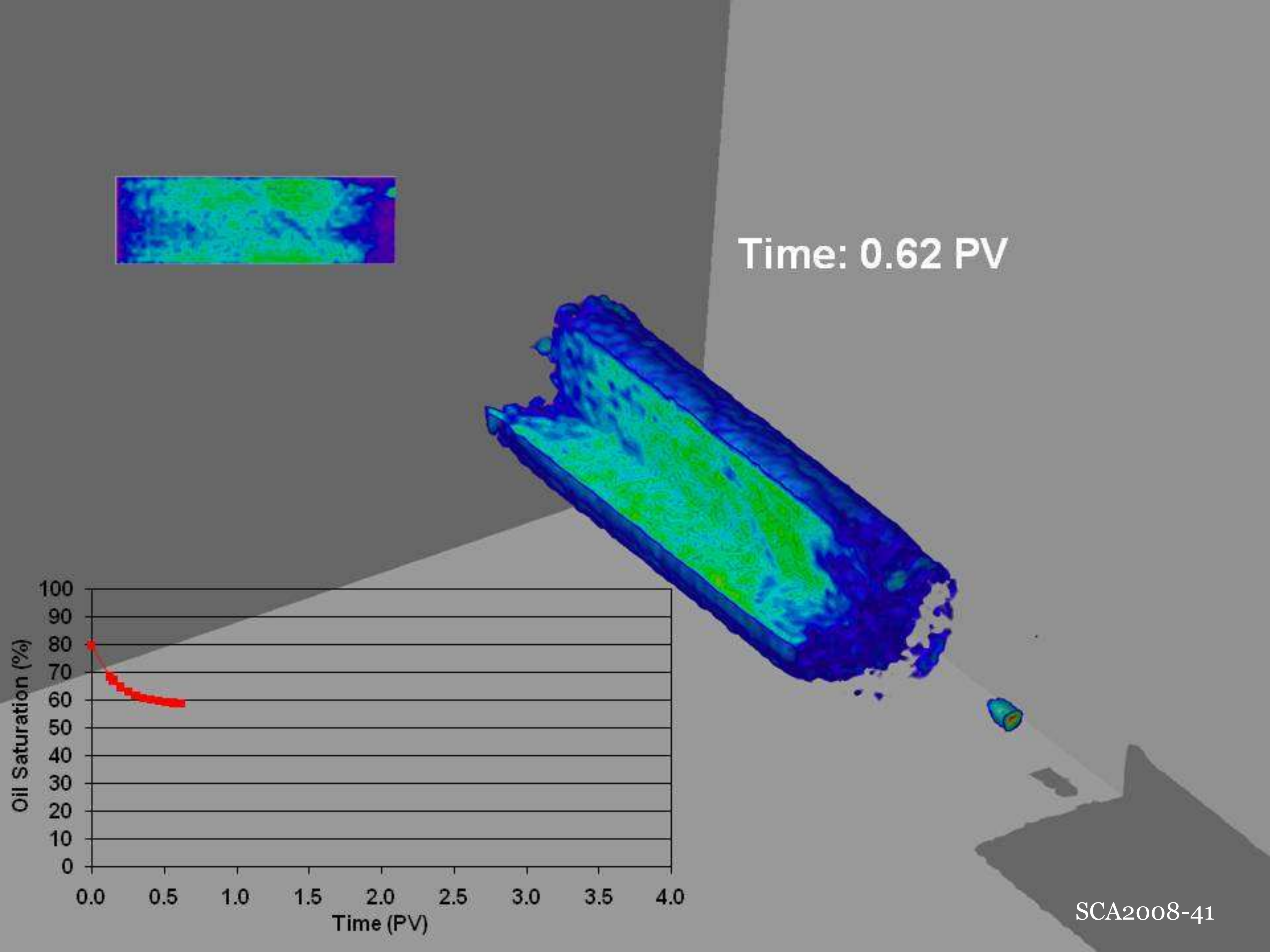


Time: 0.46 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

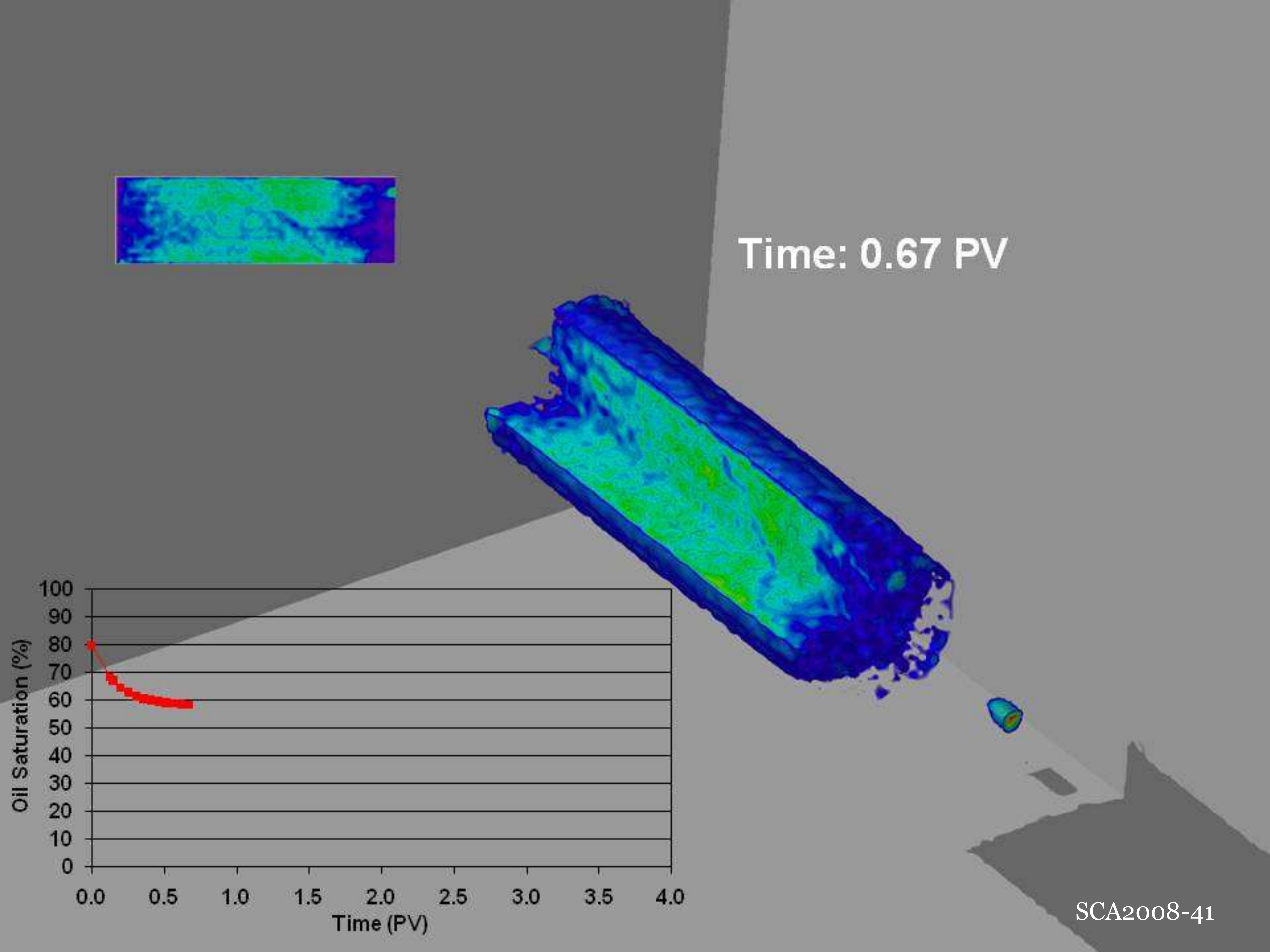

Time: 0.52 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

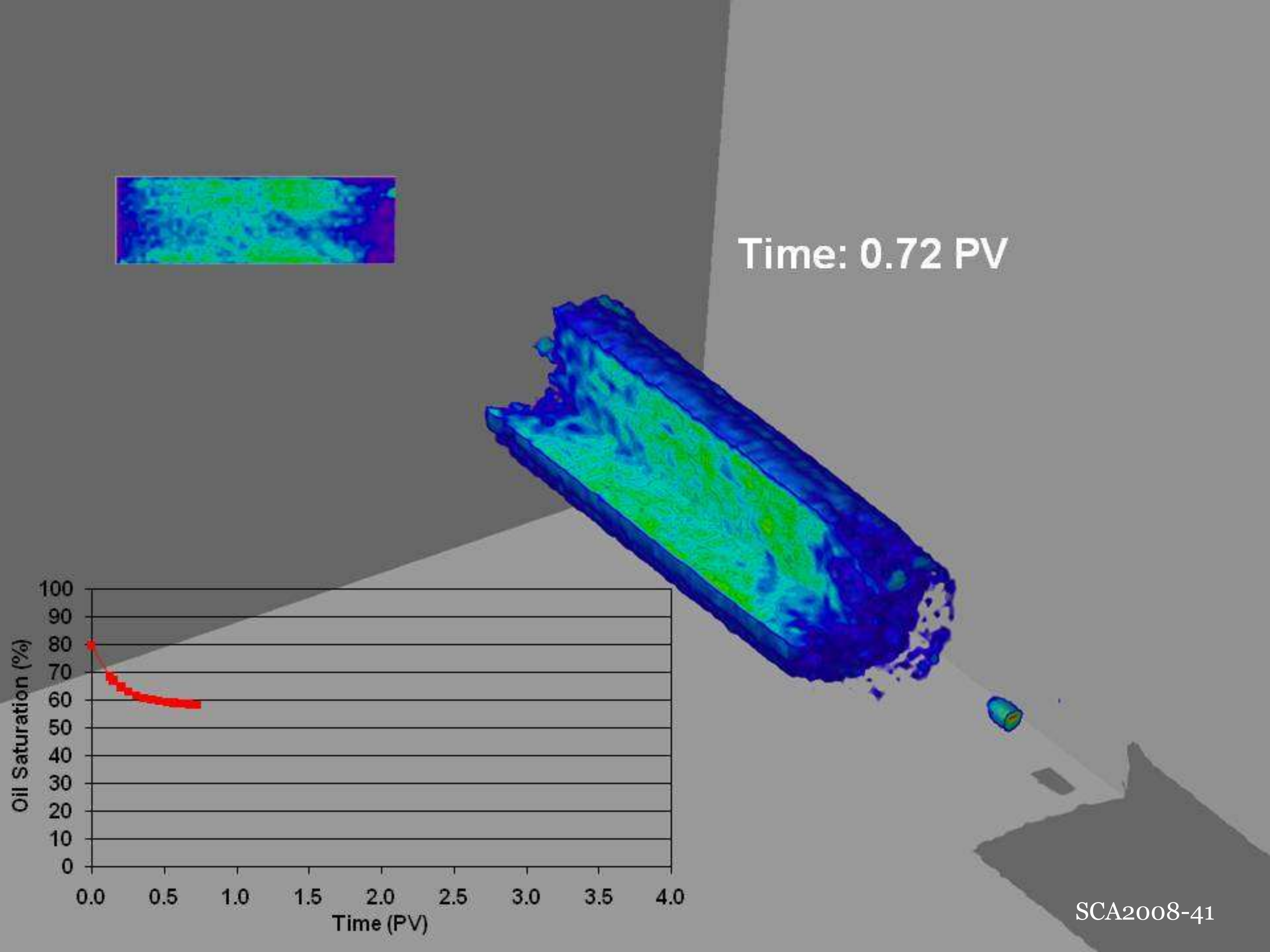


Time: 0.57 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

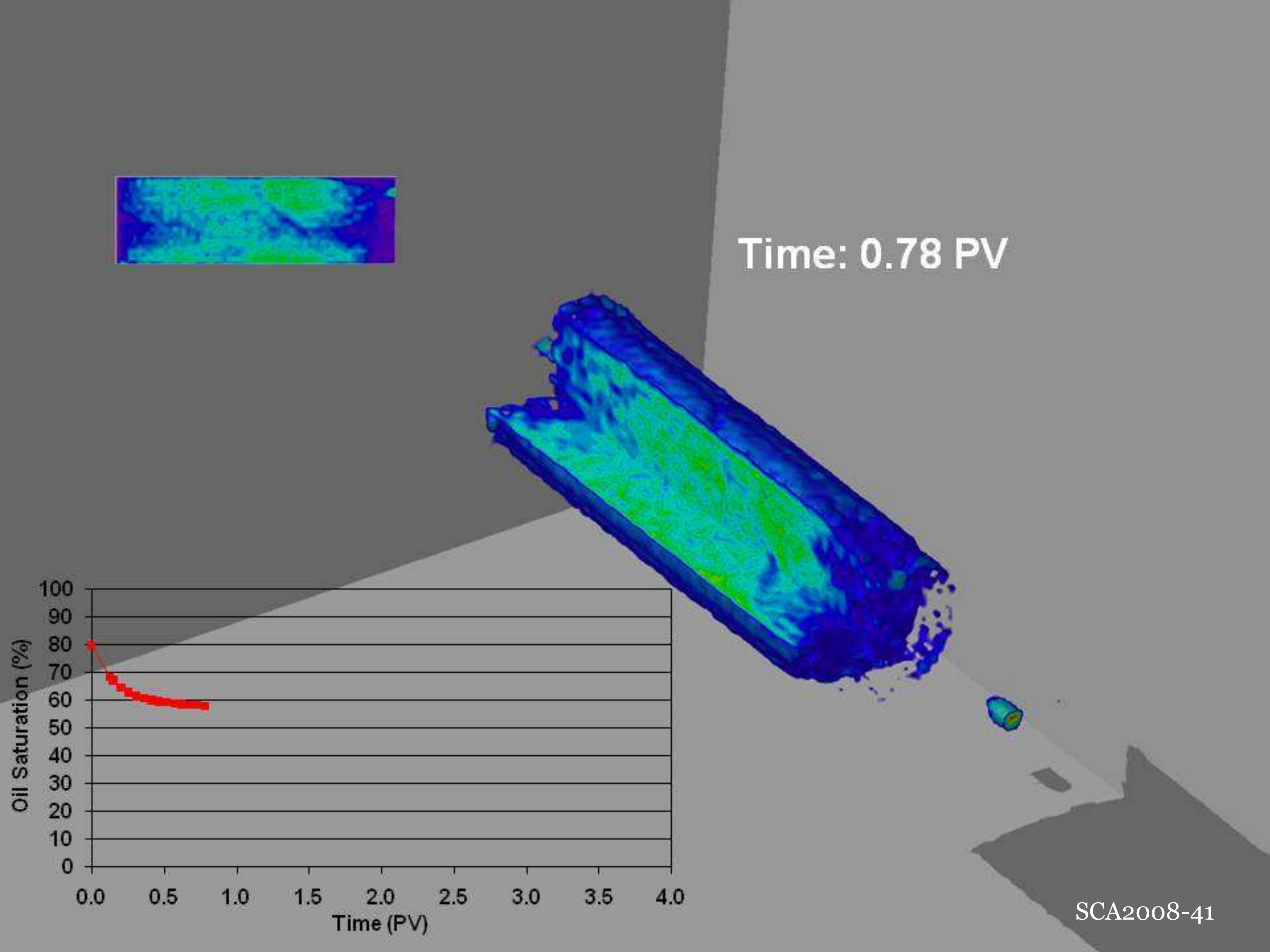


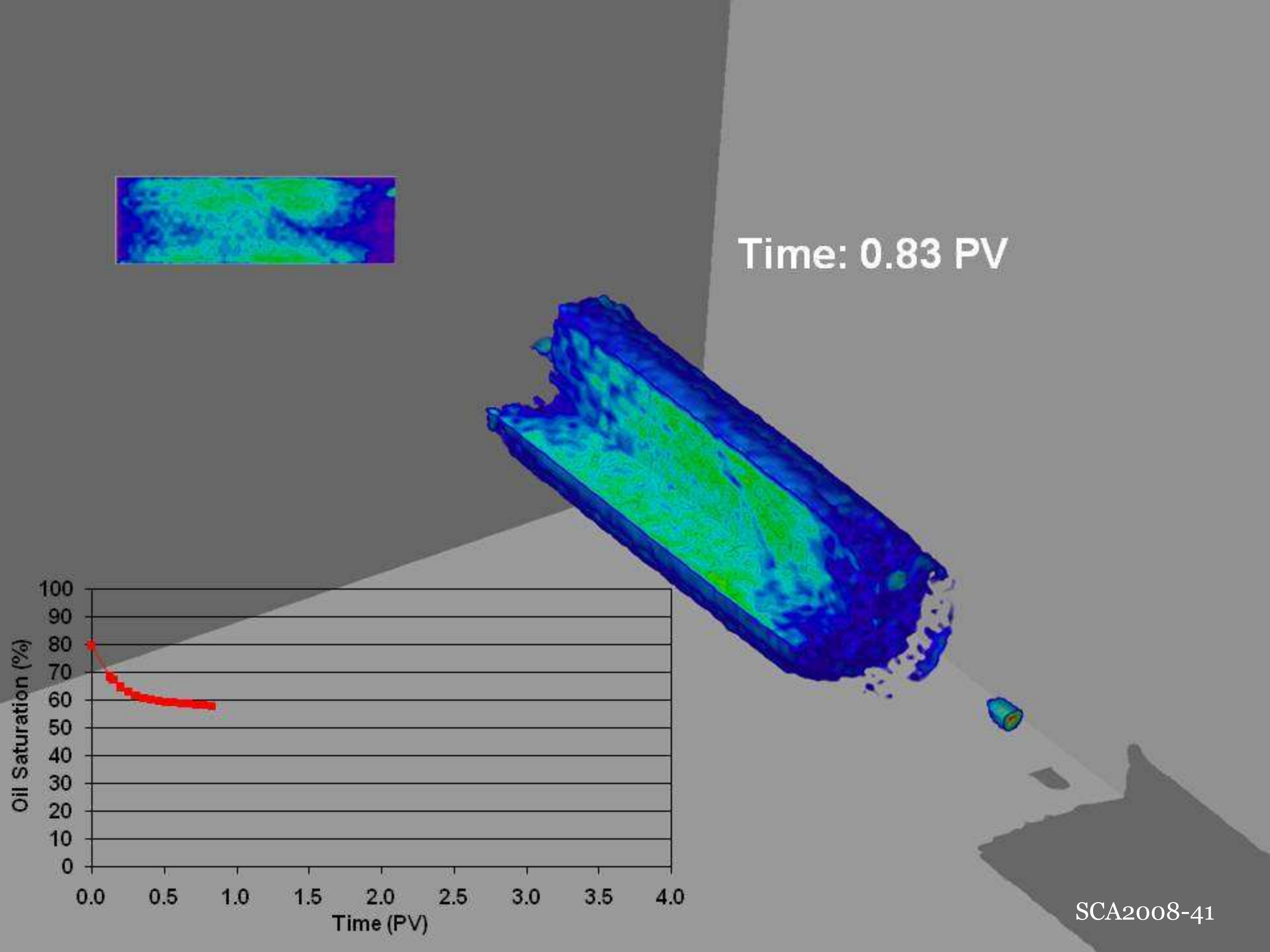
Time: 0.62 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)
SCA2008-41

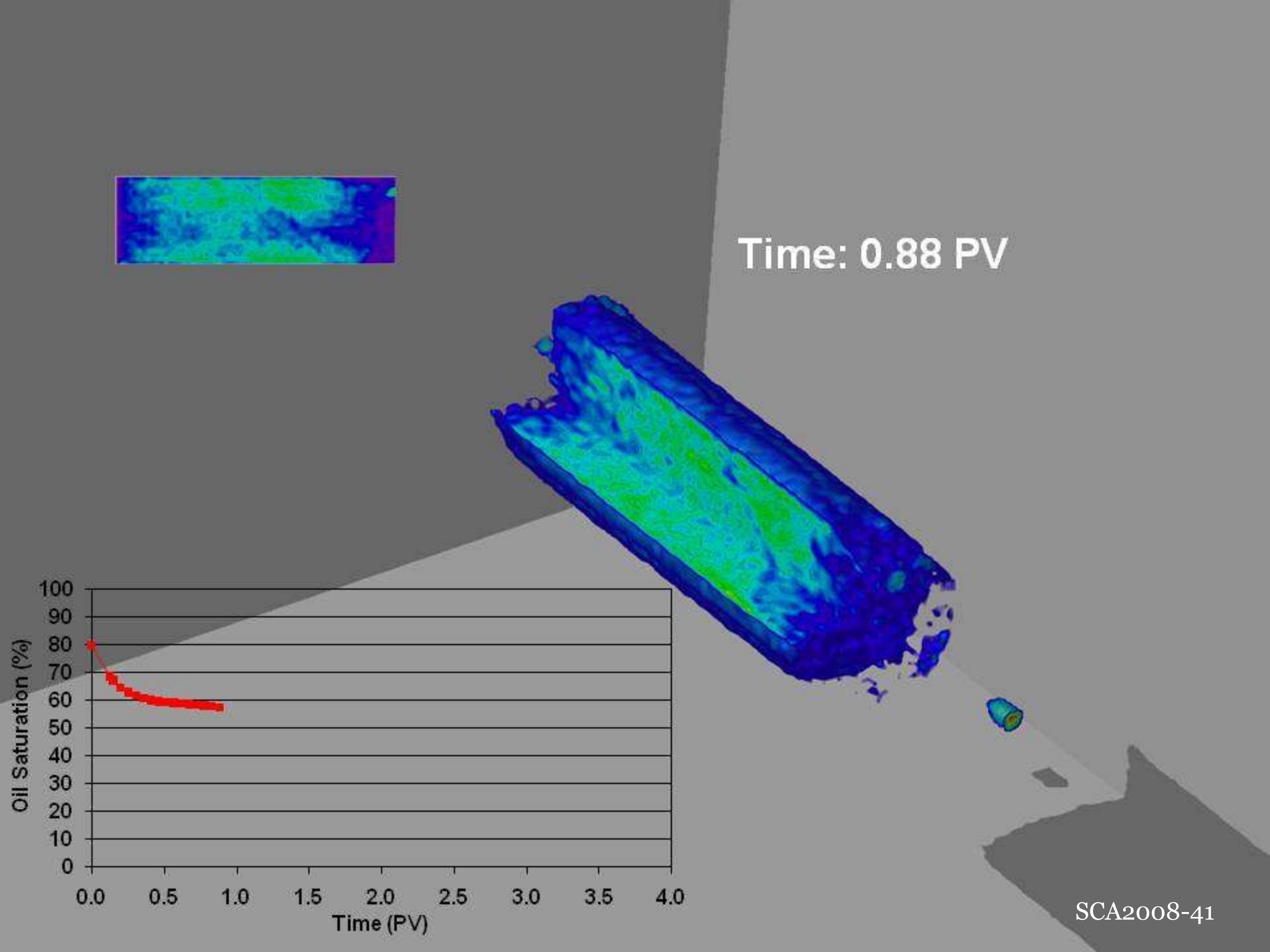

Time: 0.67 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

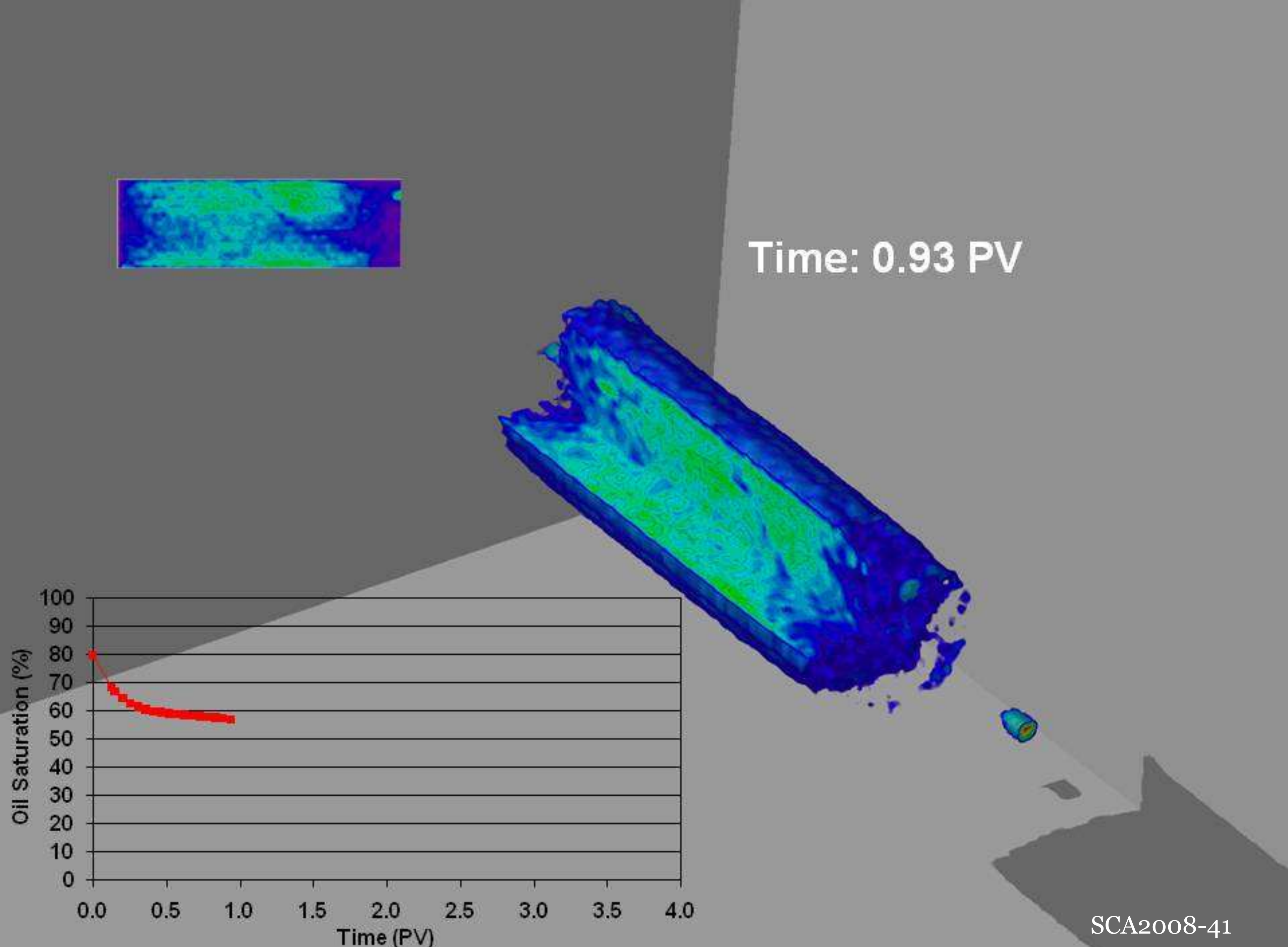


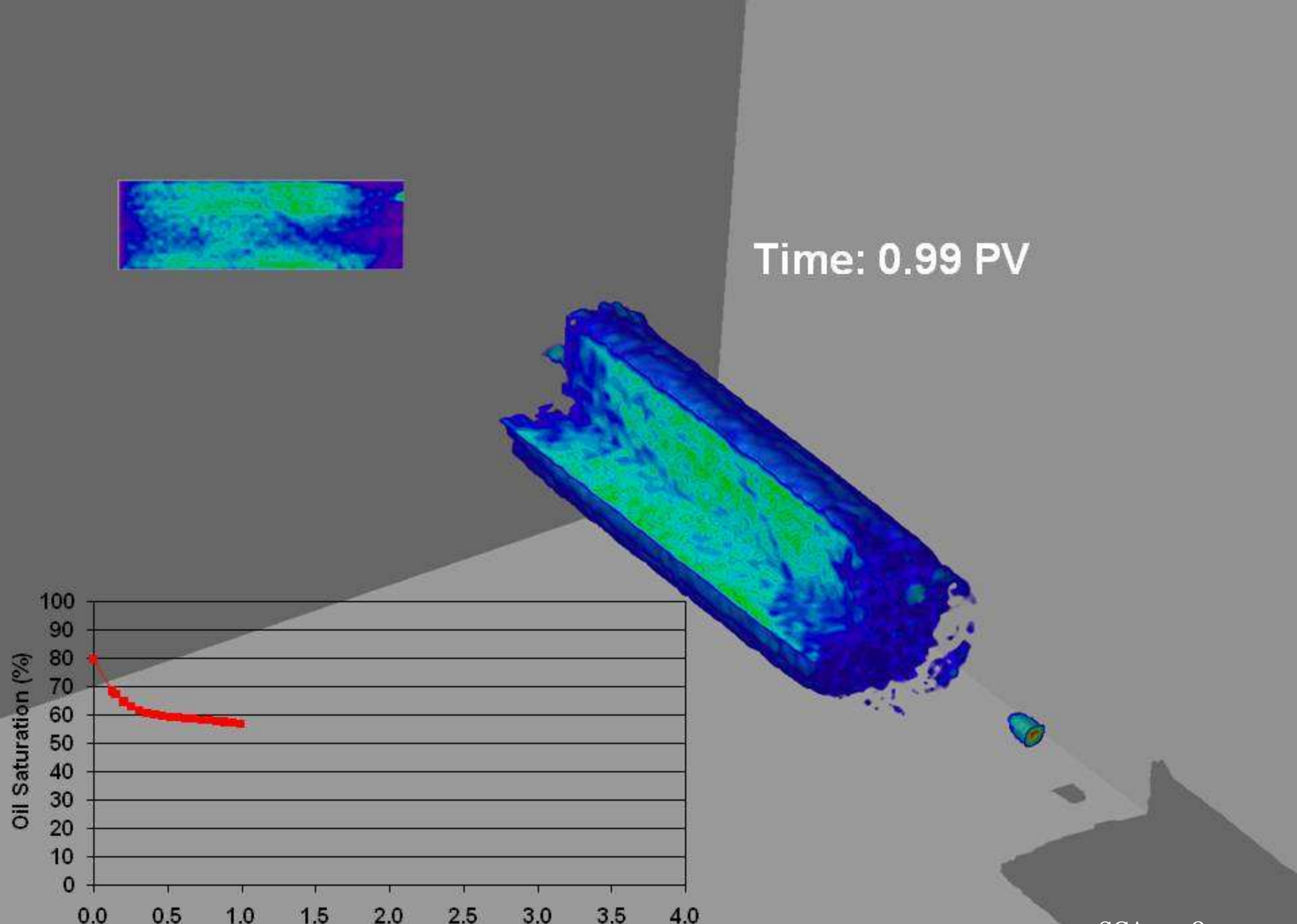
Time: 0.72 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

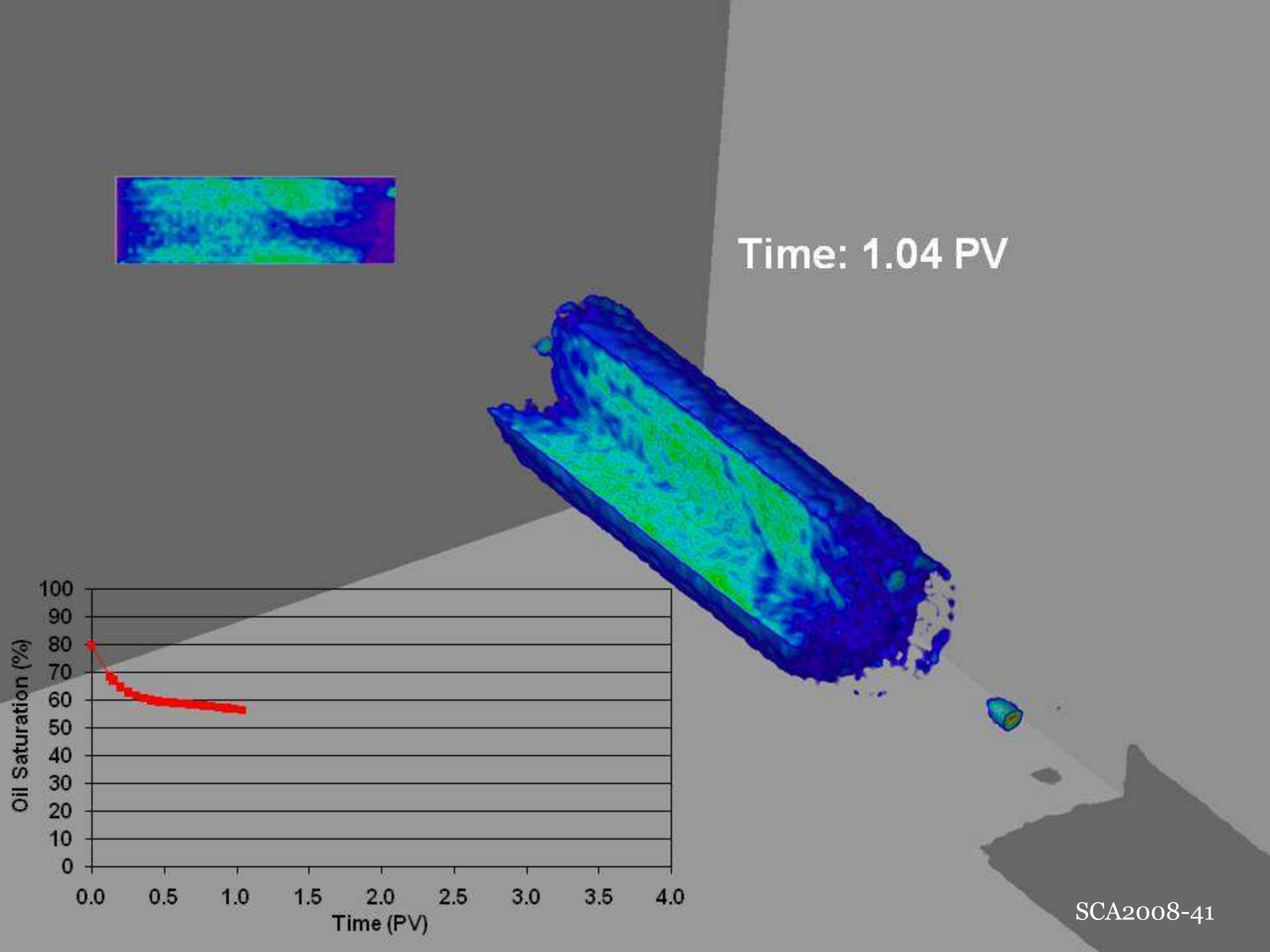

Time: 0.78 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

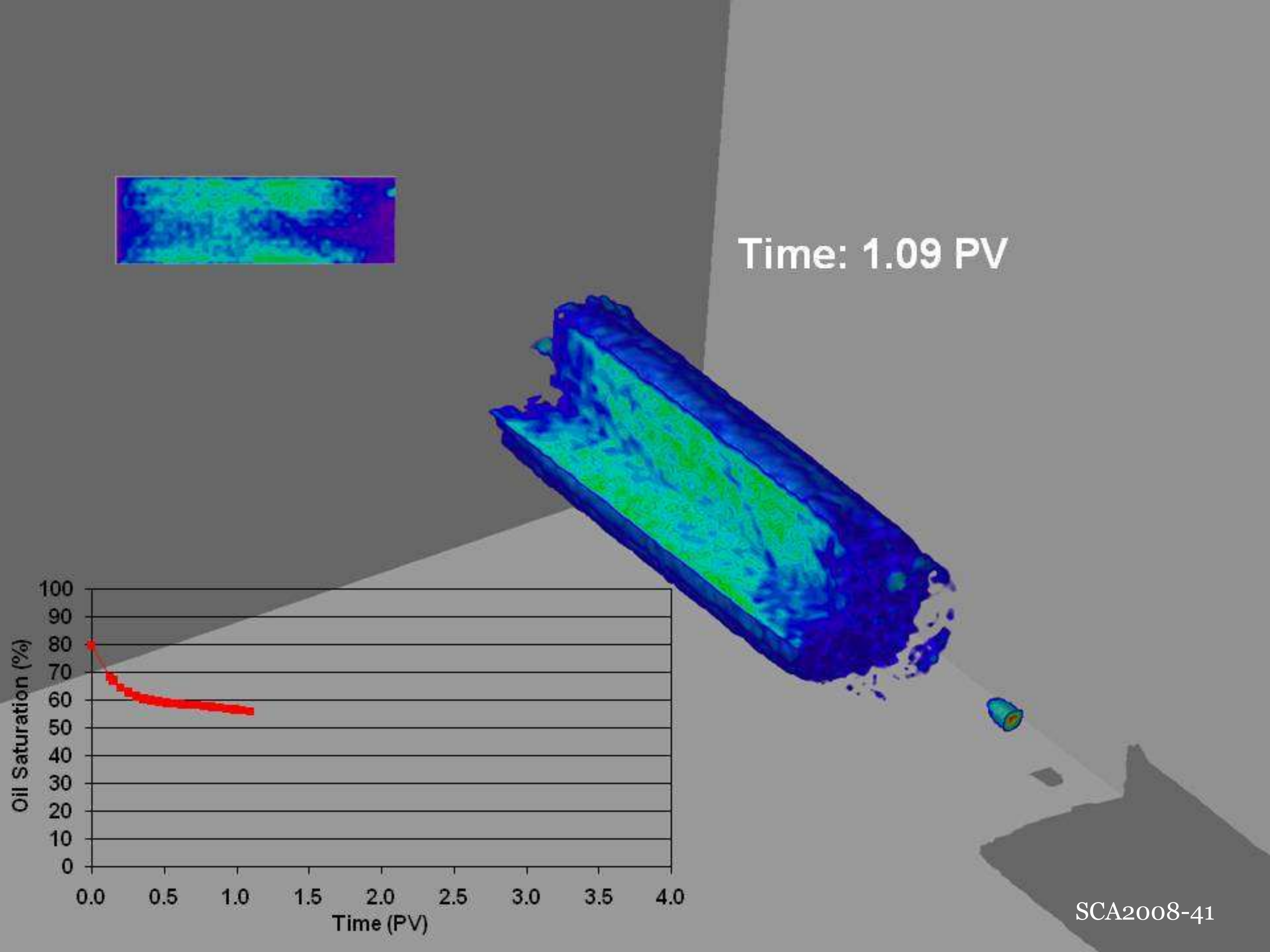

Time: 0.83 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

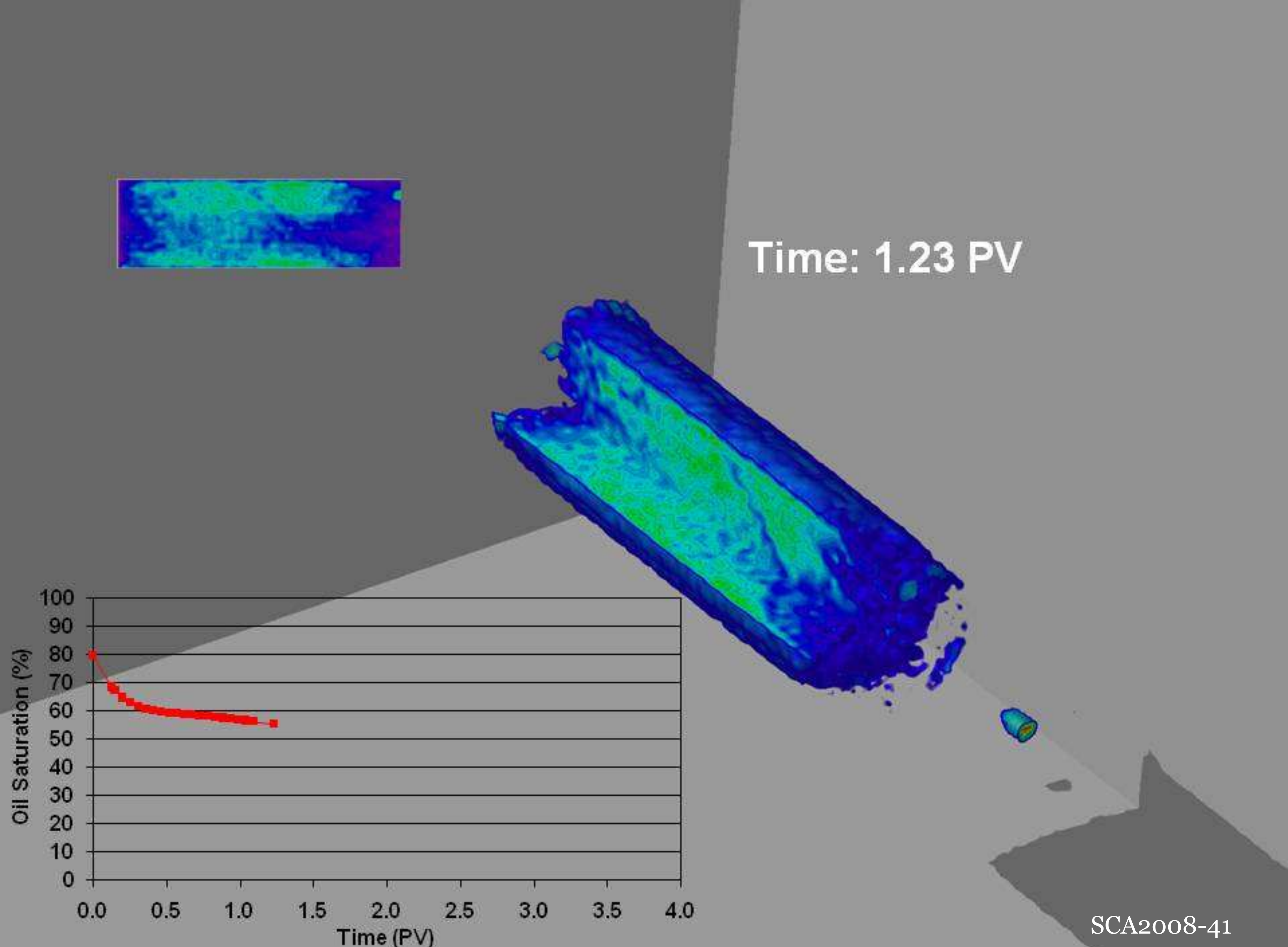

Time: 0.88 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 0.93 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

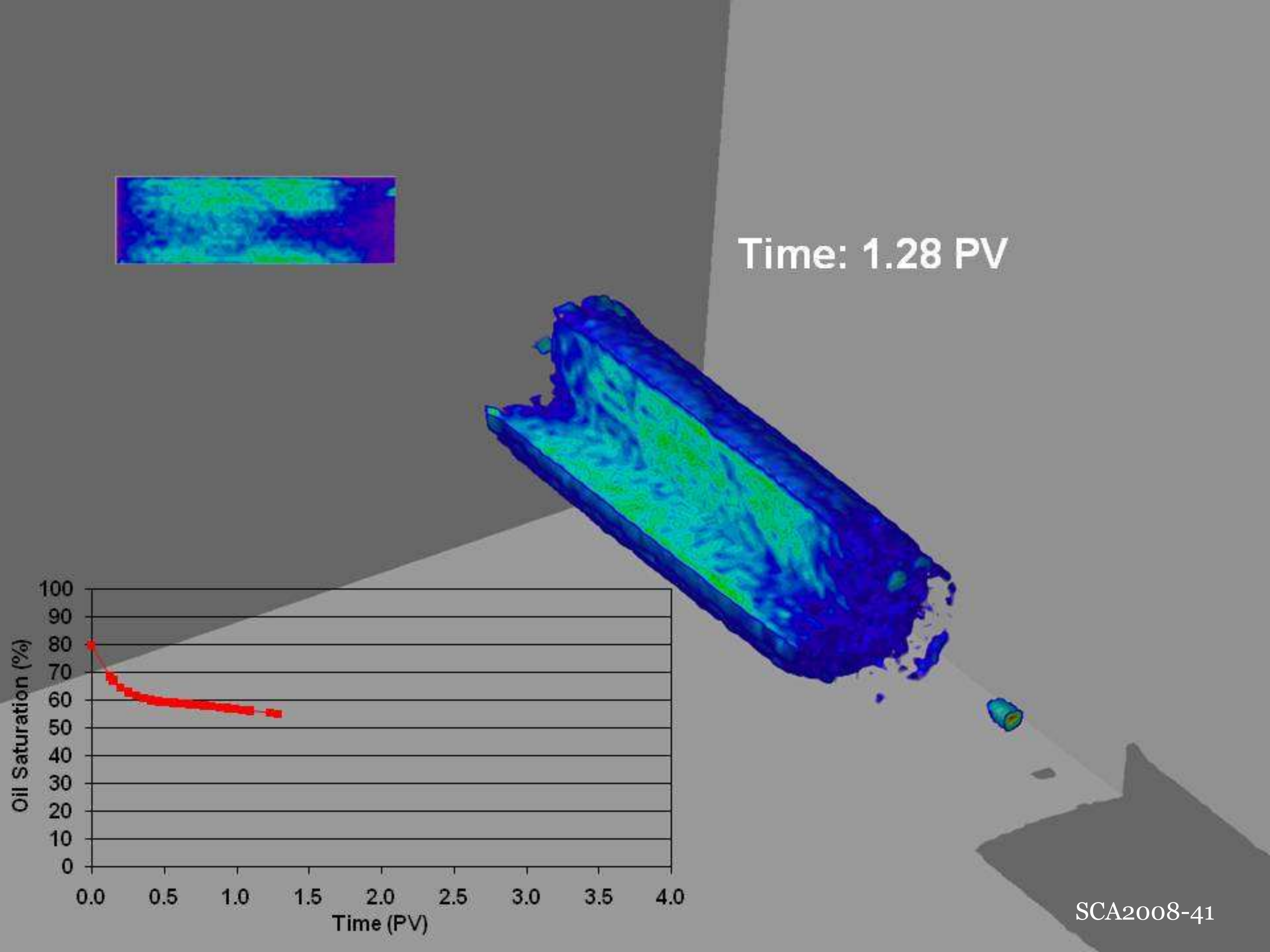

Time: 0.99 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

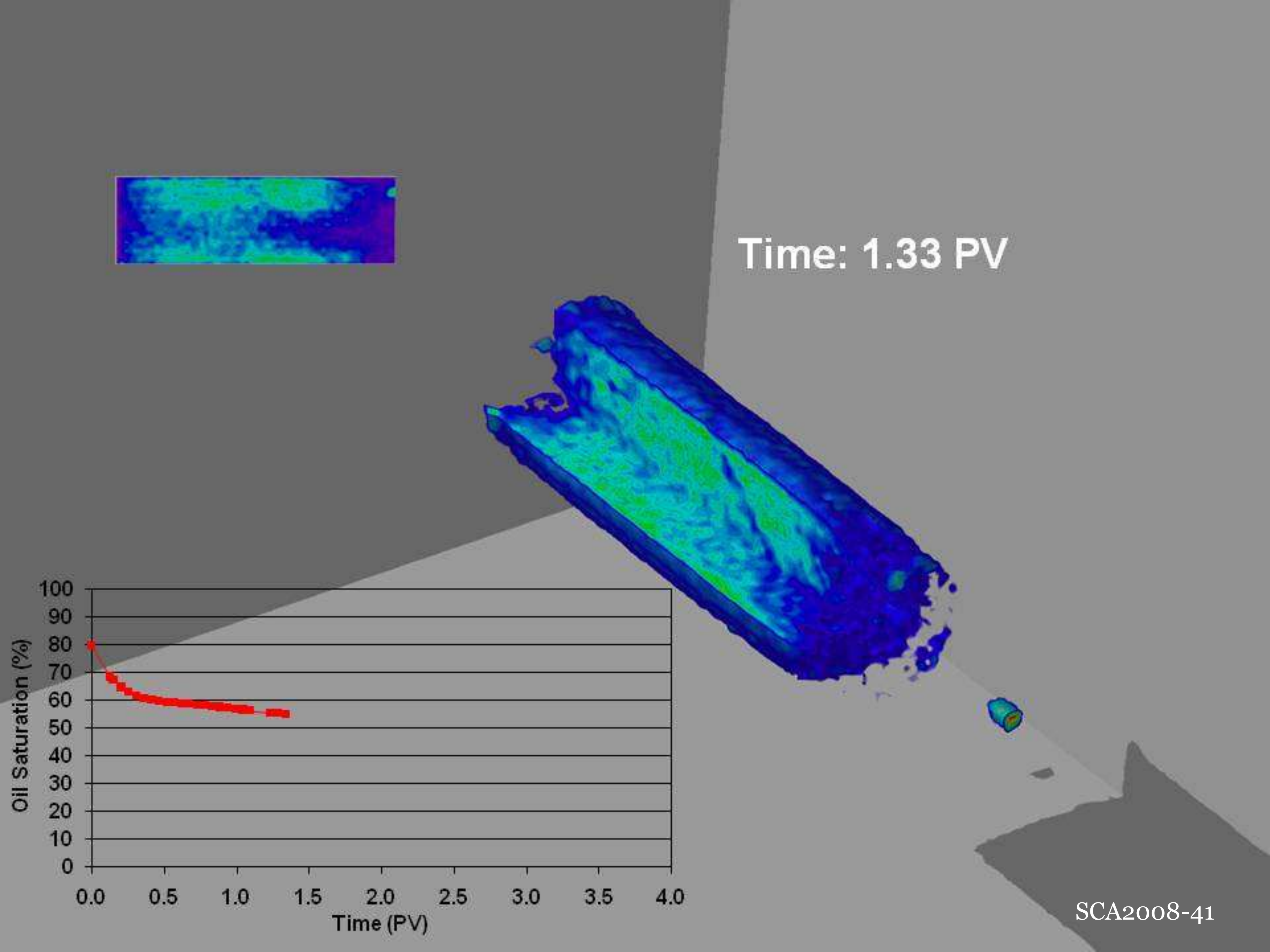

Time: 1.04 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

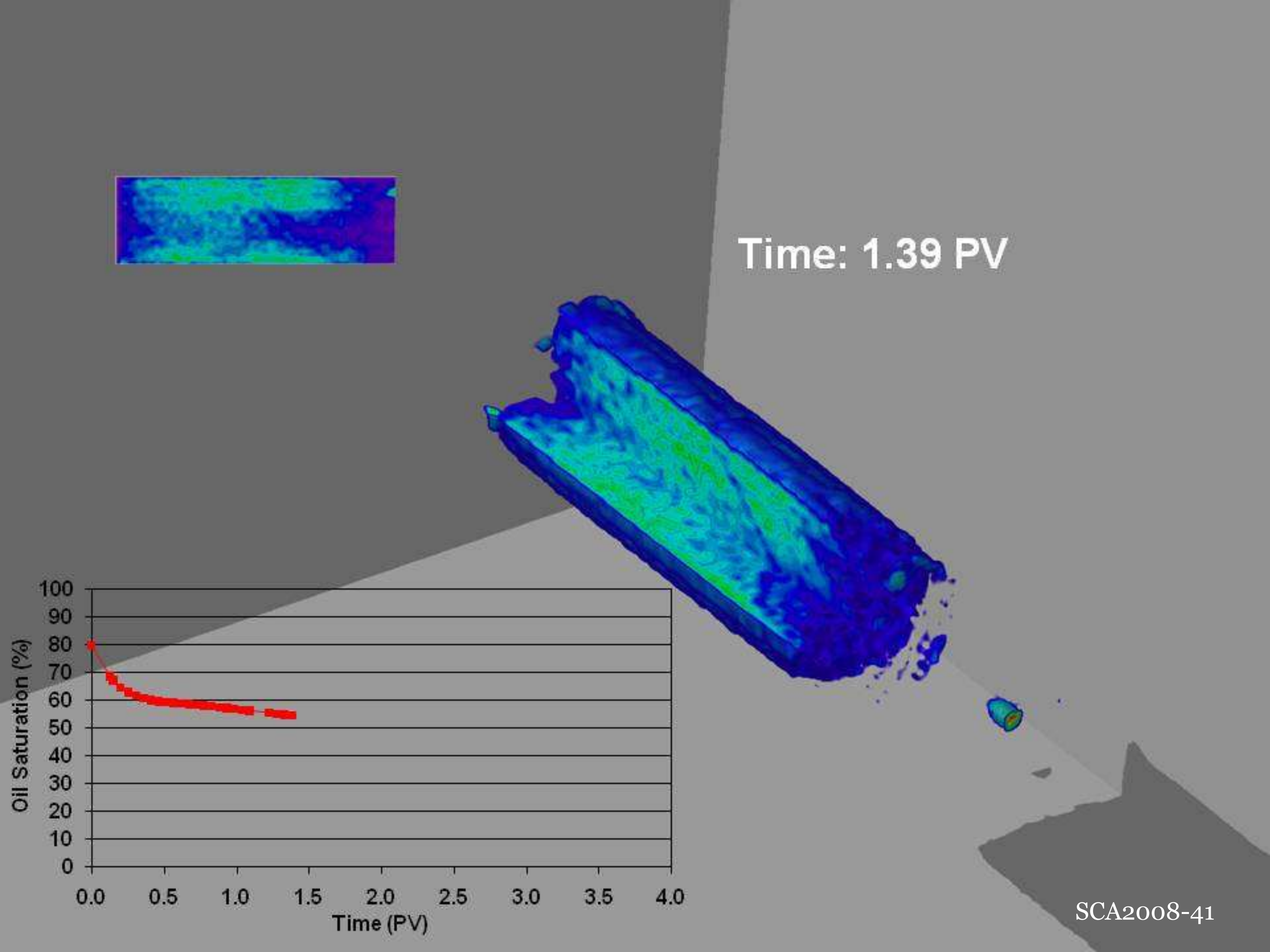

Time: 1.09 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

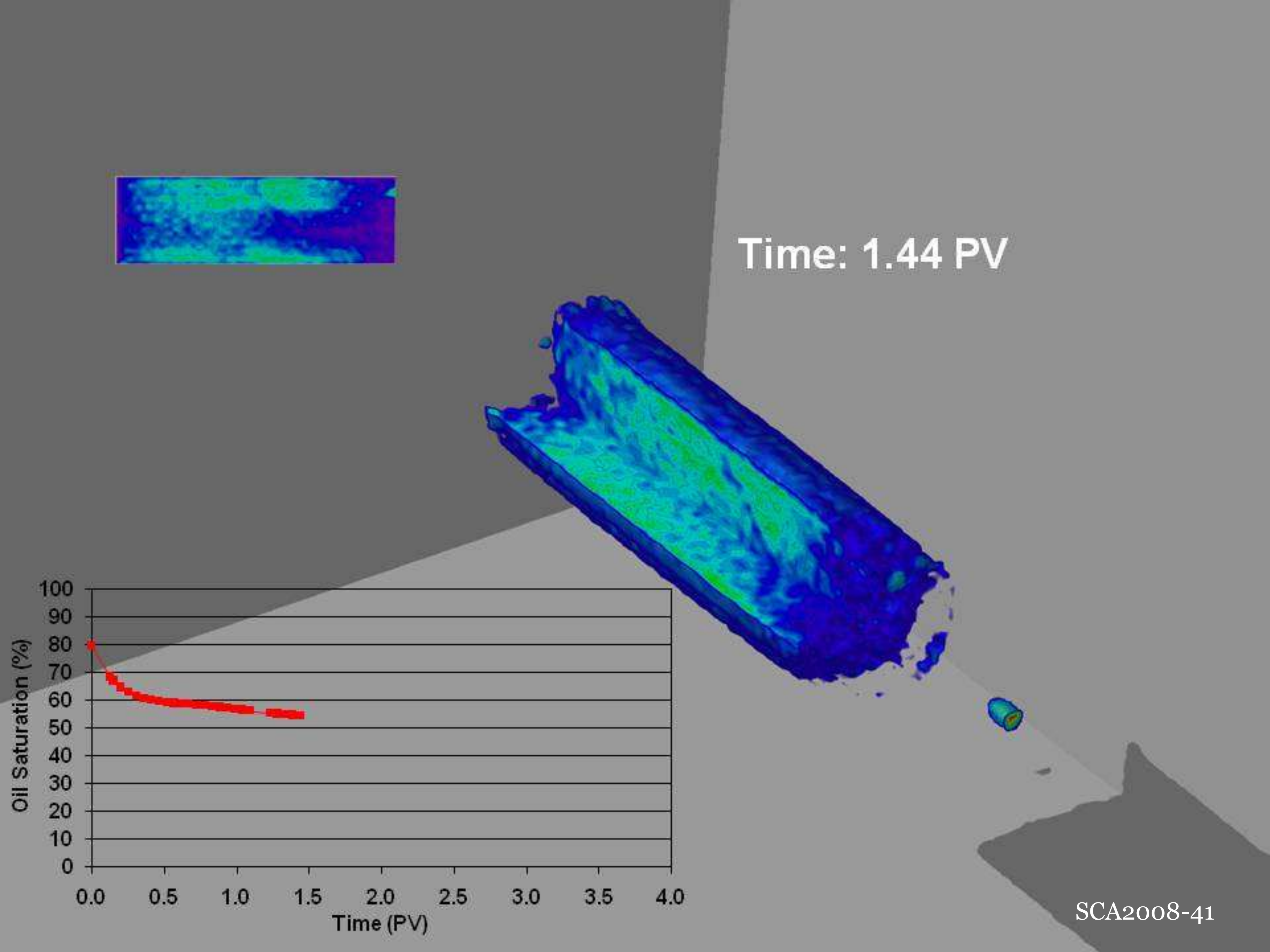


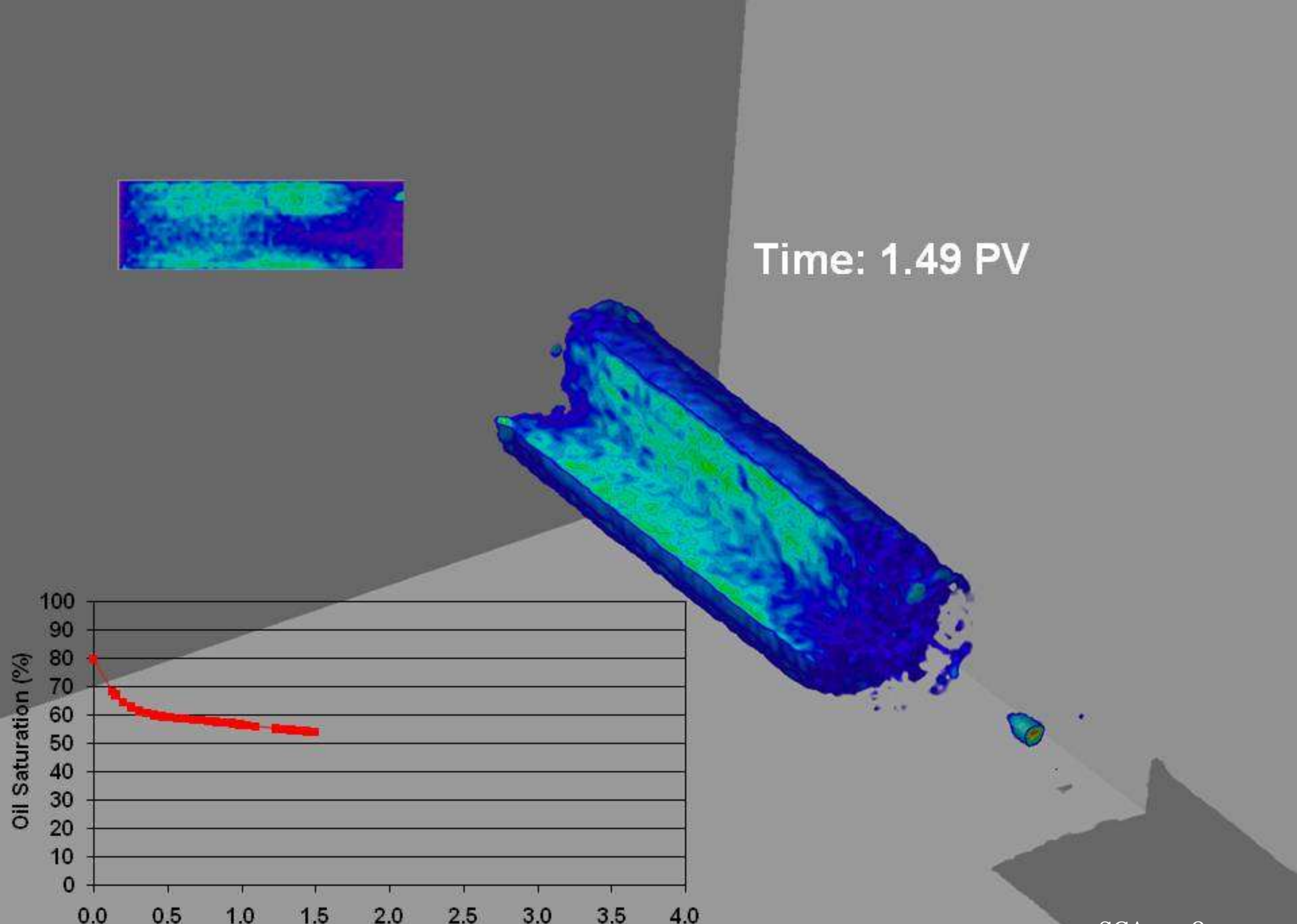
Time: 1.23 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 1.28 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

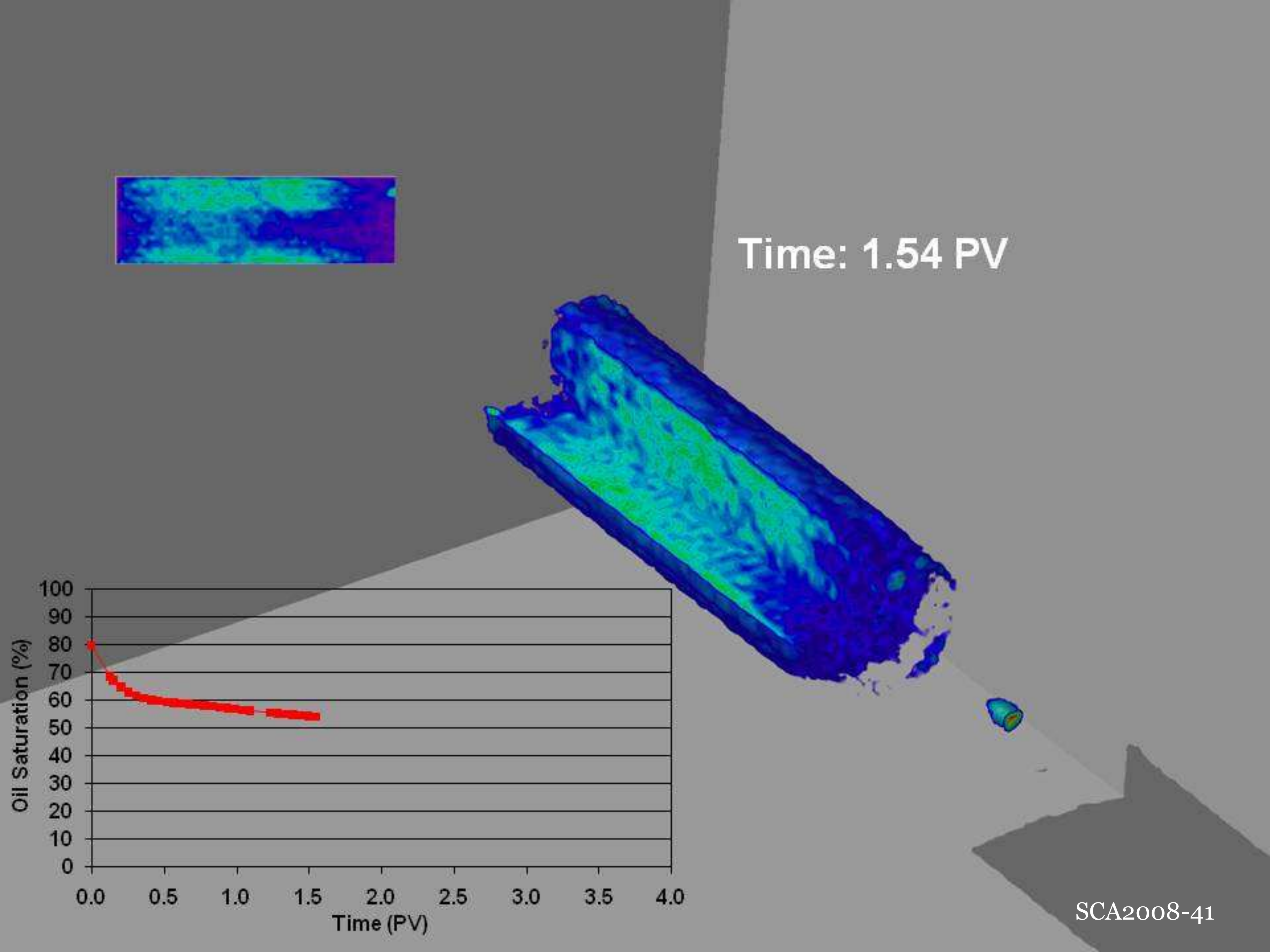

Time: 1.33 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

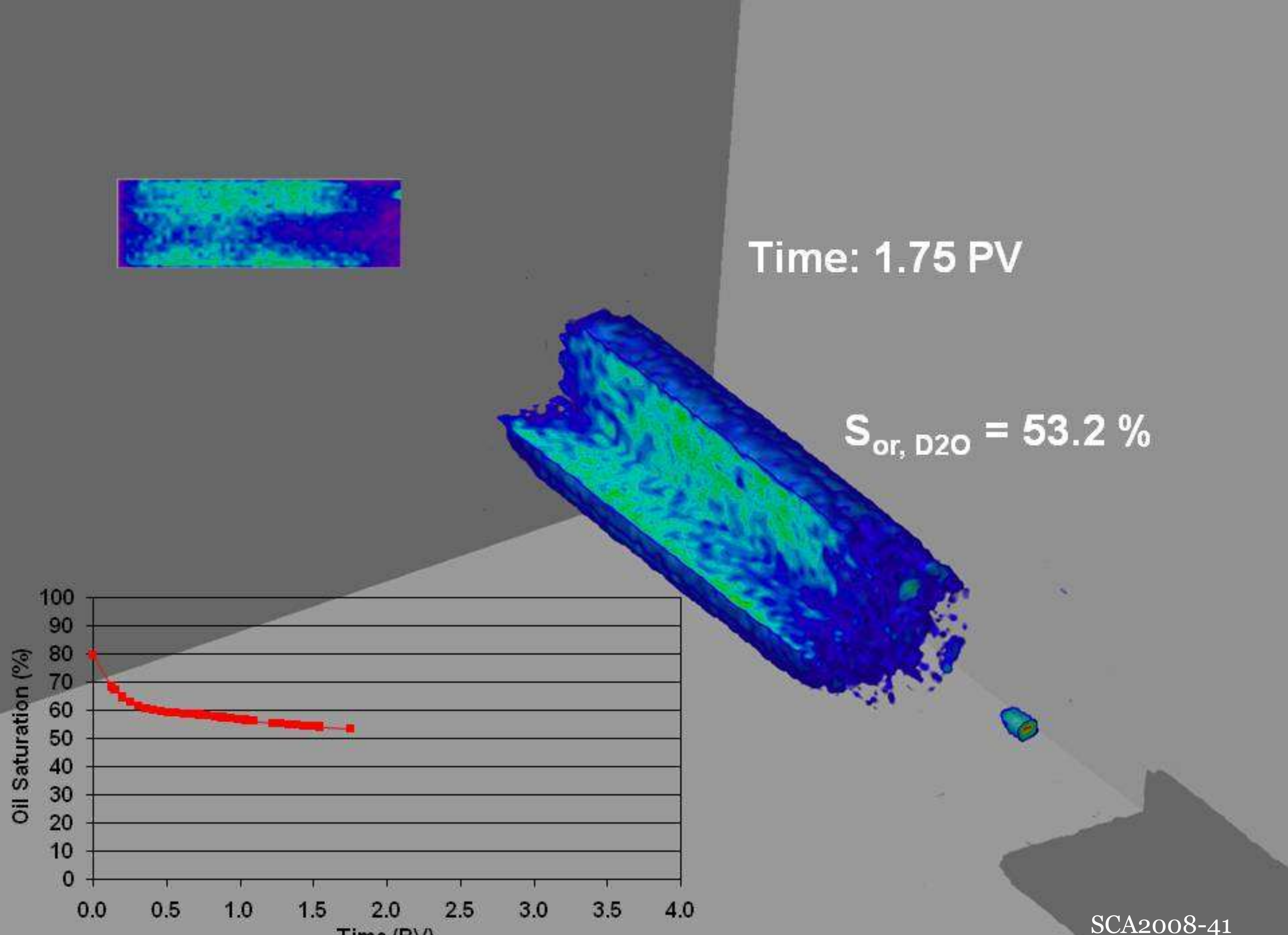

Time: 1.39 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 1.44 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

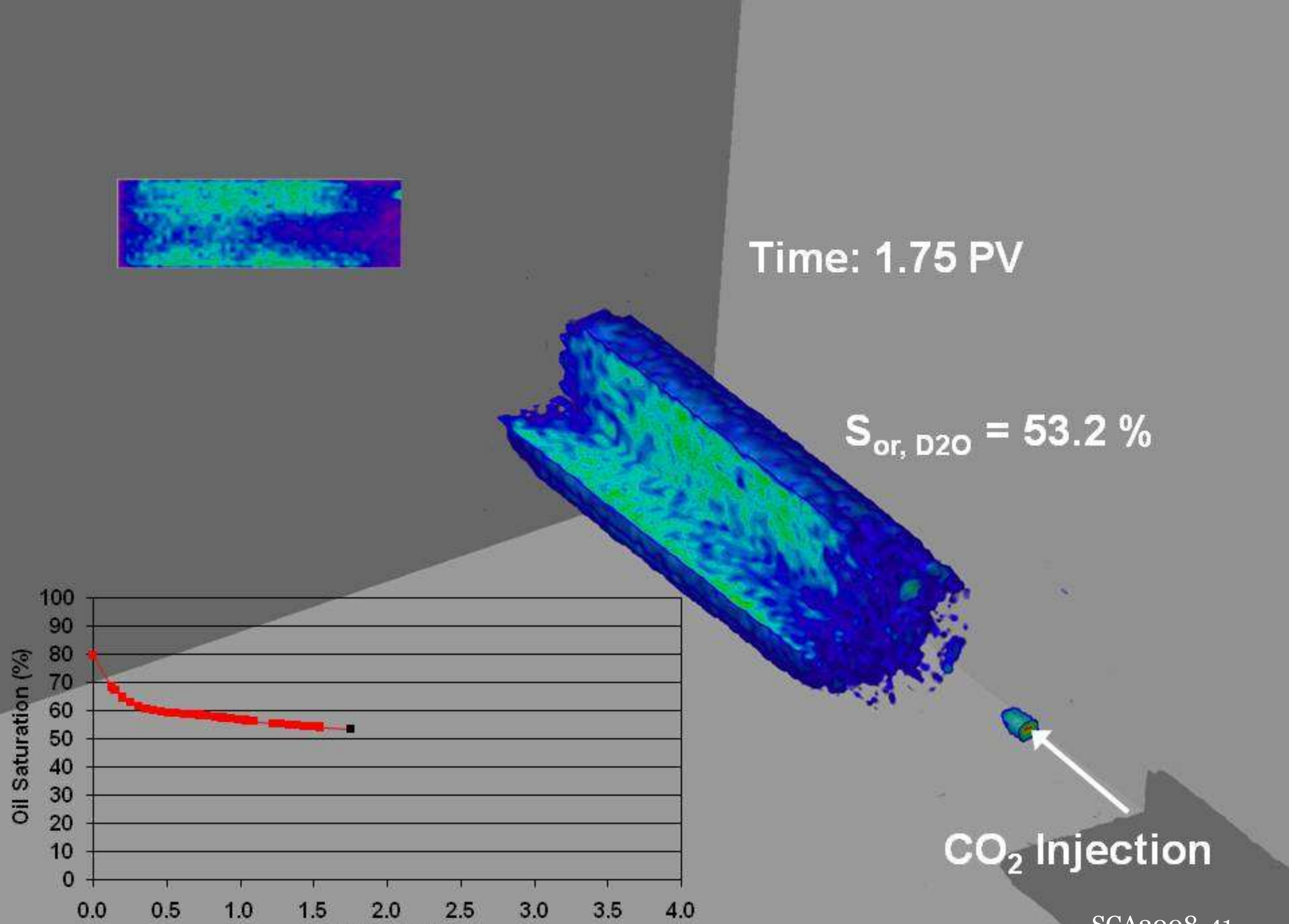


Time: 1.49 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

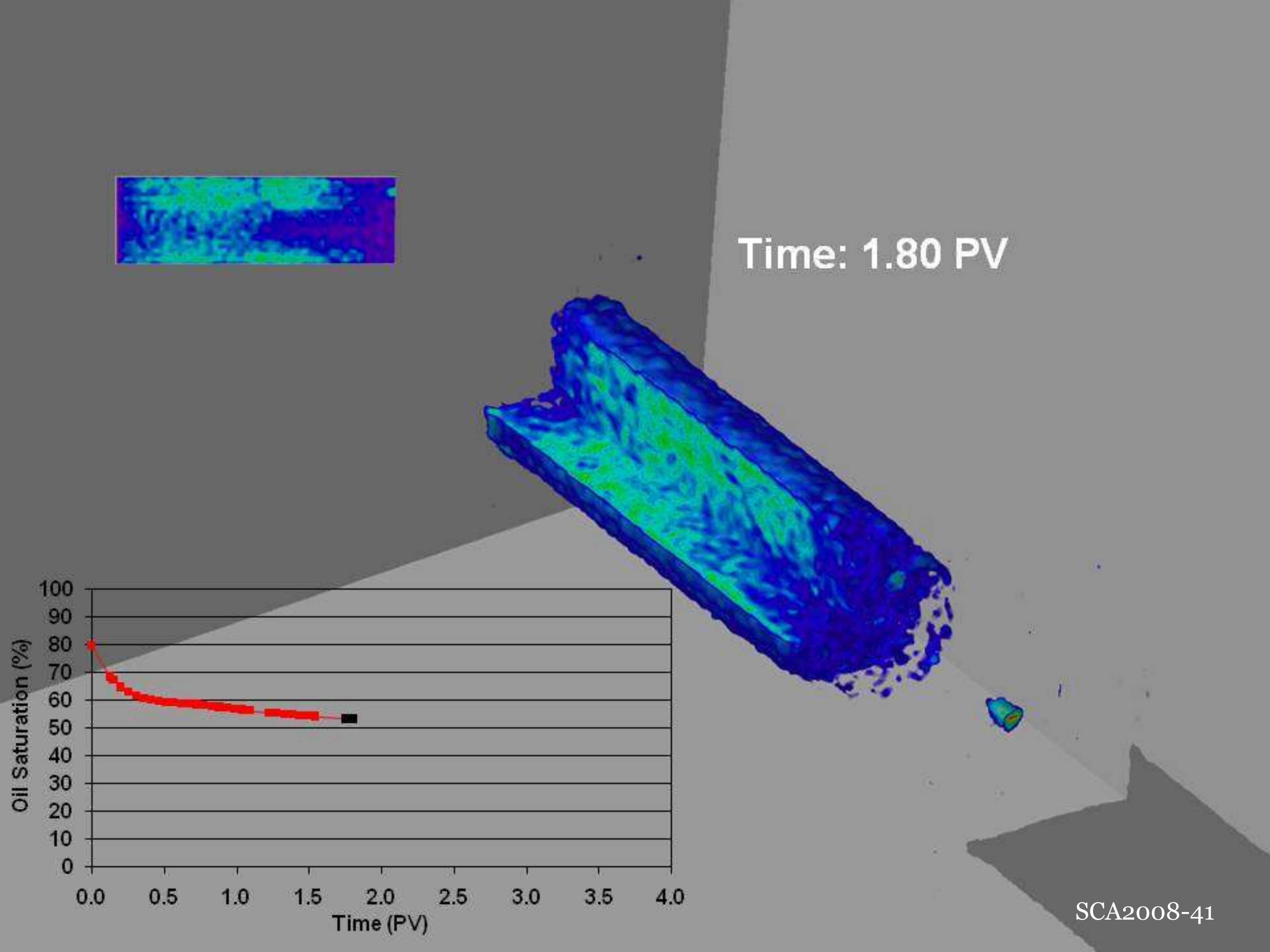

Time: 1.54 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

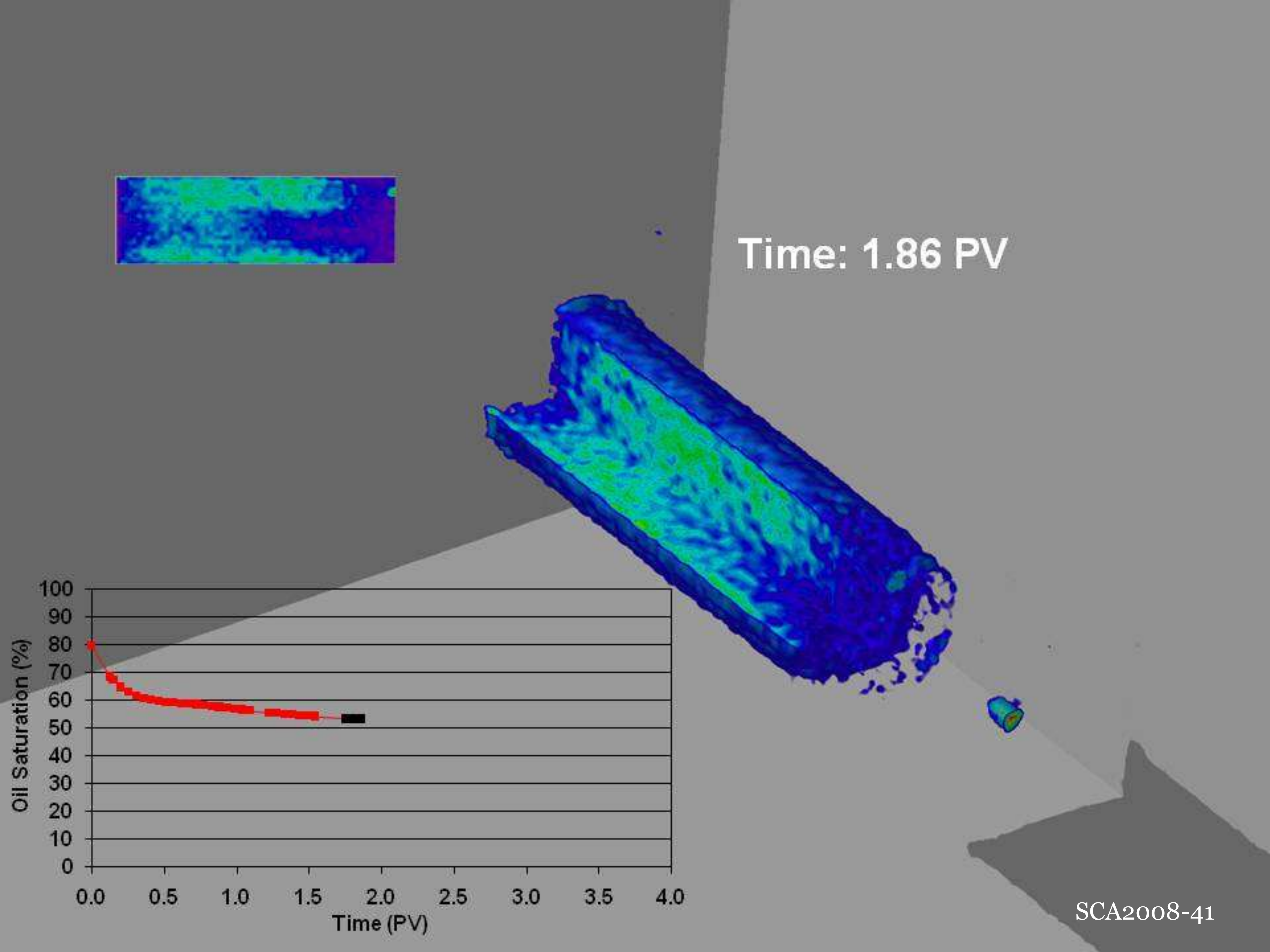


Time: 1.75 PV
$S_{or,\ D2O}$ = 53.2 %
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

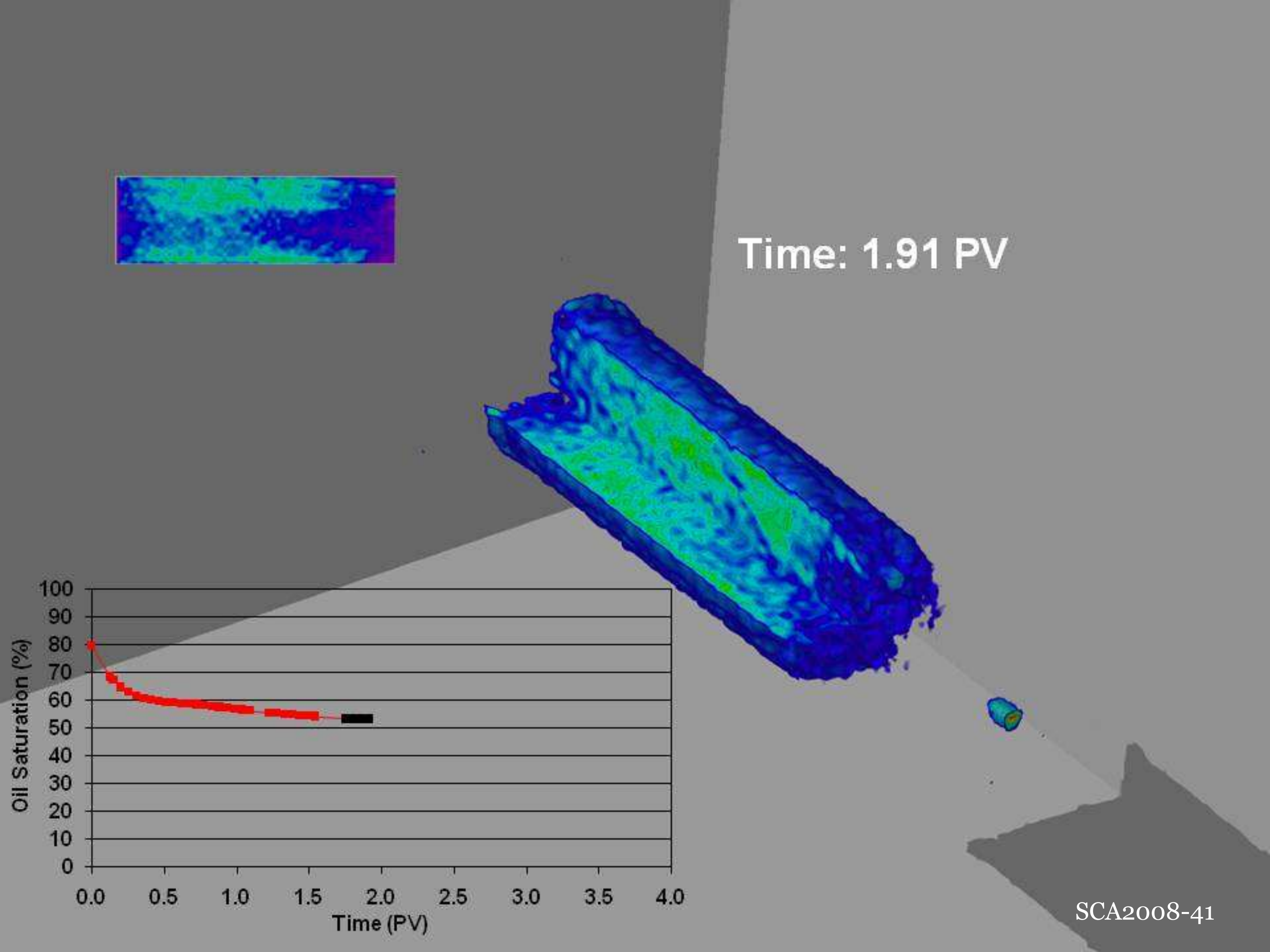


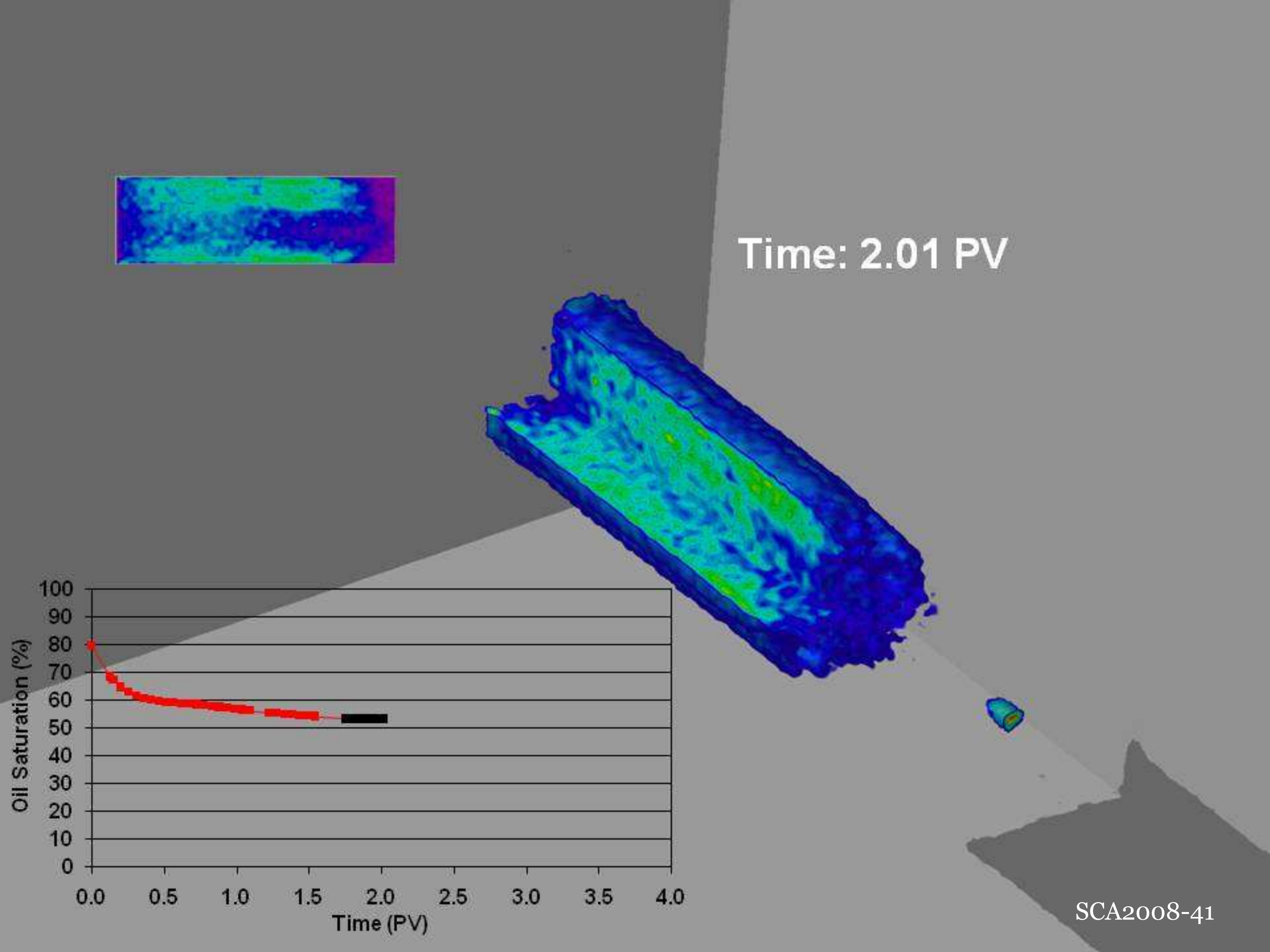
Time: 1.75 PV
$S_{or, D2O}$ = 53.2 %
CO_2 Injection
Oil Saturation (%)
Time (PV)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

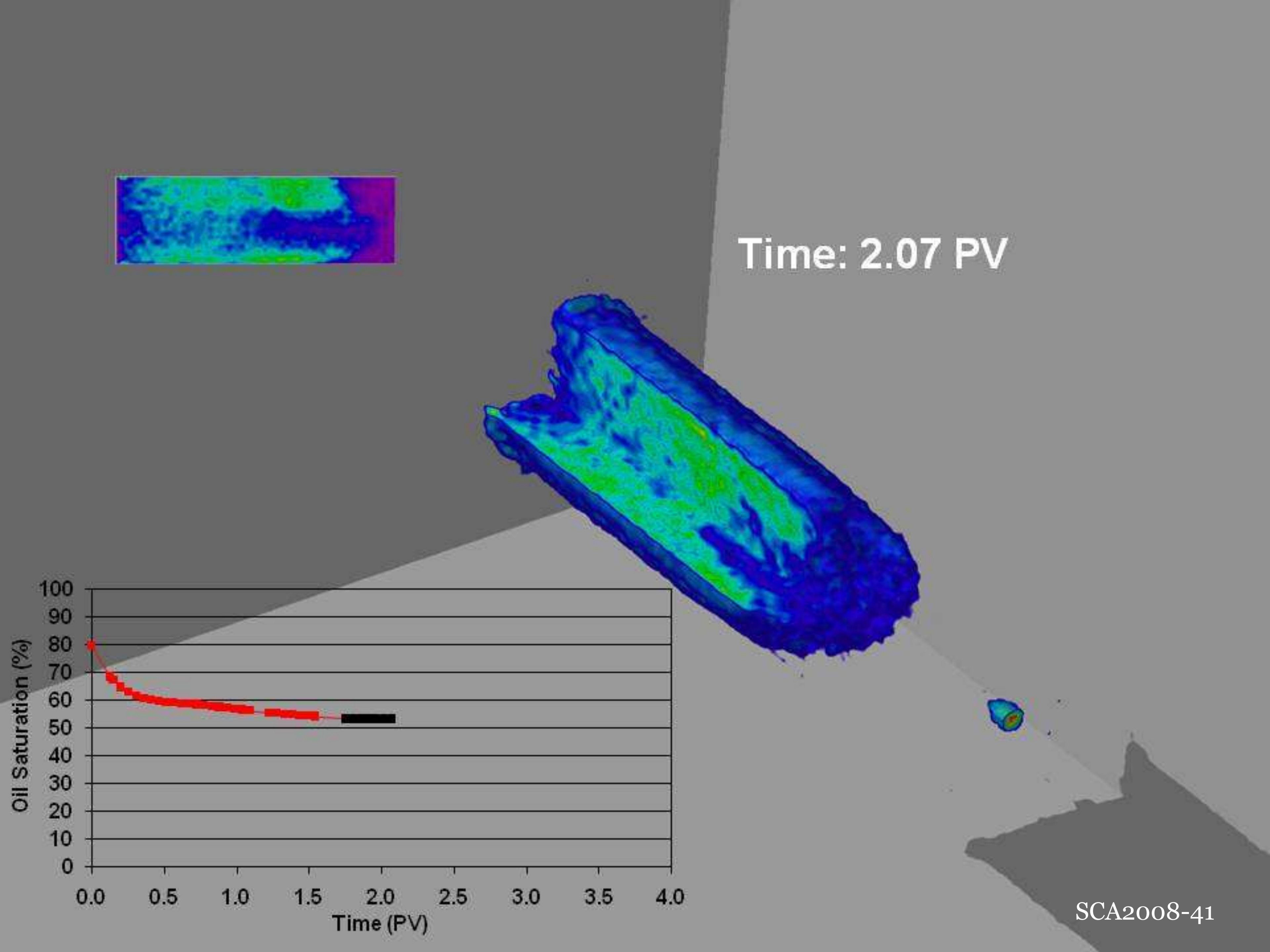

Time: 1.80 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

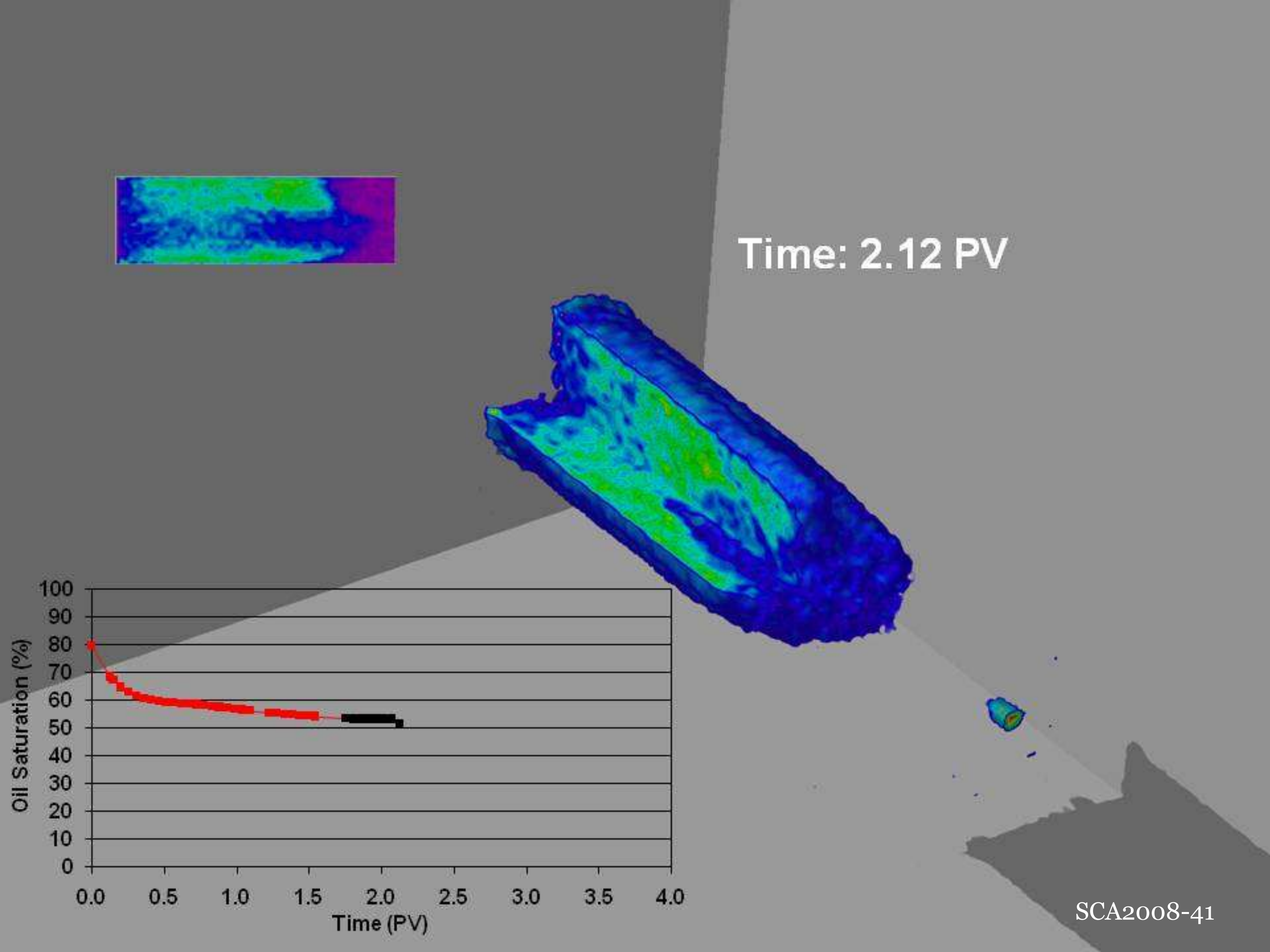


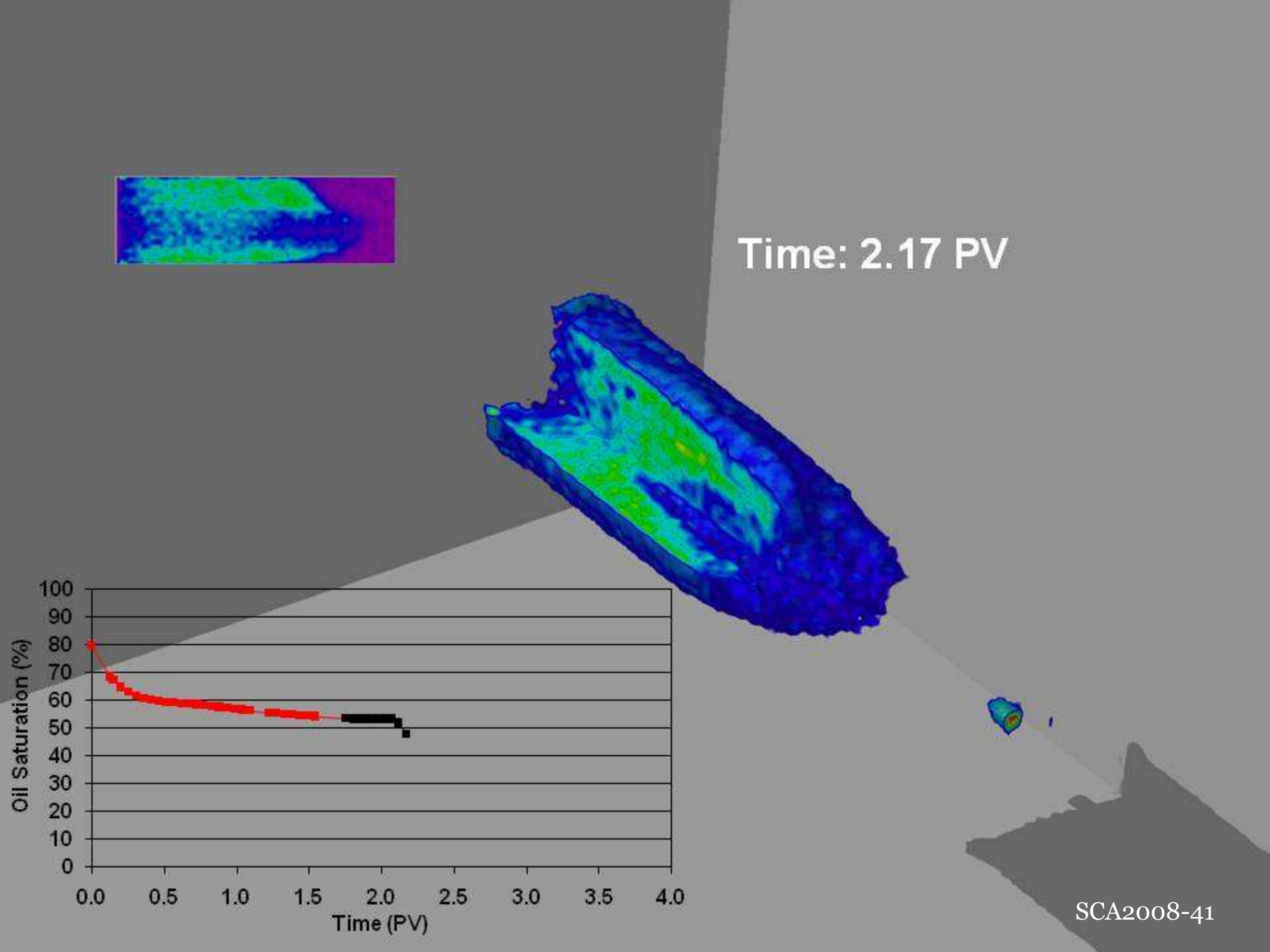
Time: 1.86 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

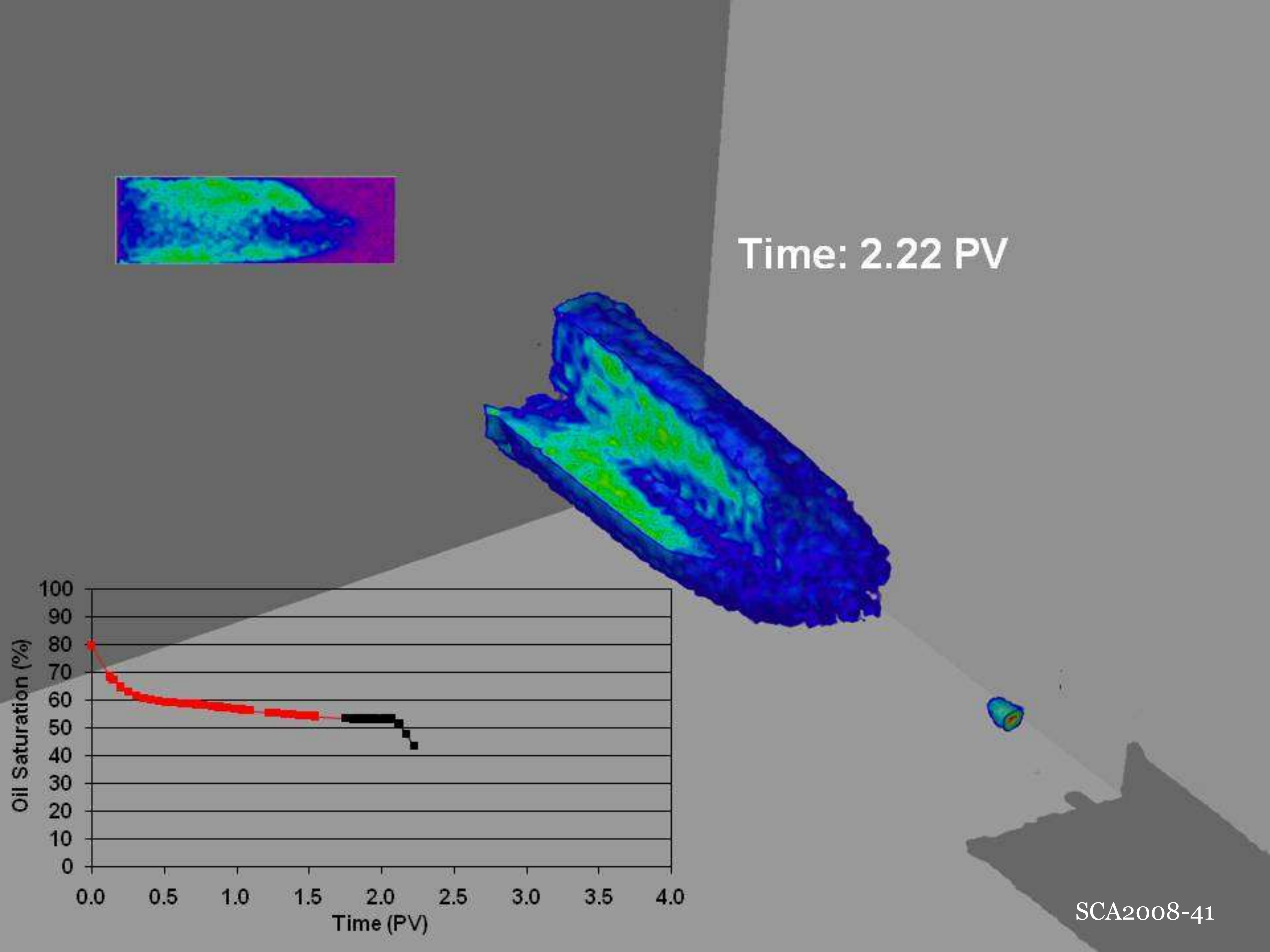

Time: 1.91 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

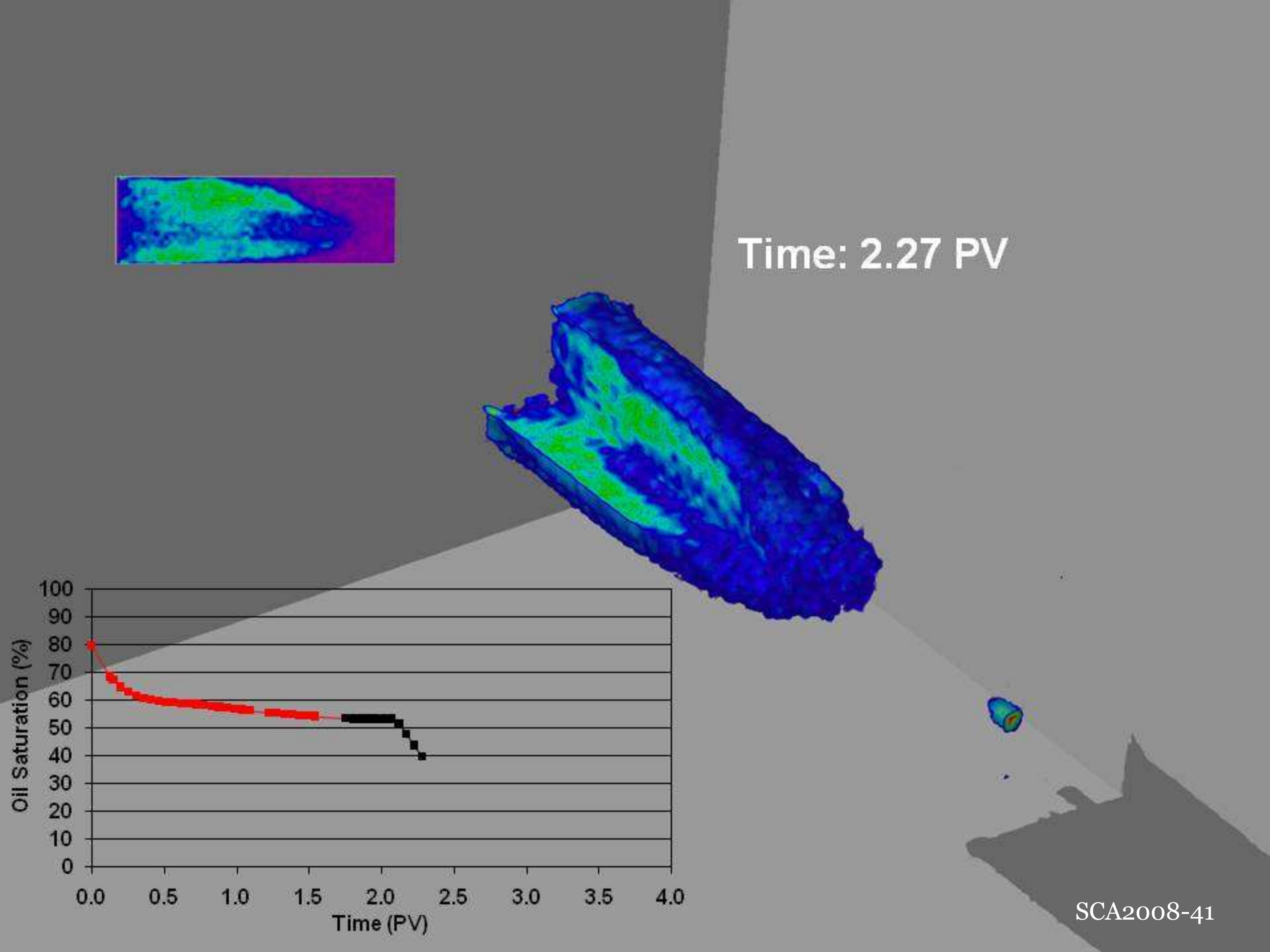

Time: 2.01 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 2.07 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

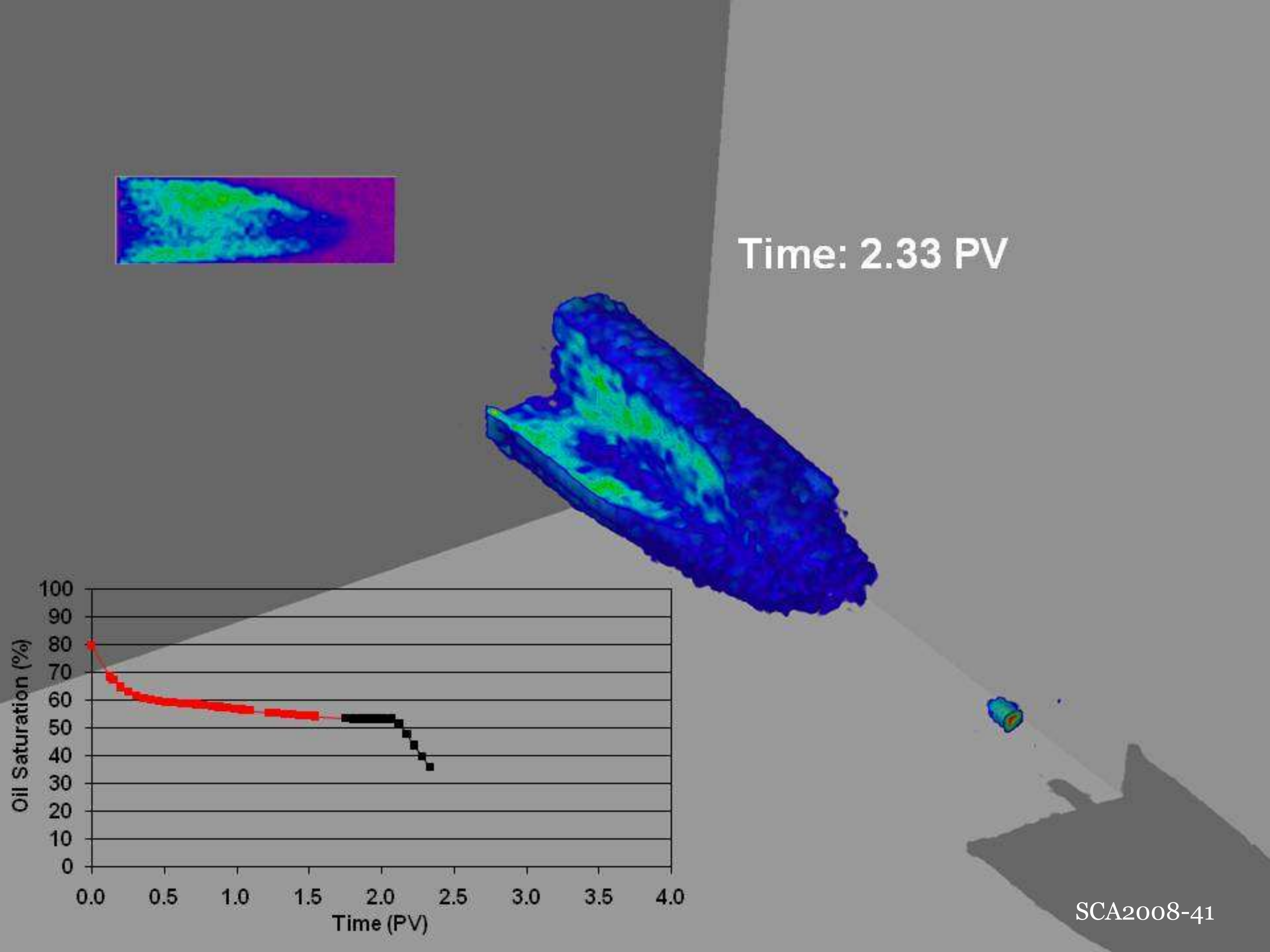

Time: 2.12 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

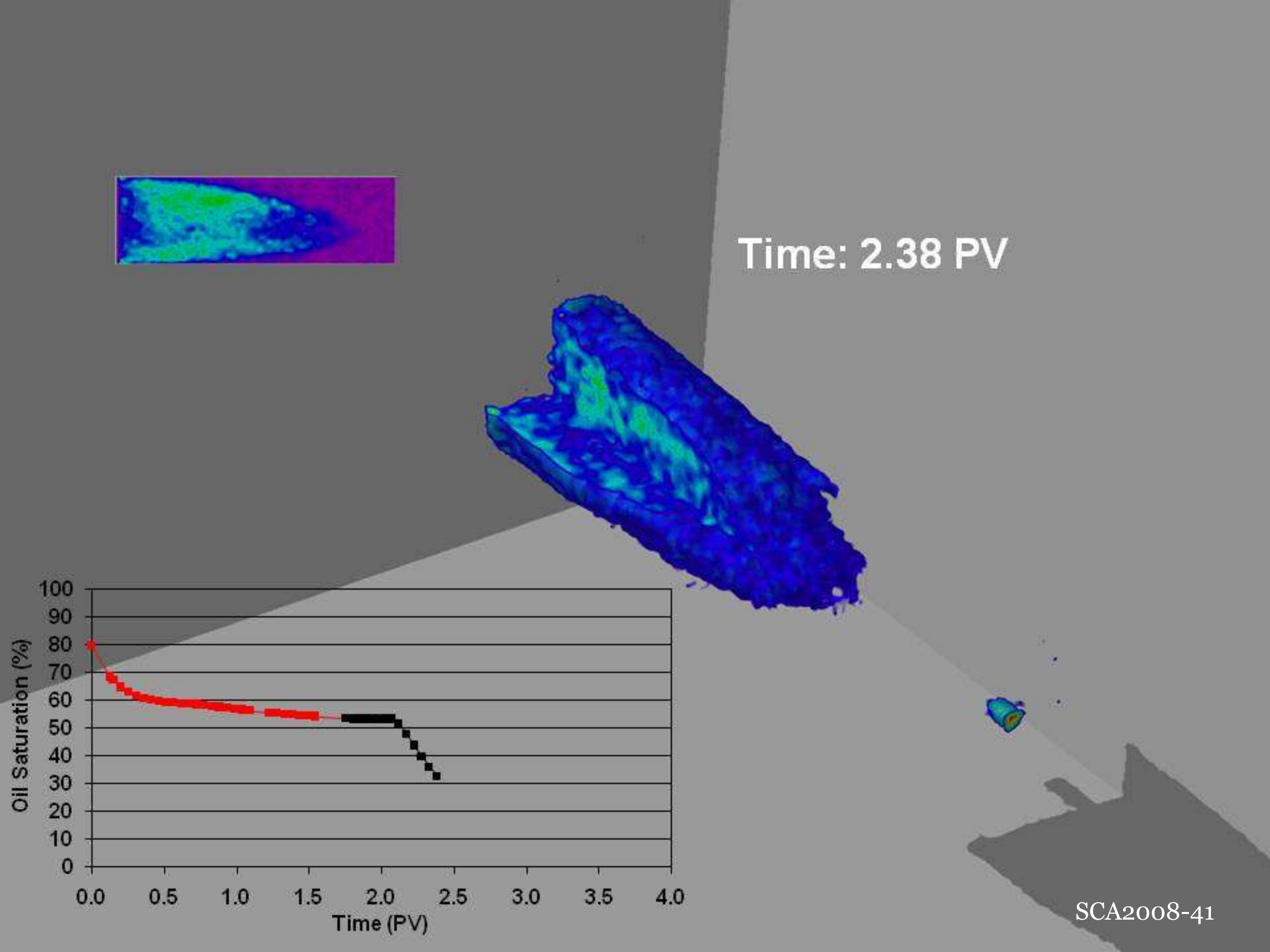

Time: 2.17 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 2.22 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

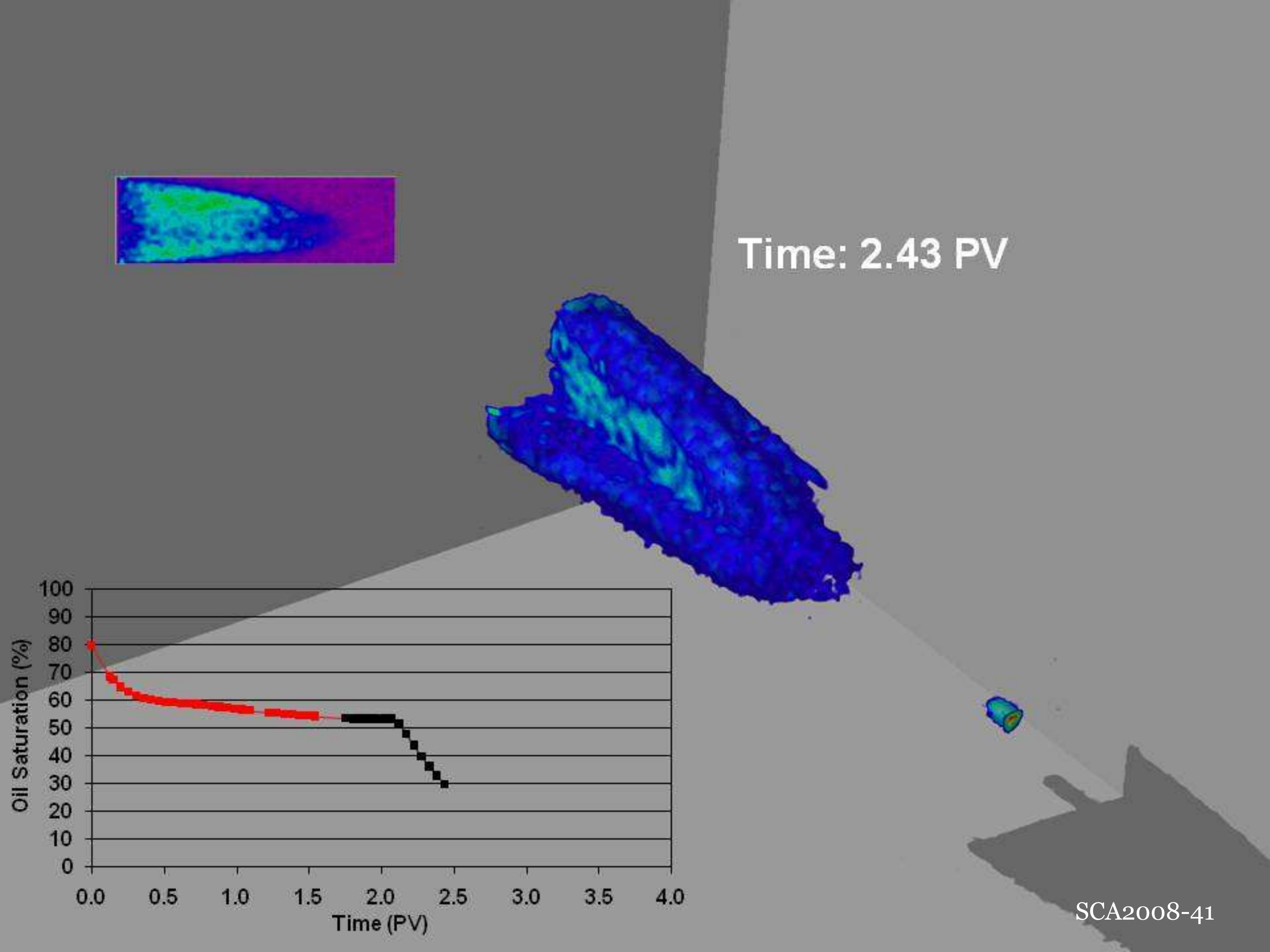


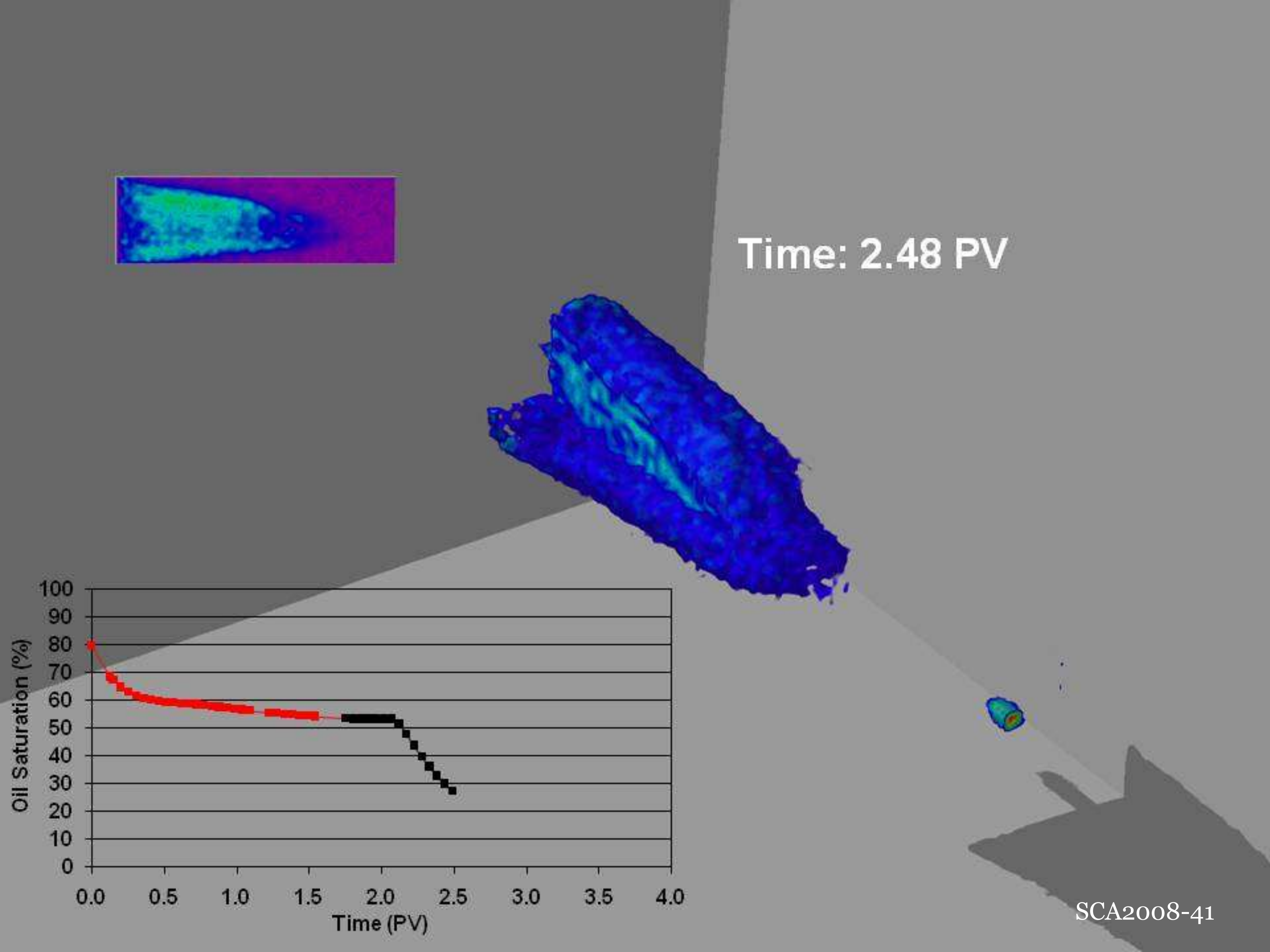
Time: 2.27 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

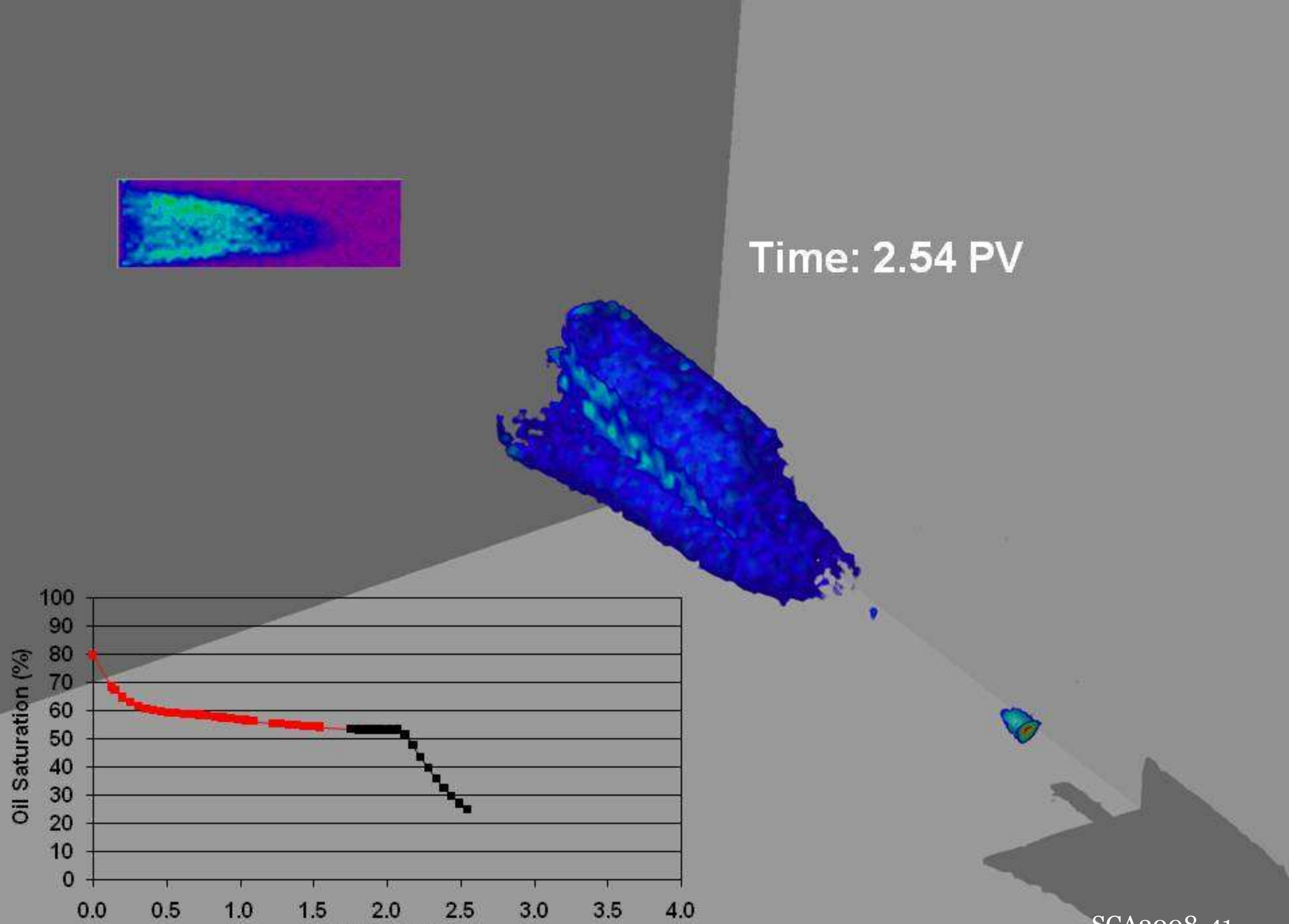

Time: 2.33 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

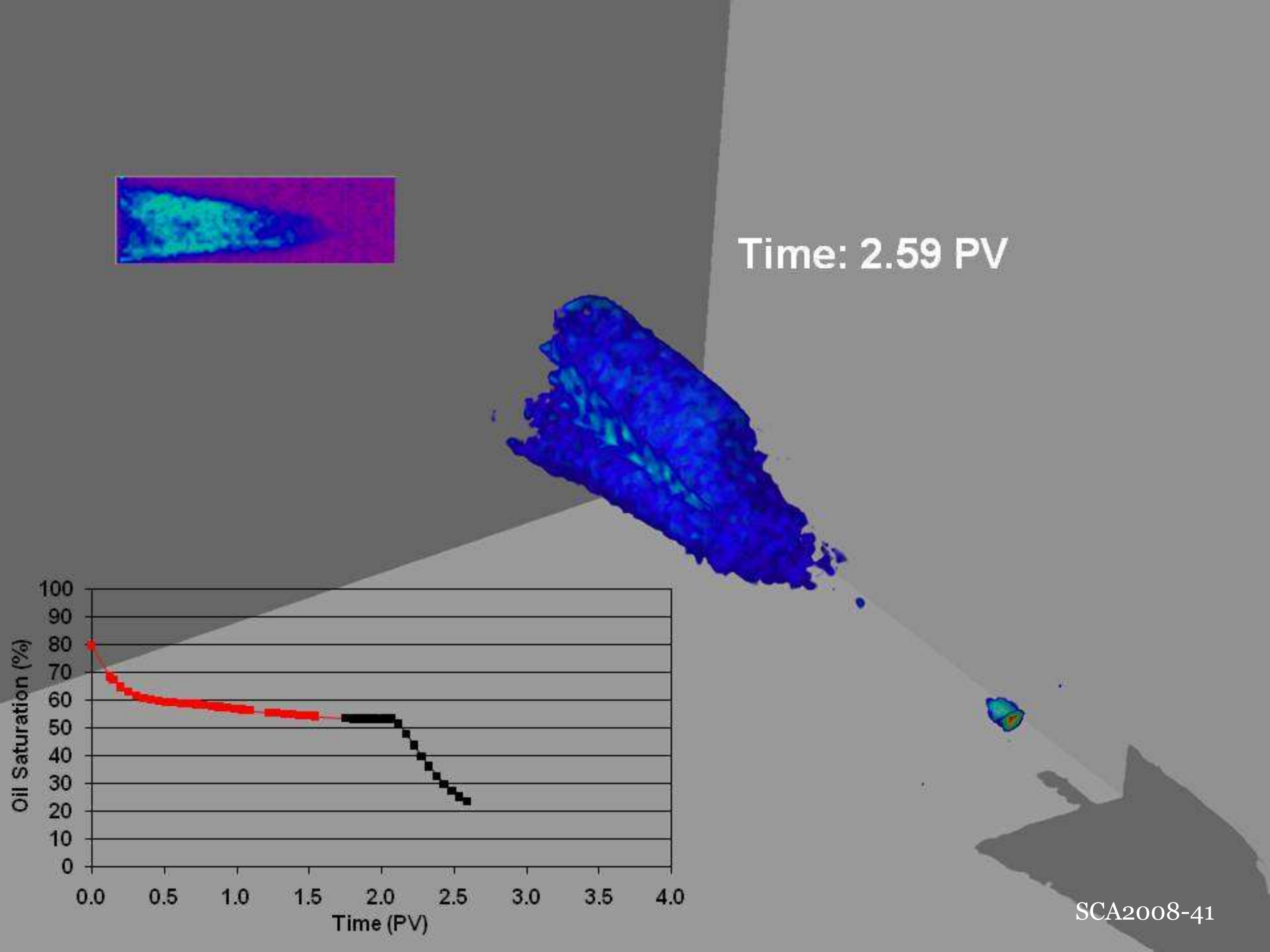


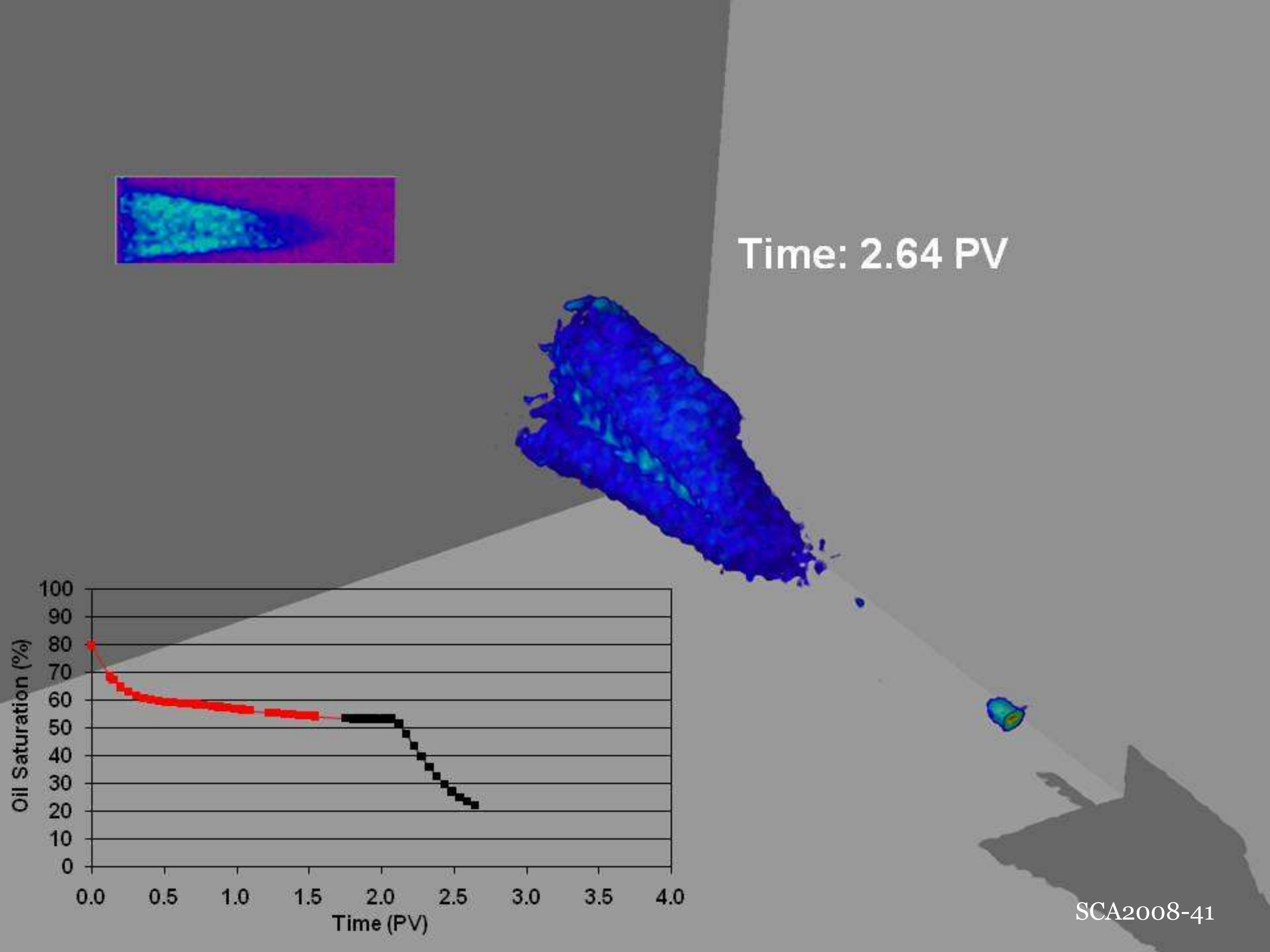
Time: 2.38 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

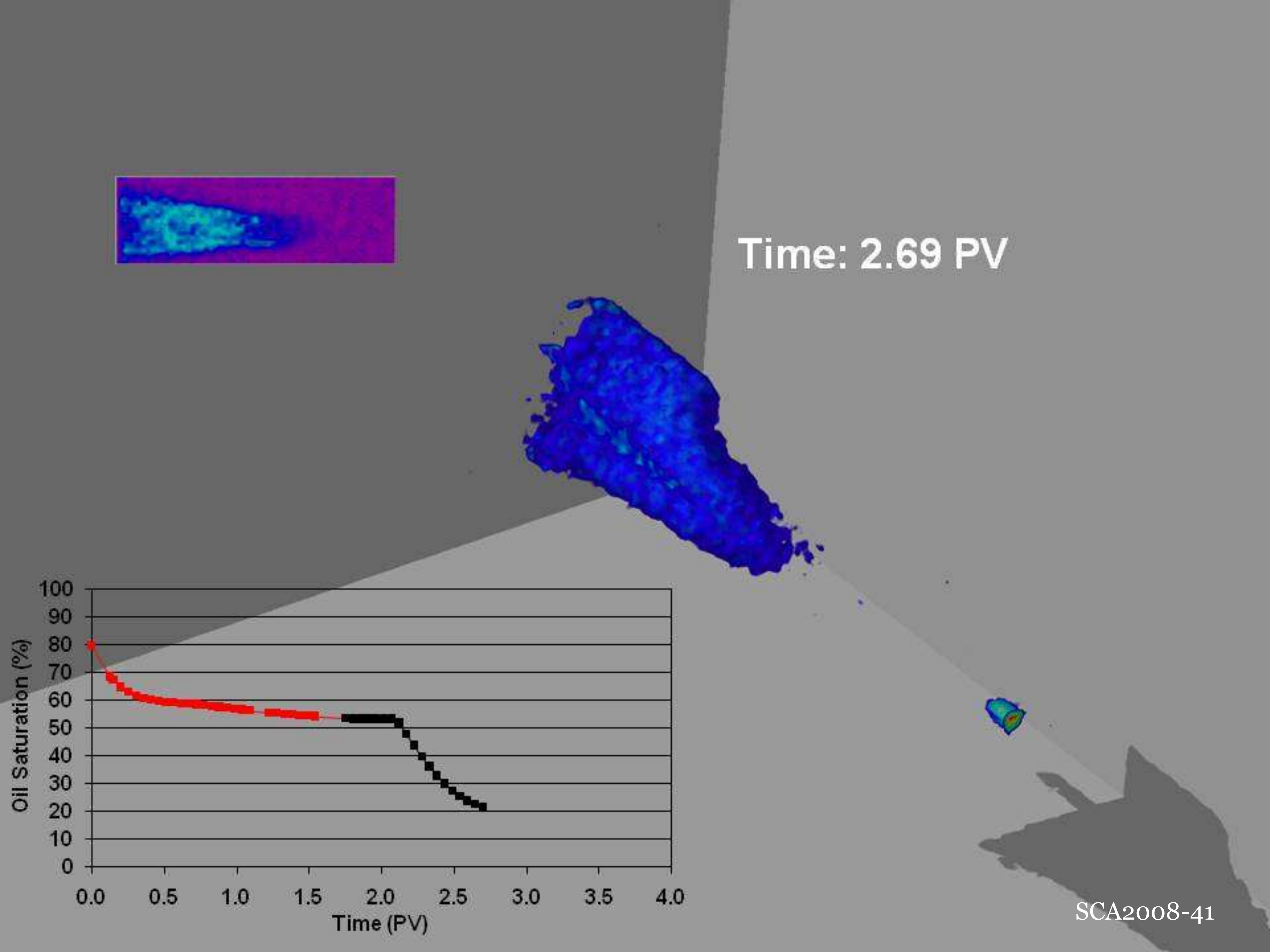

Time: 2.43 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

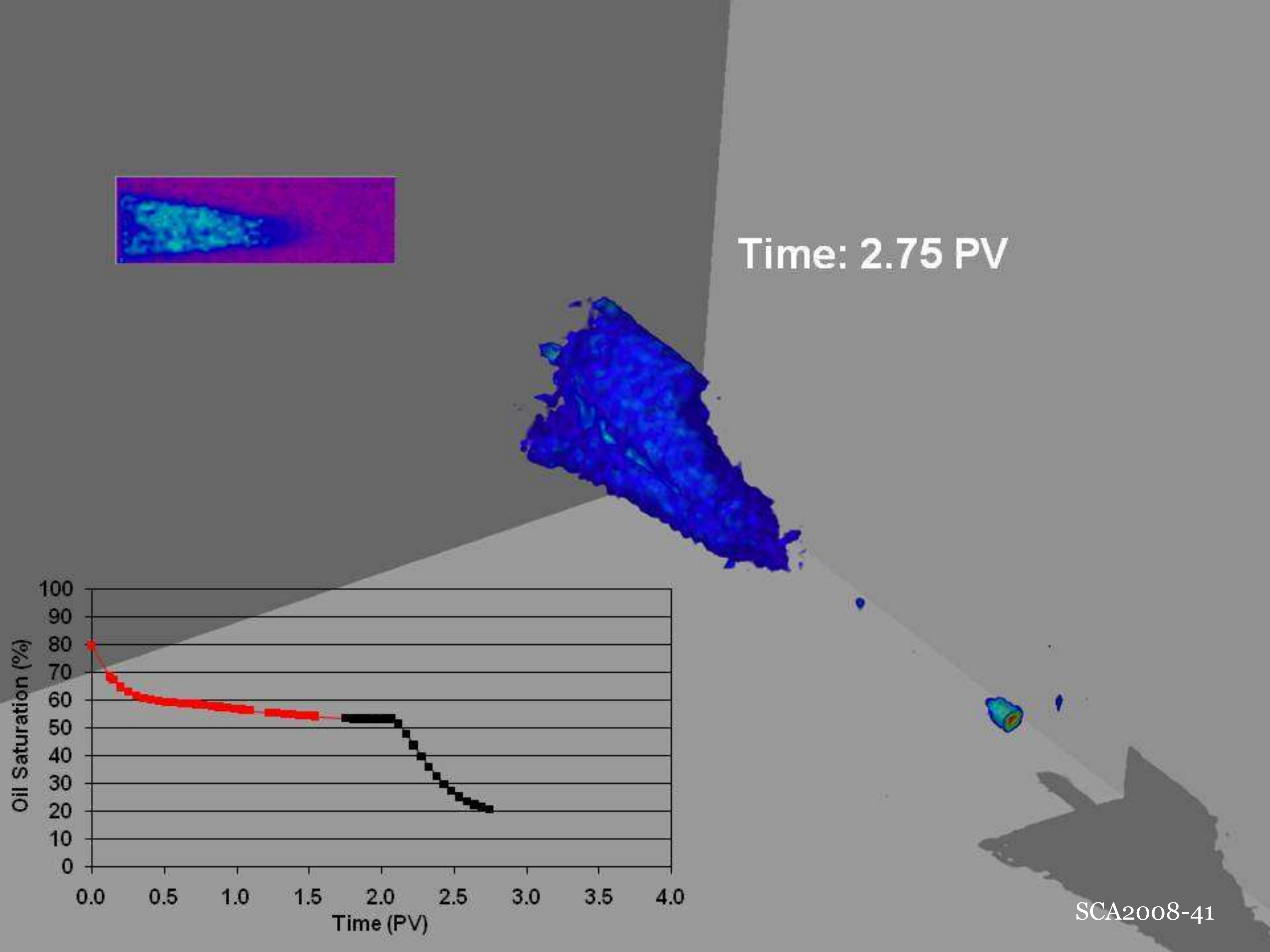

Time: 2.48 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

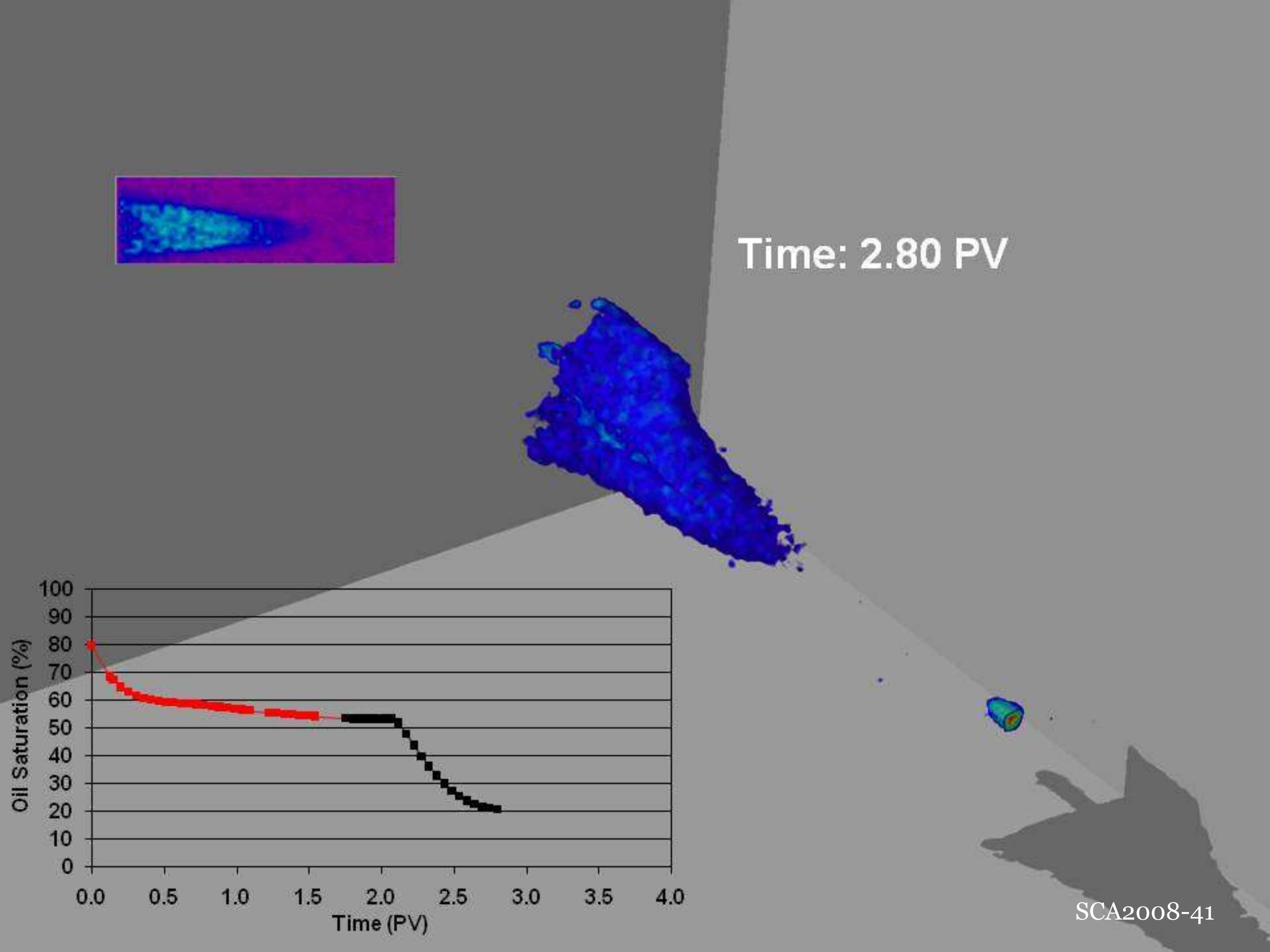

Time: 2.54 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

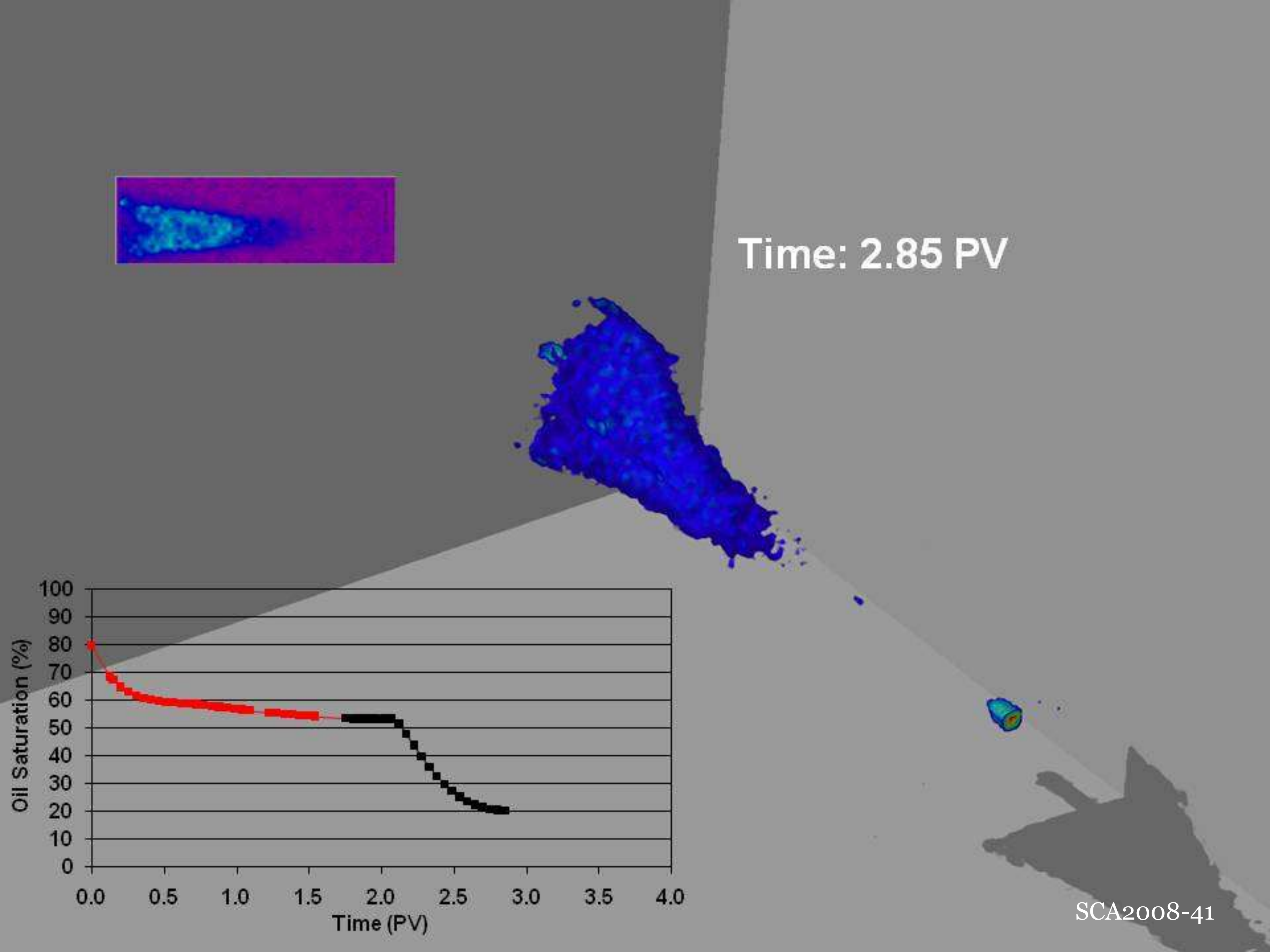

Time: 2.59 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

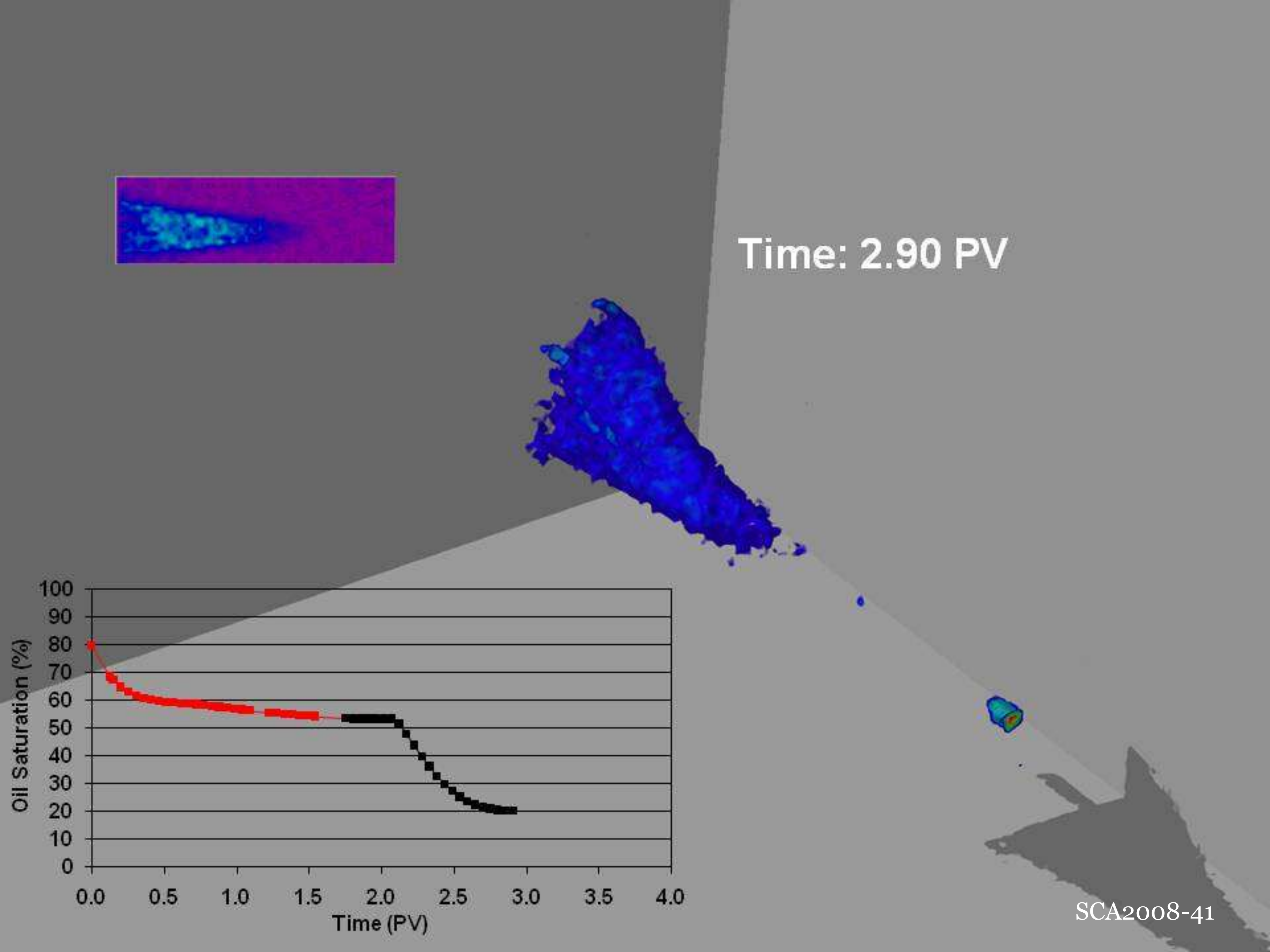

Time: 2.64 PV
Oil Saturation (%)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

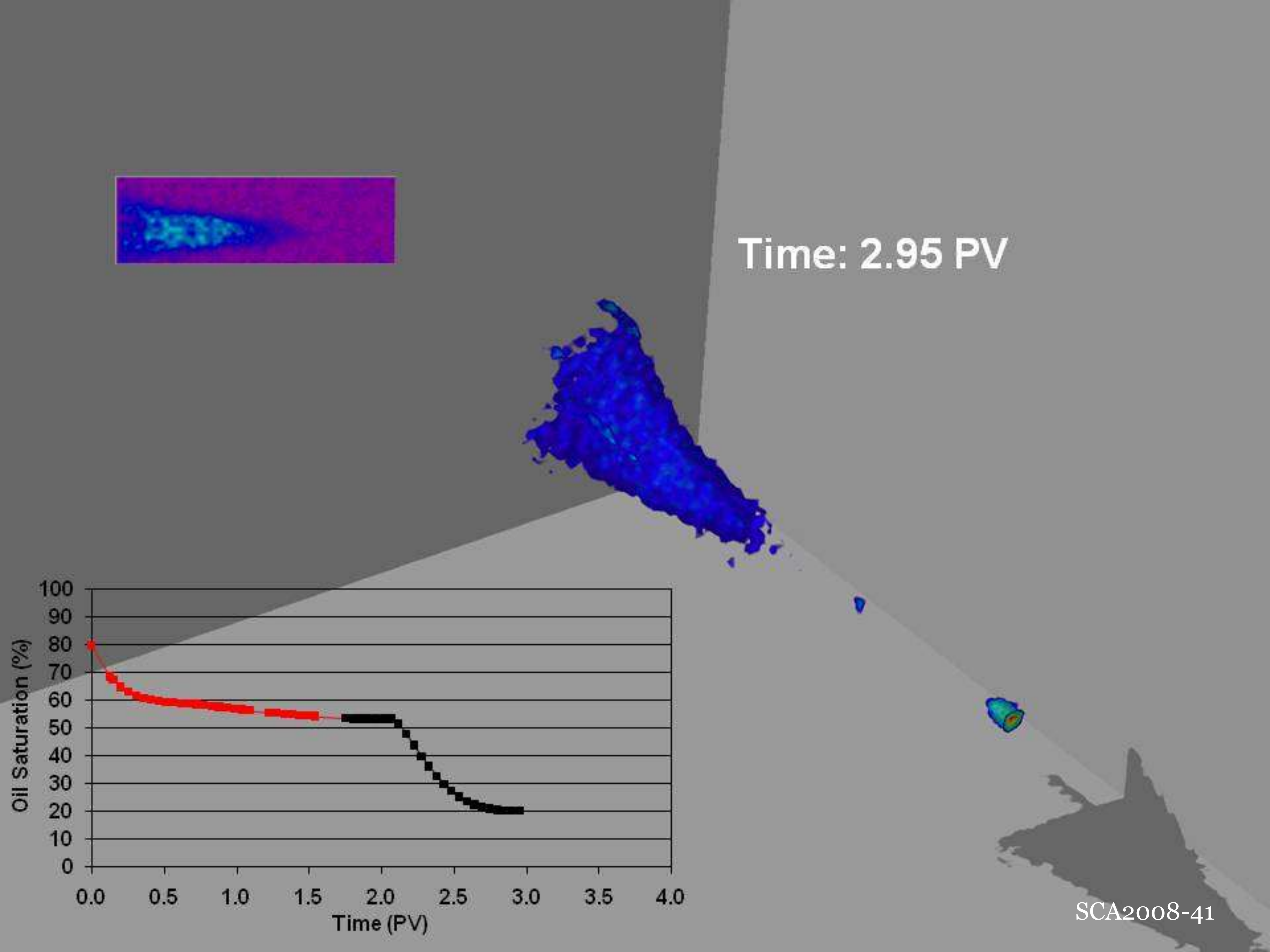

Time: 2.69 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 2.75 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

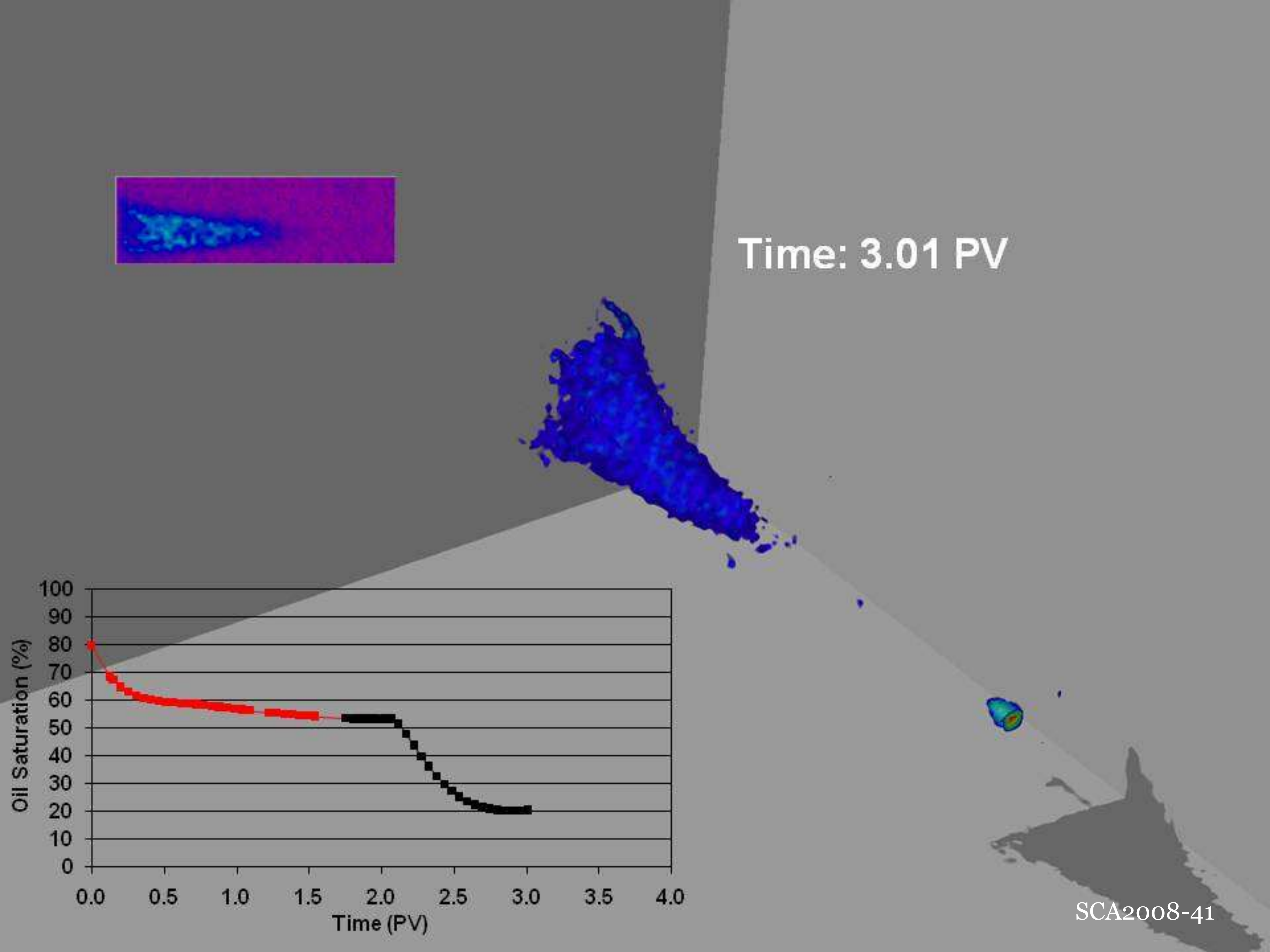

Time: 2.80 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

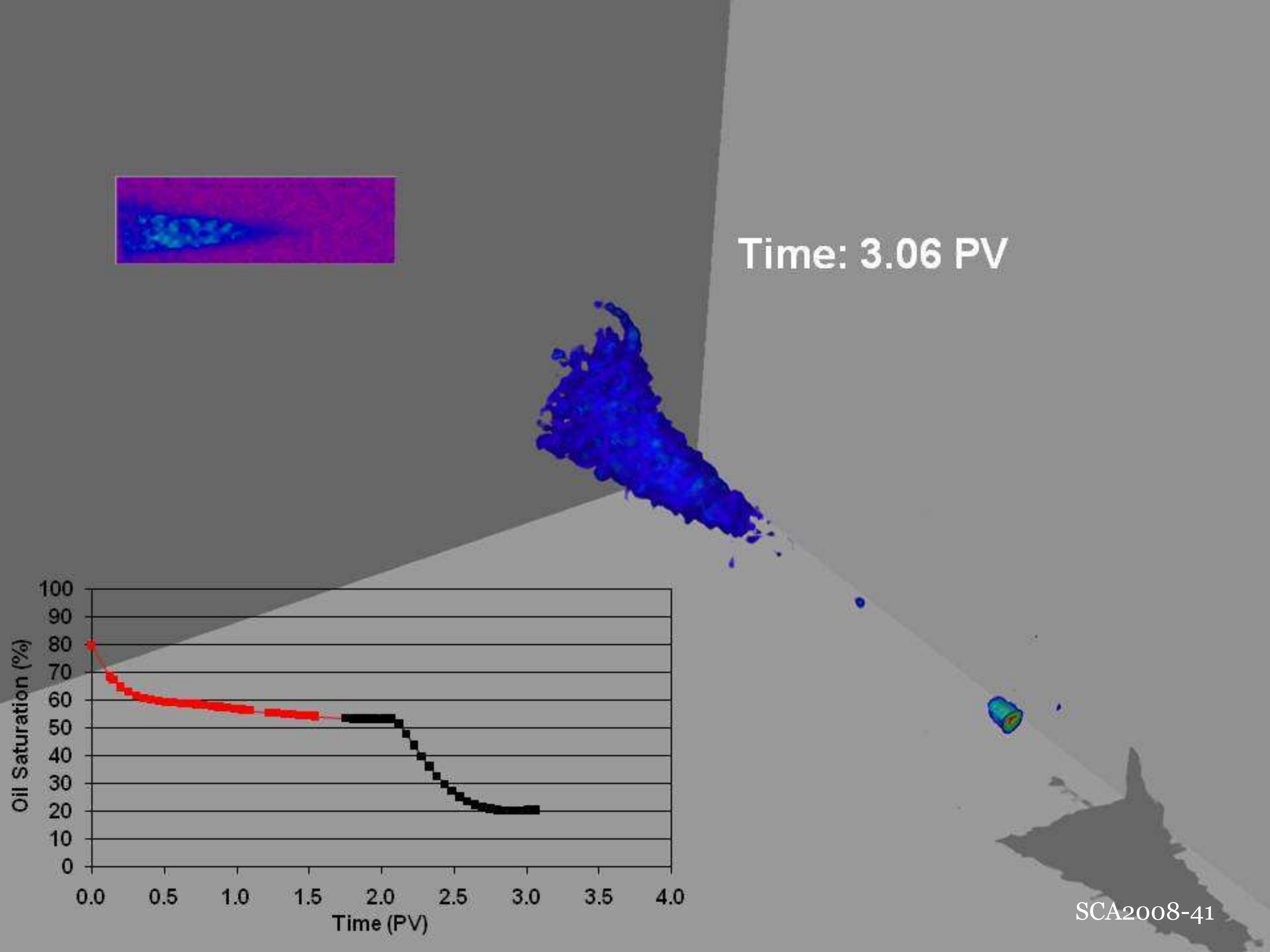

Time: 2.85 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

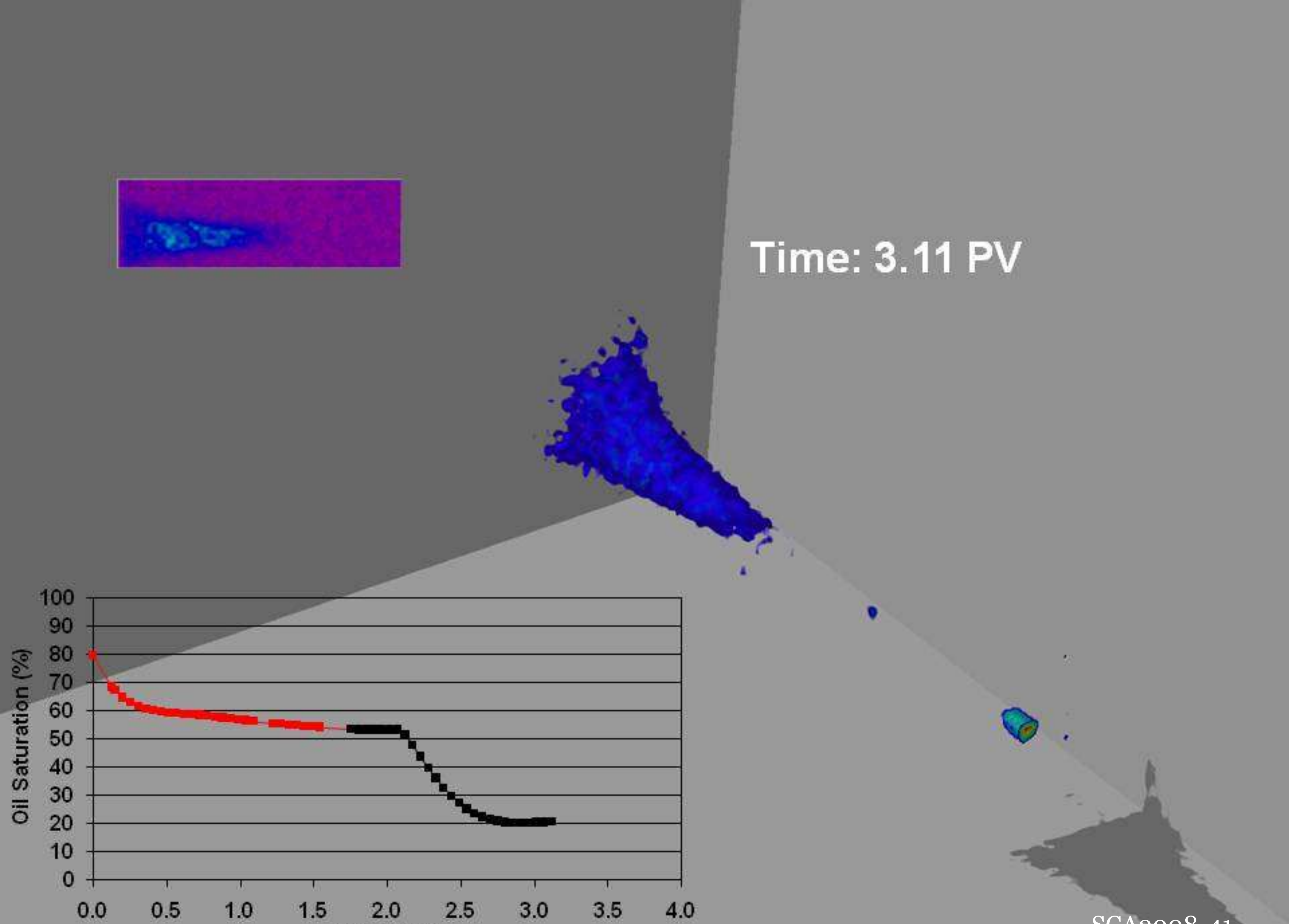

Time: 2.90 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)



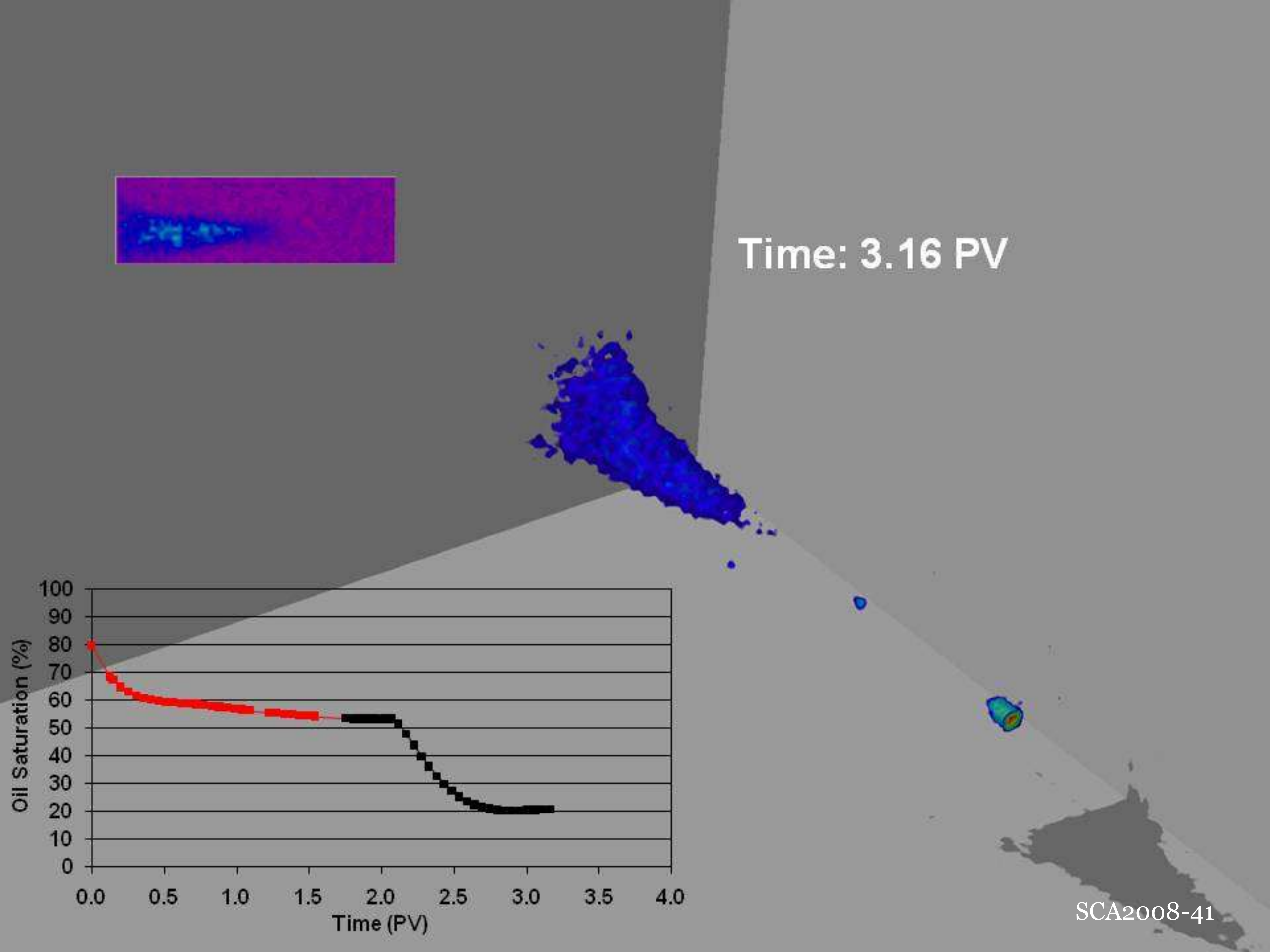
Time: 2.95 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 3.01 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

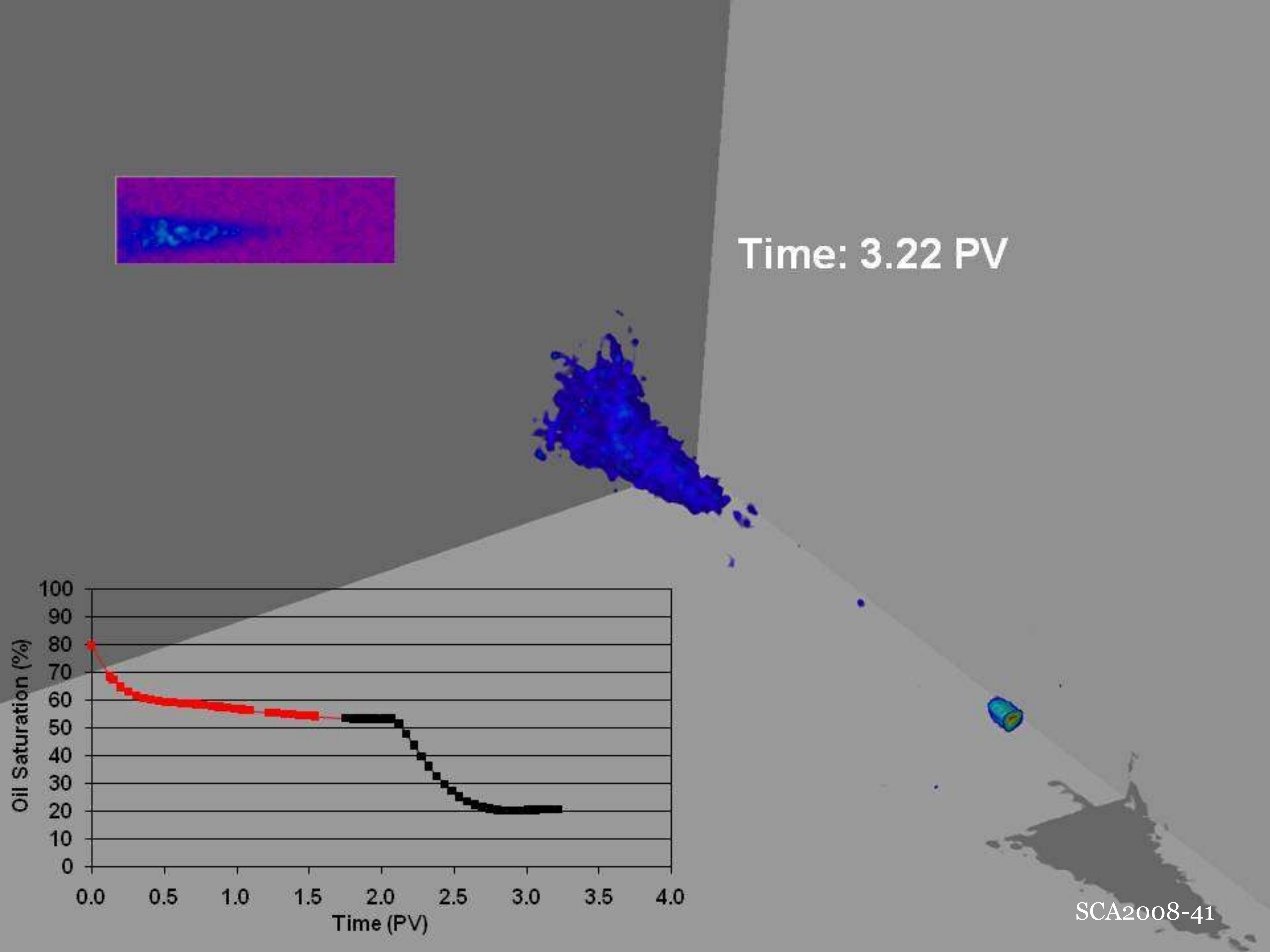

Time: 3.06 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)



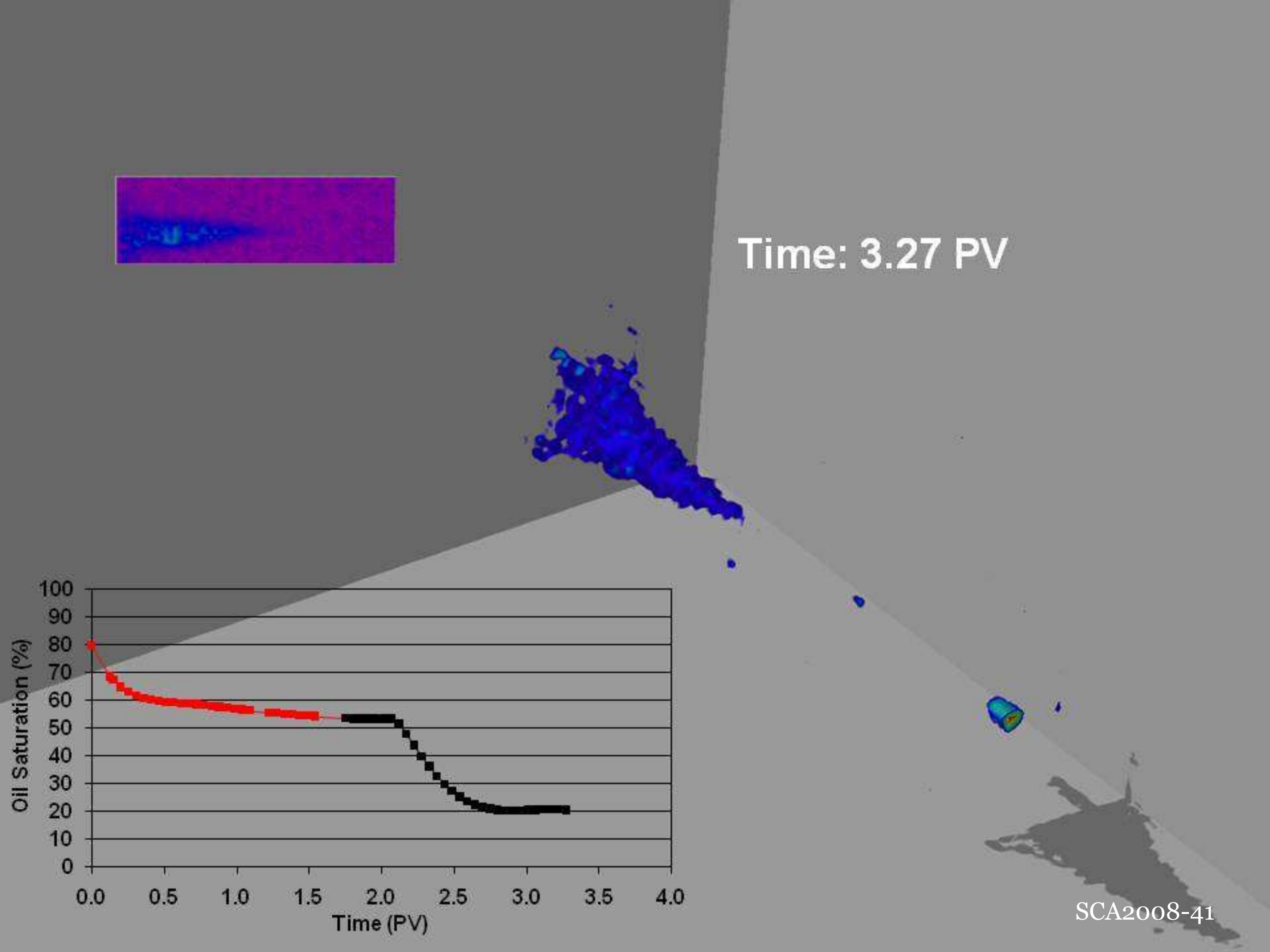
Time: 3.11 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

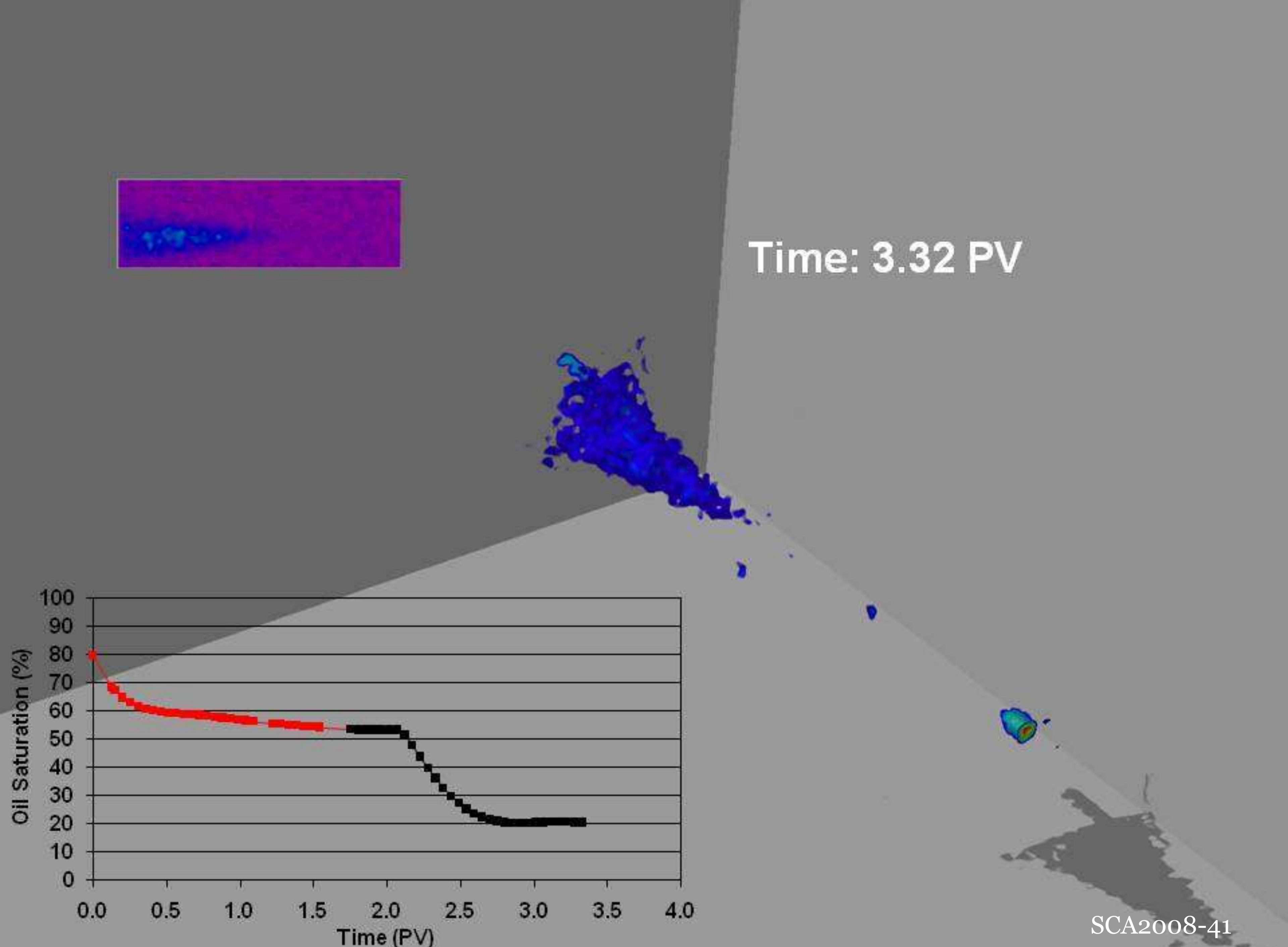


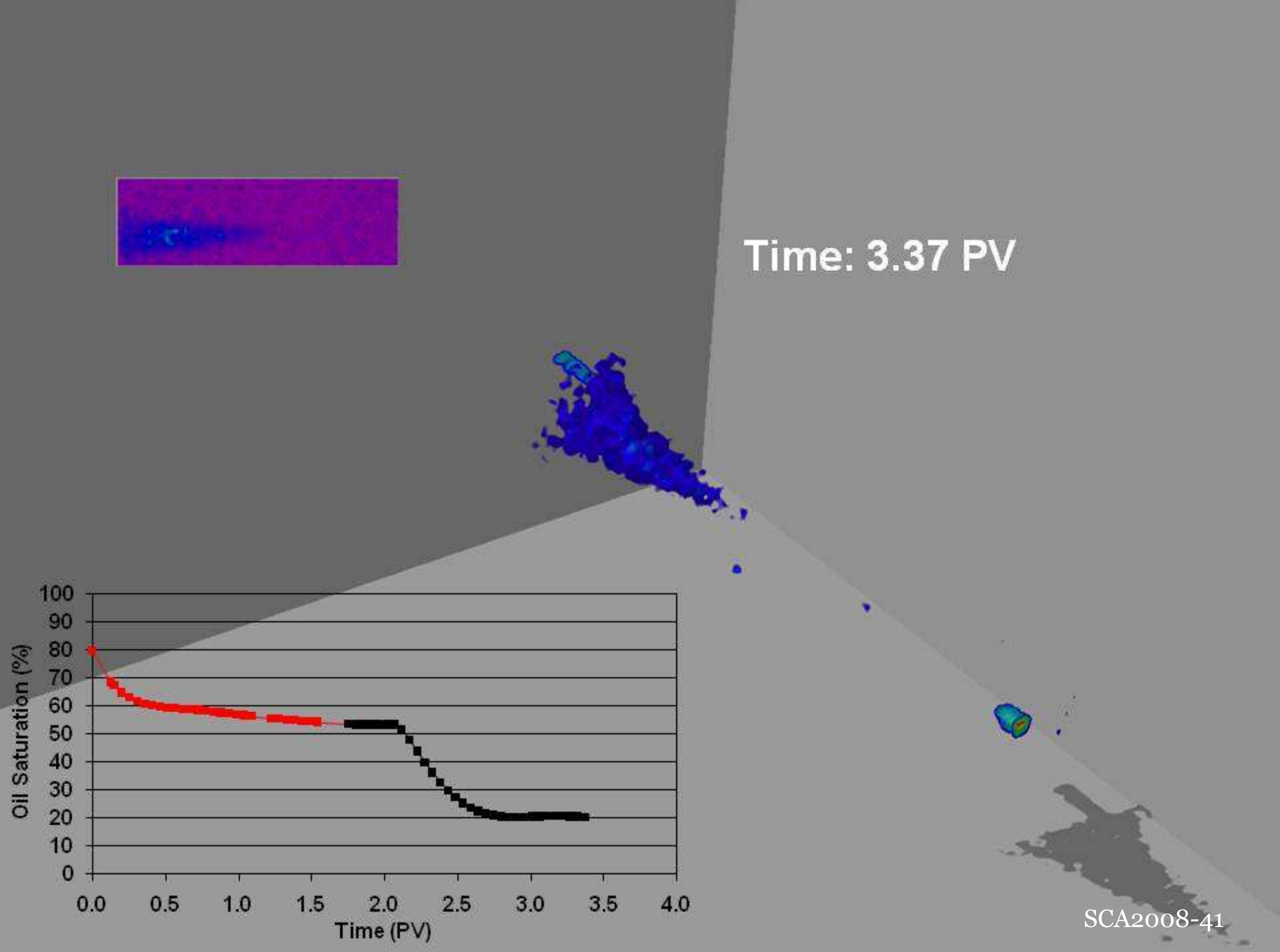
Time: 3.16 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

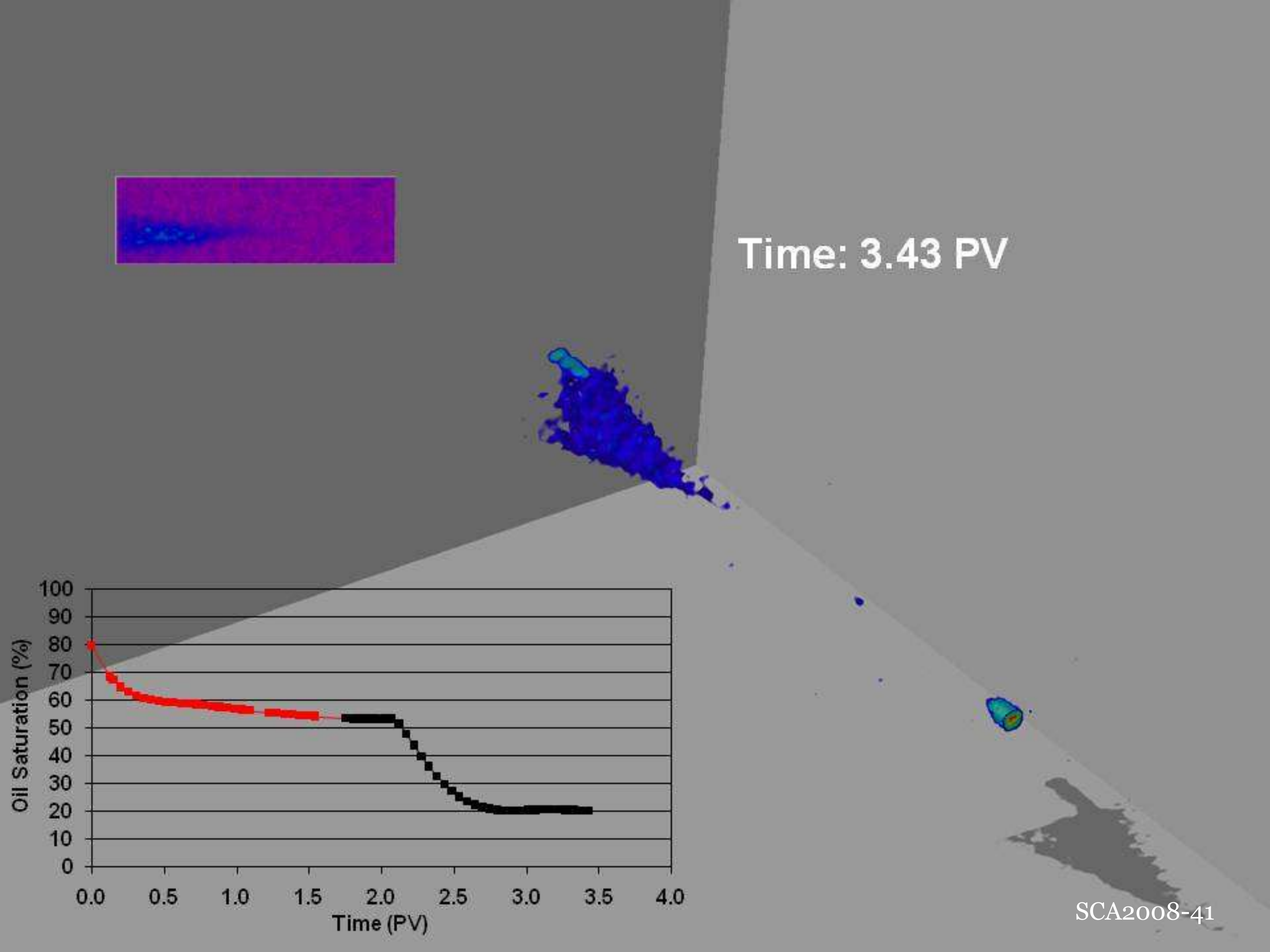


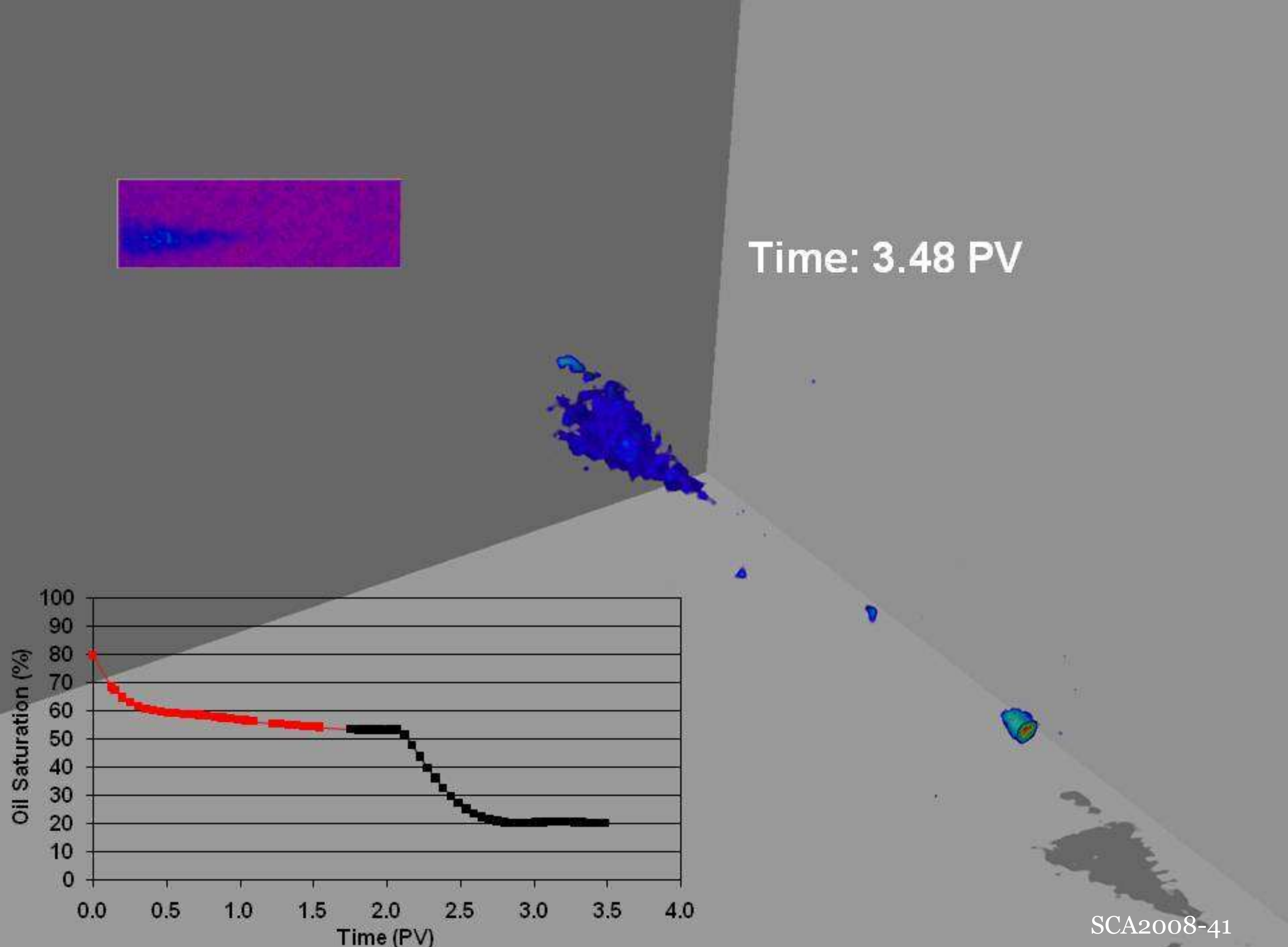
Time: 3.22 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

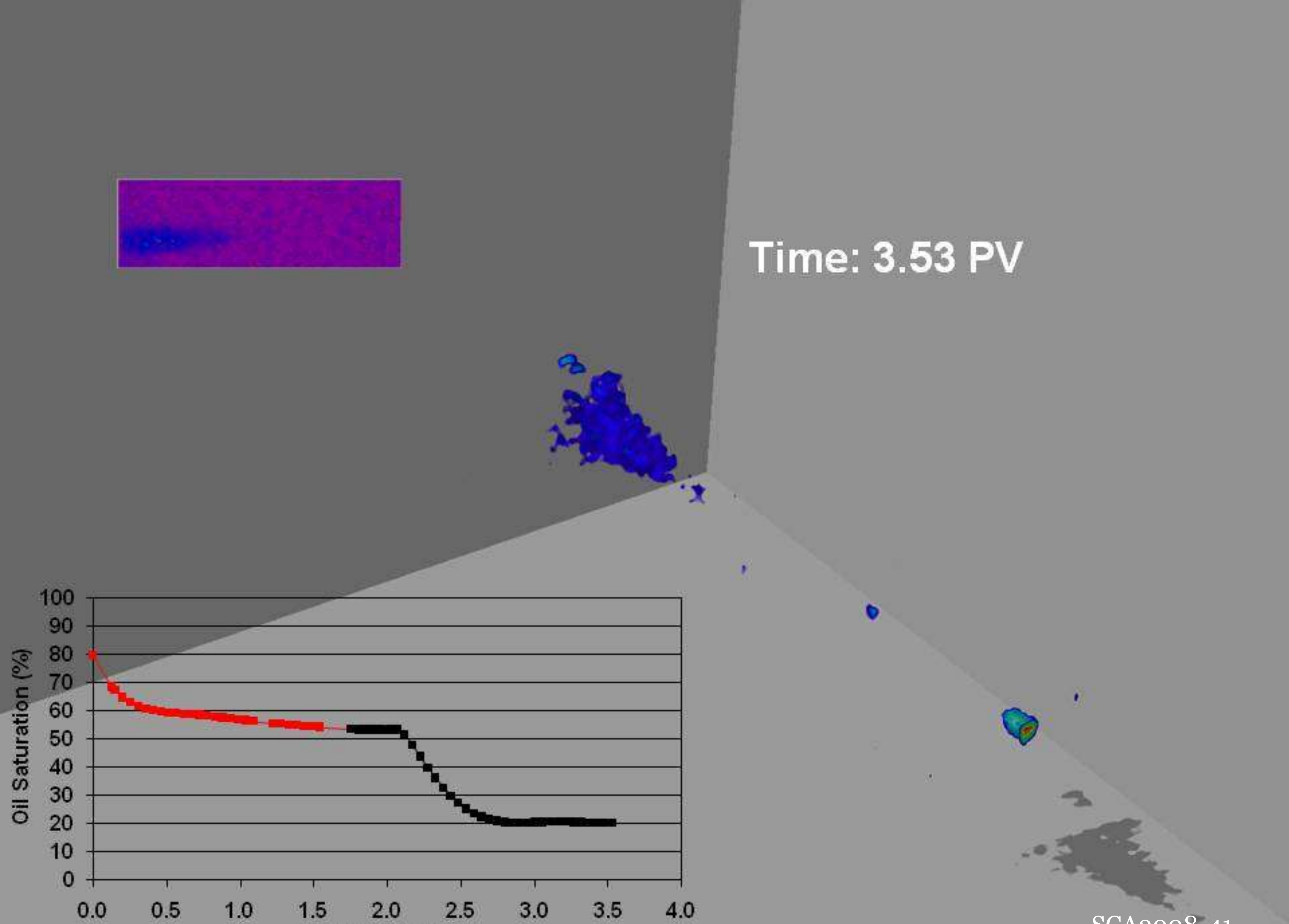

Time: 3.27 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

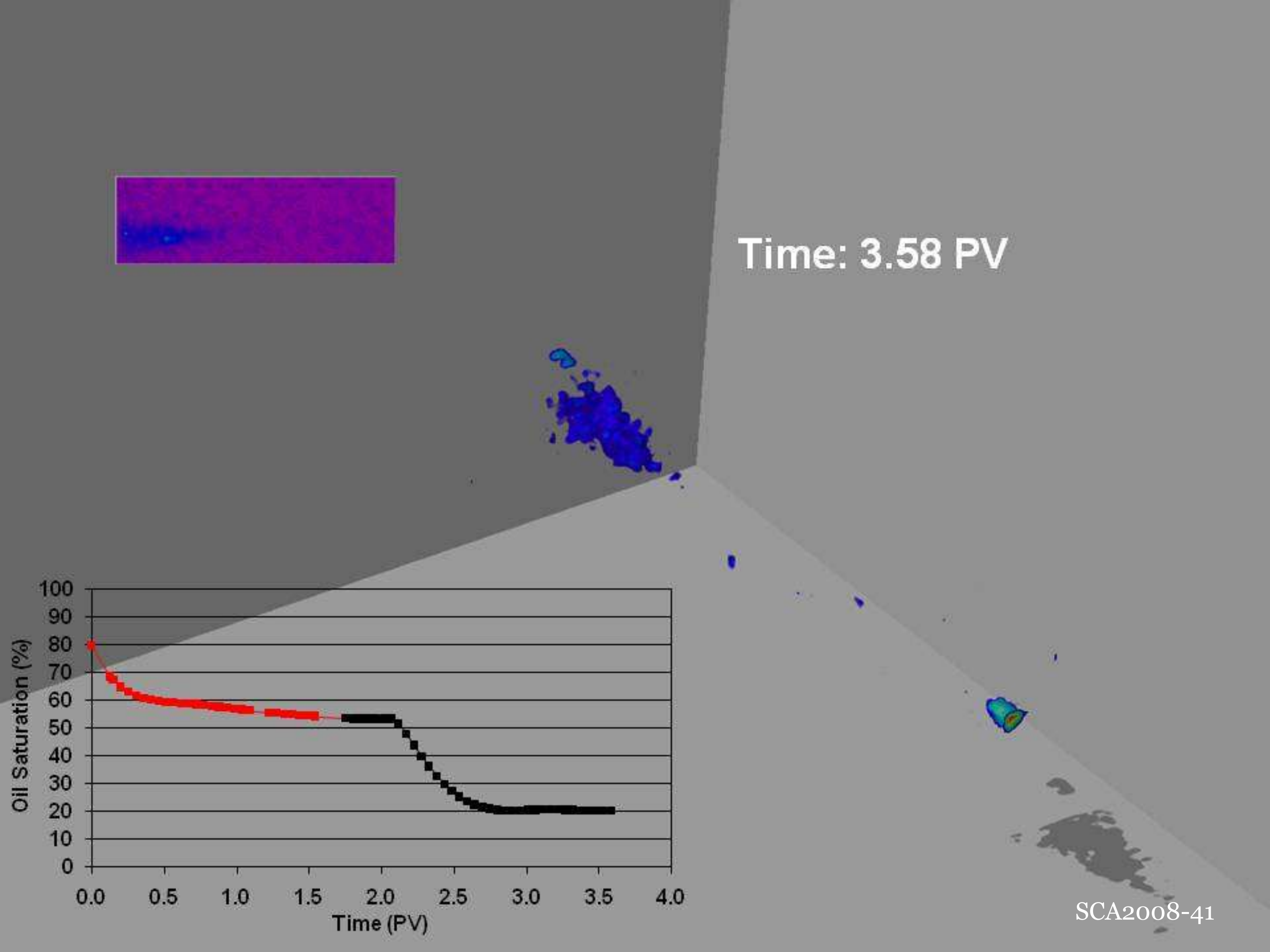

Time: 3.32 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

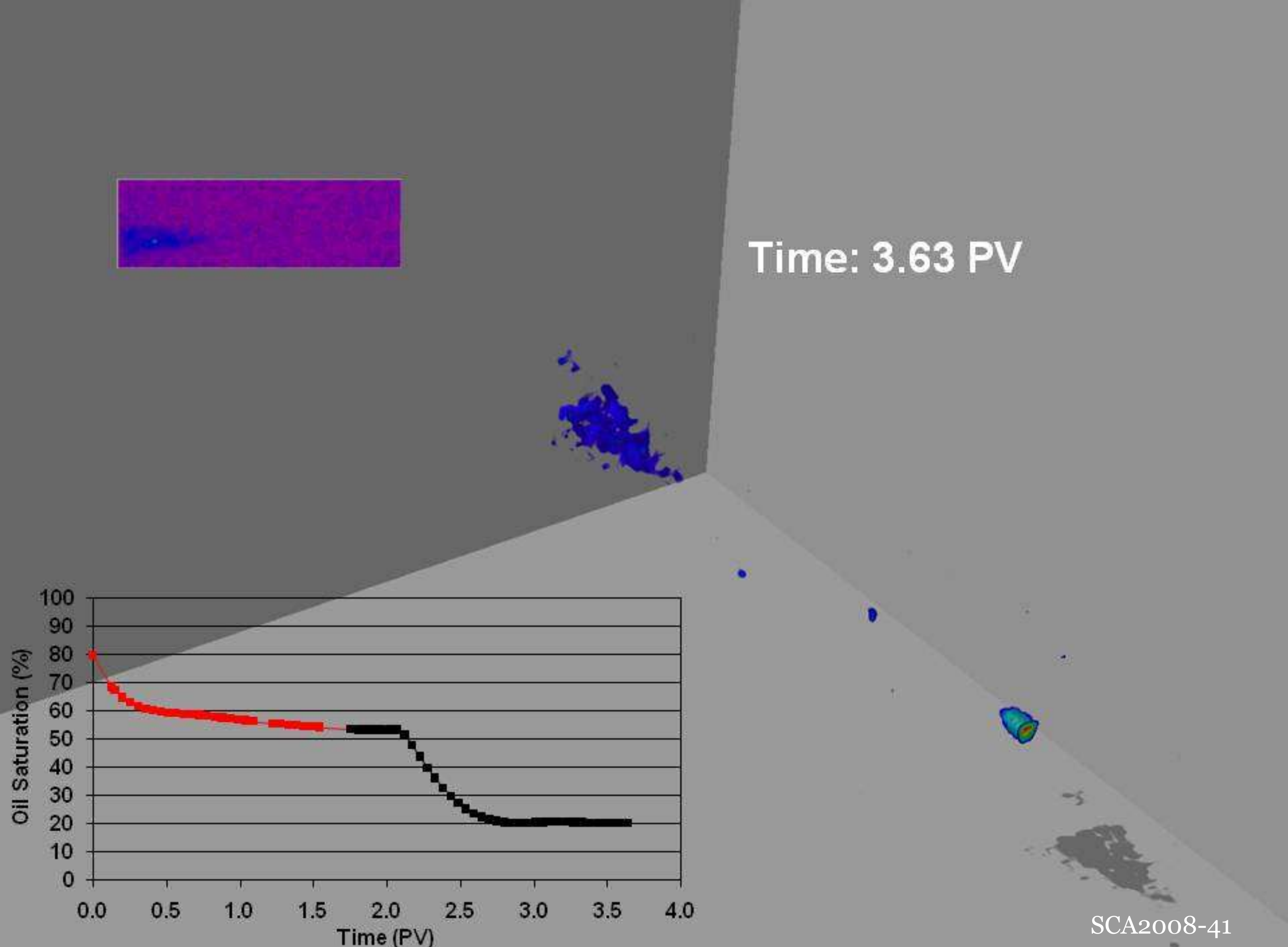

Time: 3.37 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 3.43 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

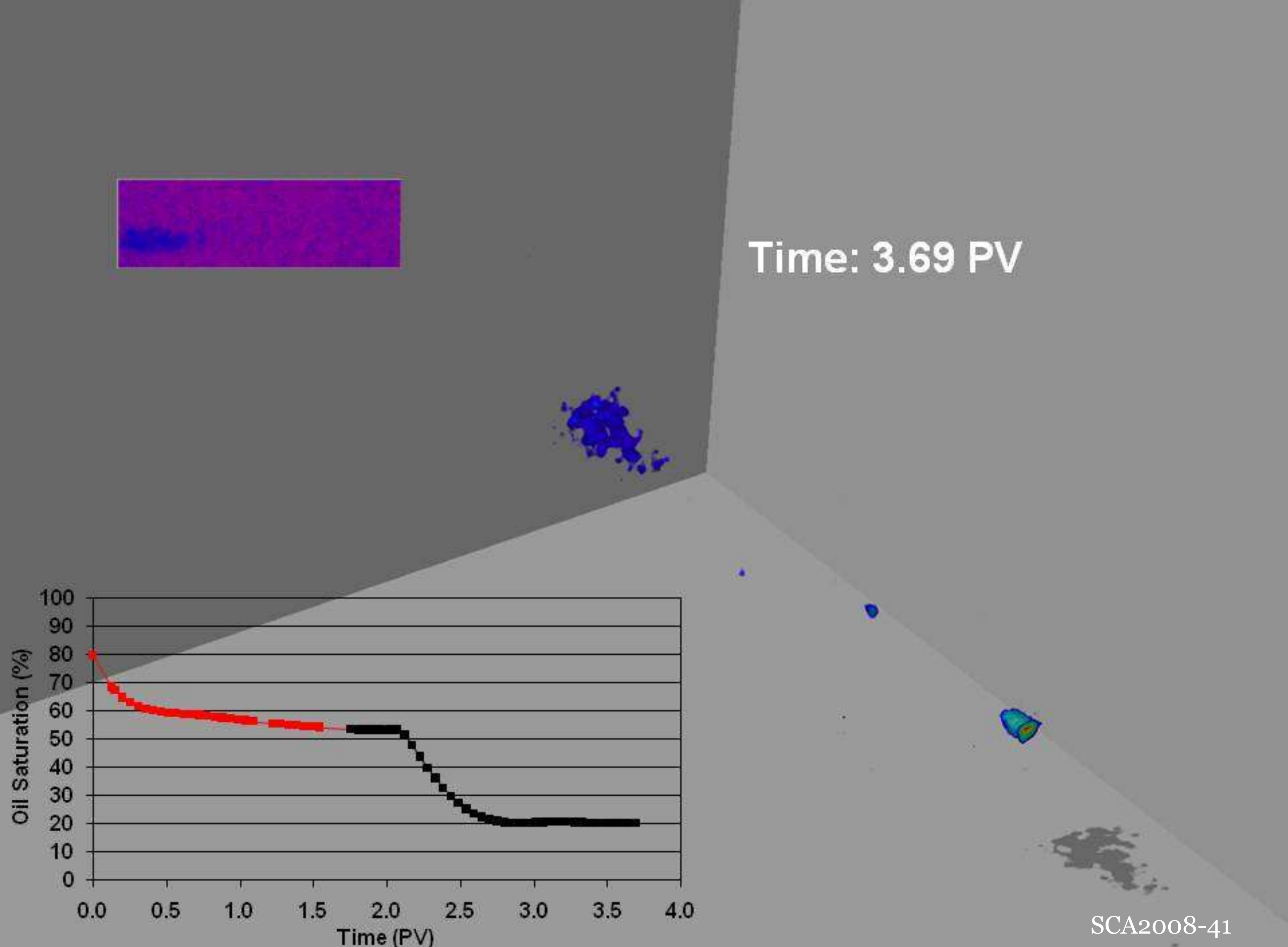

Time: 3.48 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

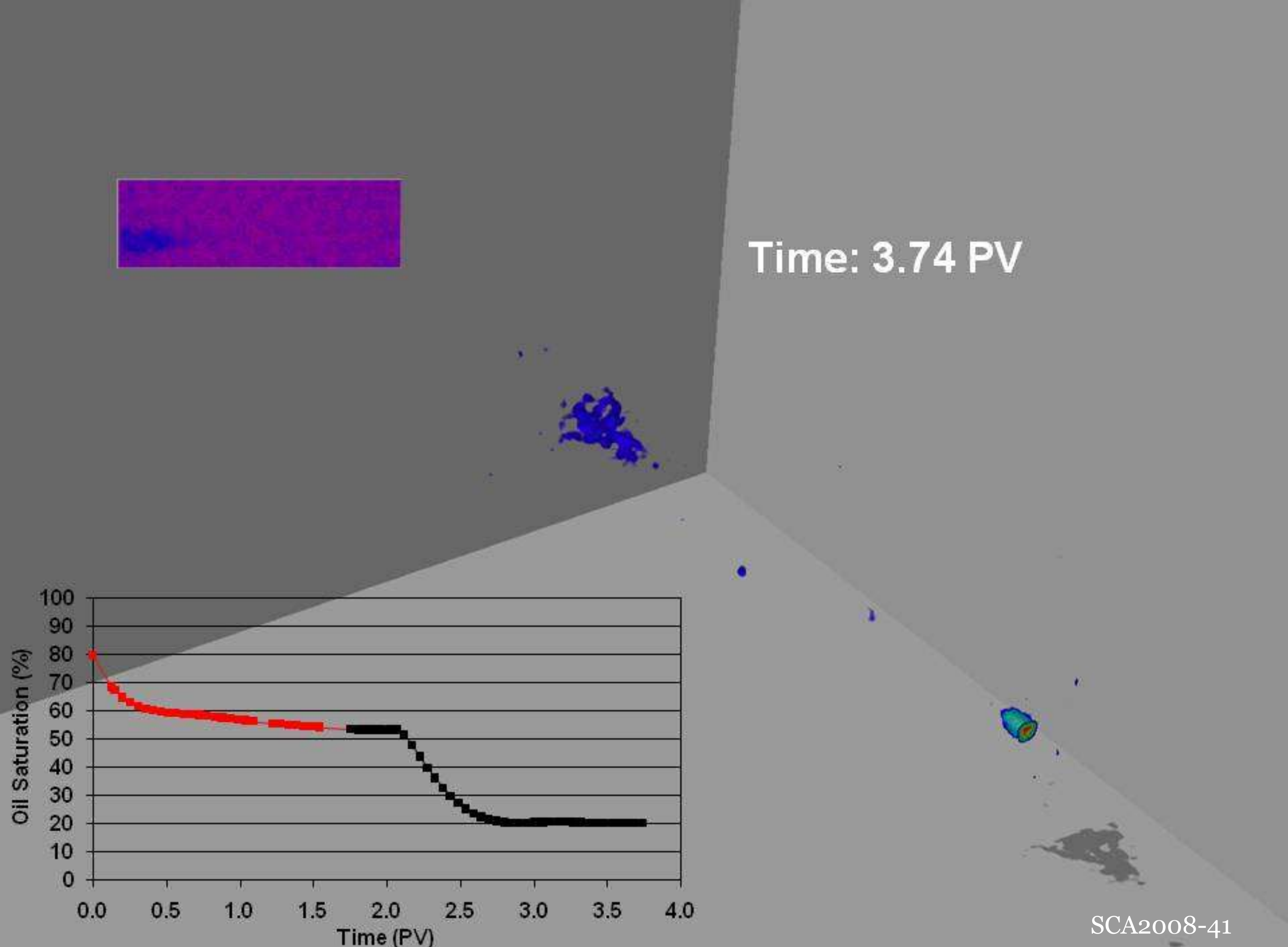

Time: 3.53 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)


Time: 3.58 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

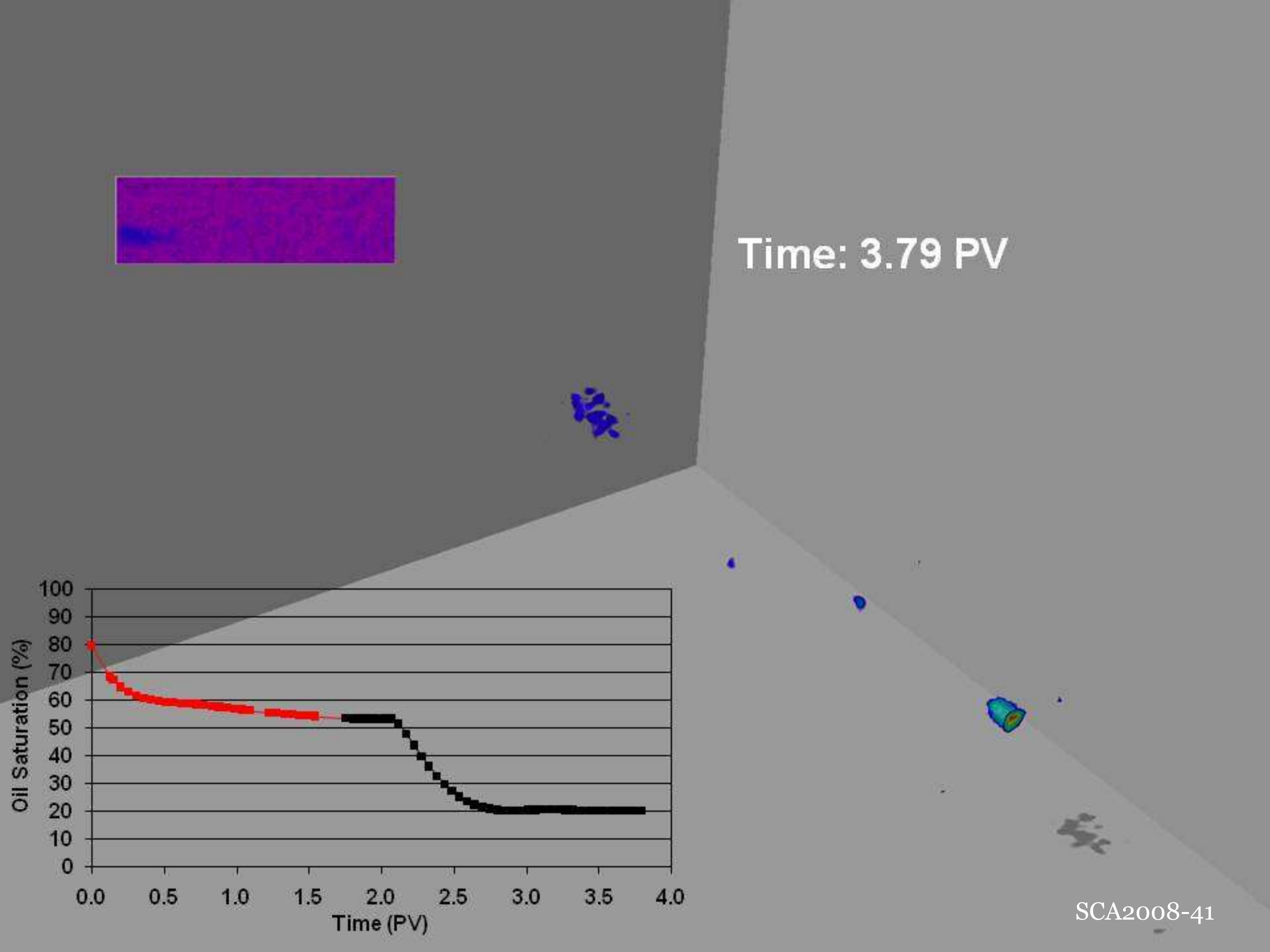


Time: 3.63 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

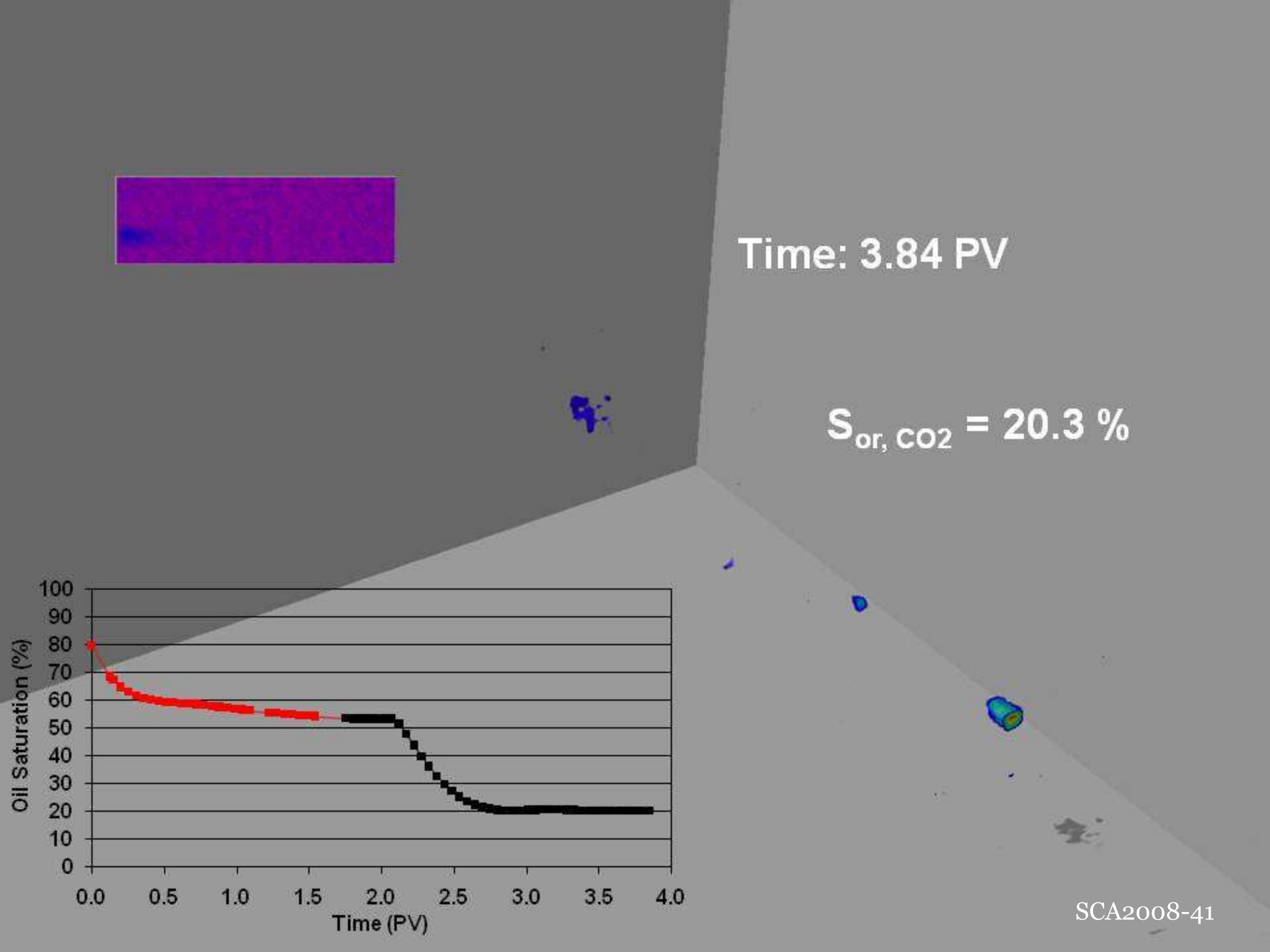

Time: 3.69 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)



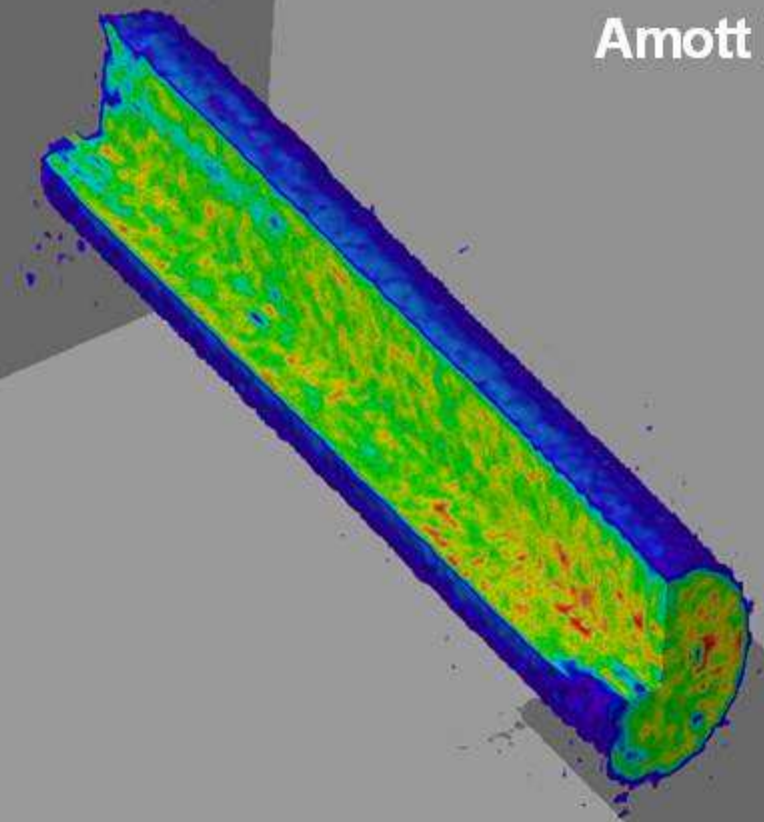
Time: 3.74 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

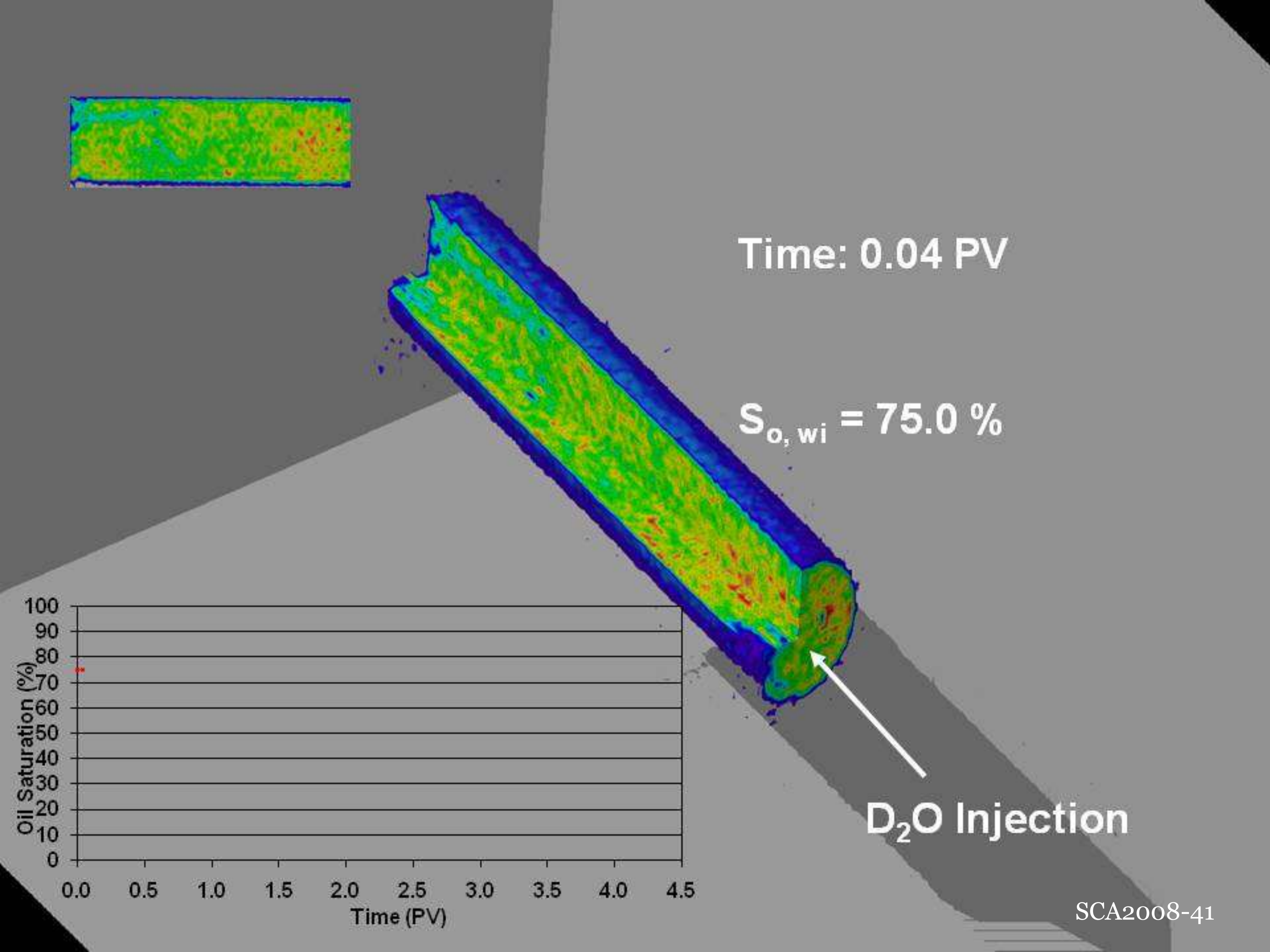


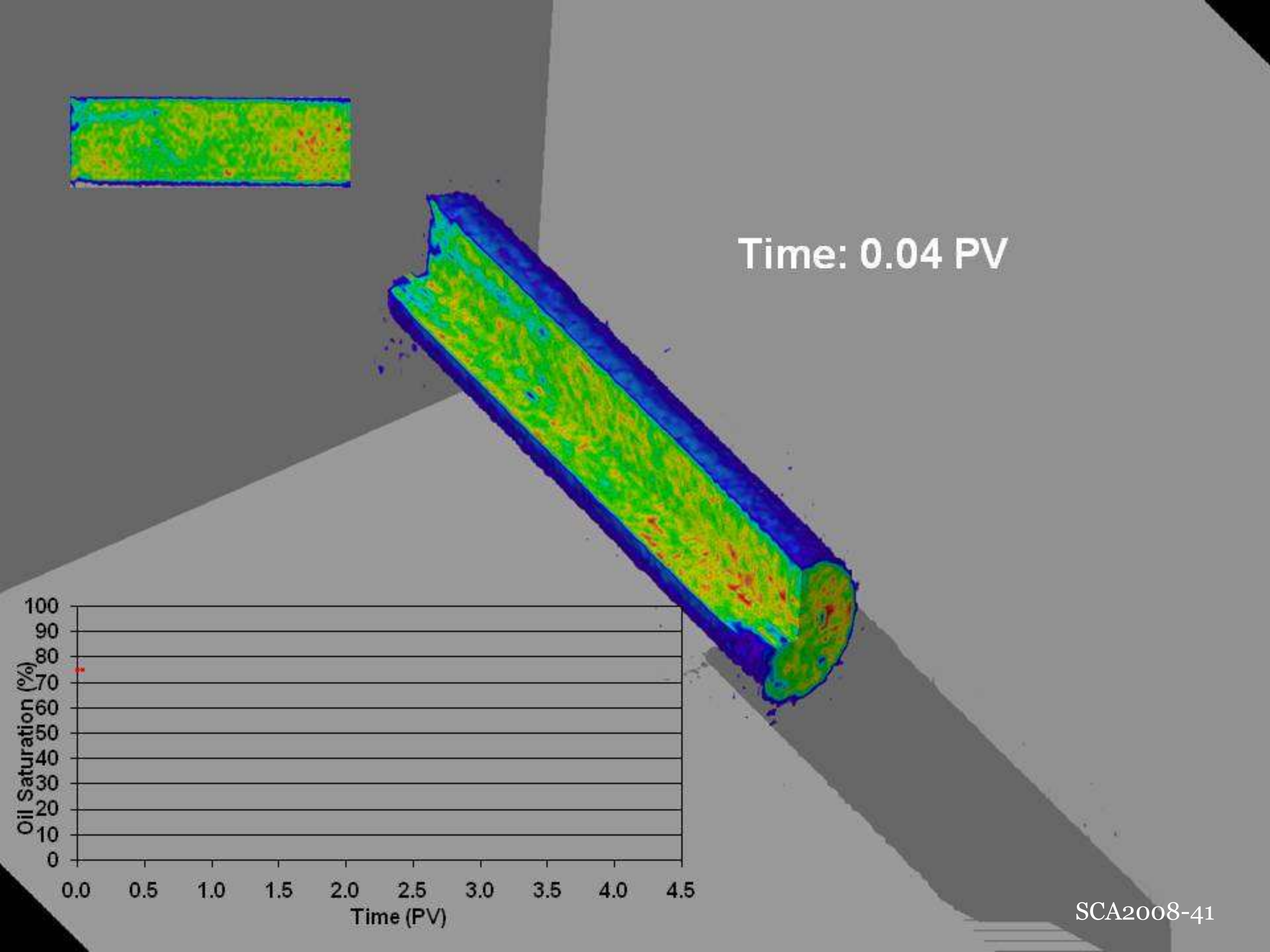
Time: 3.79 PV
Oil Saturation (%)
Time (PV)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

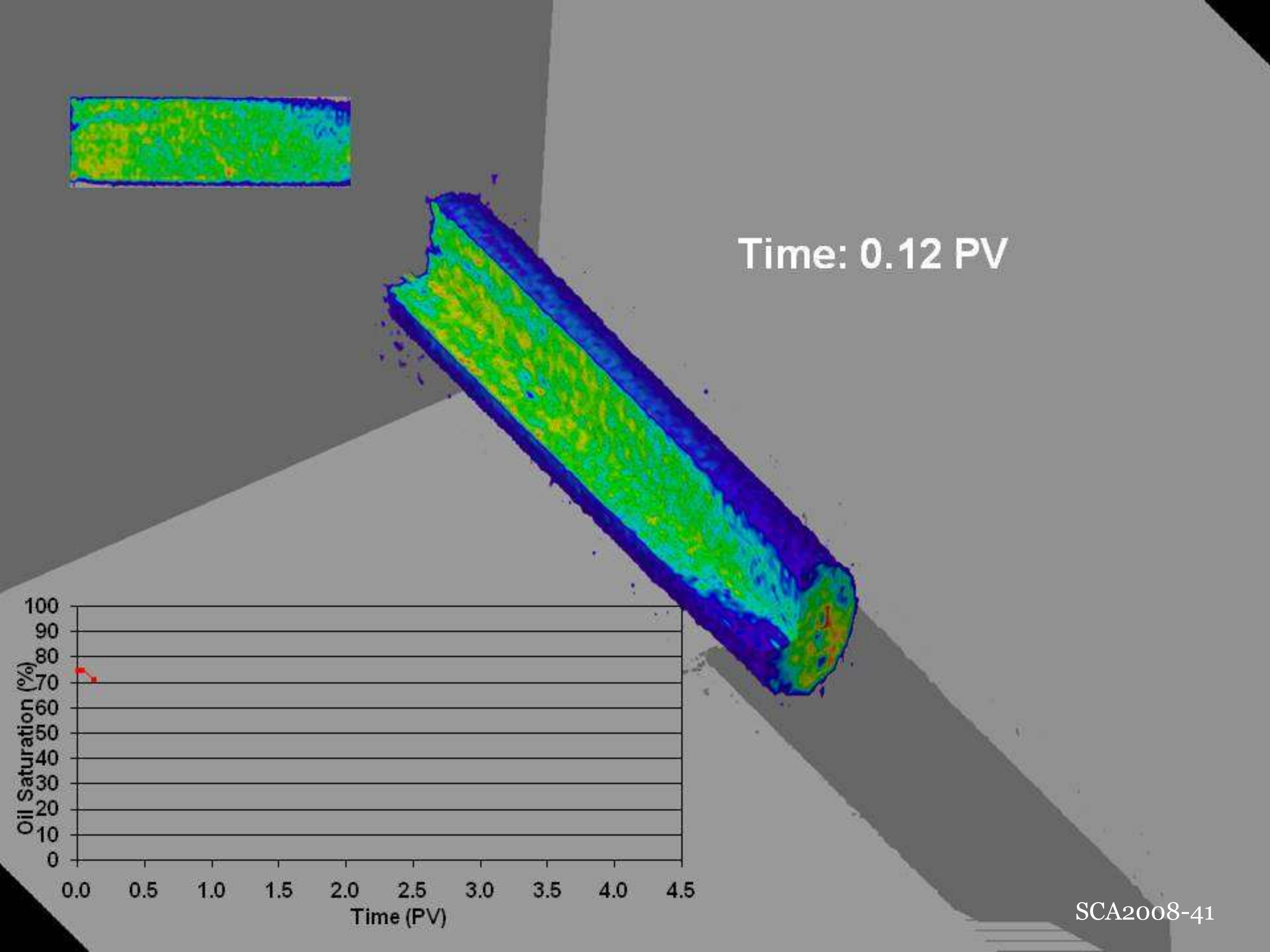

Time: 3.84 PV
$S_{or, CO2}$ = 20.3 %
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Time (PV)

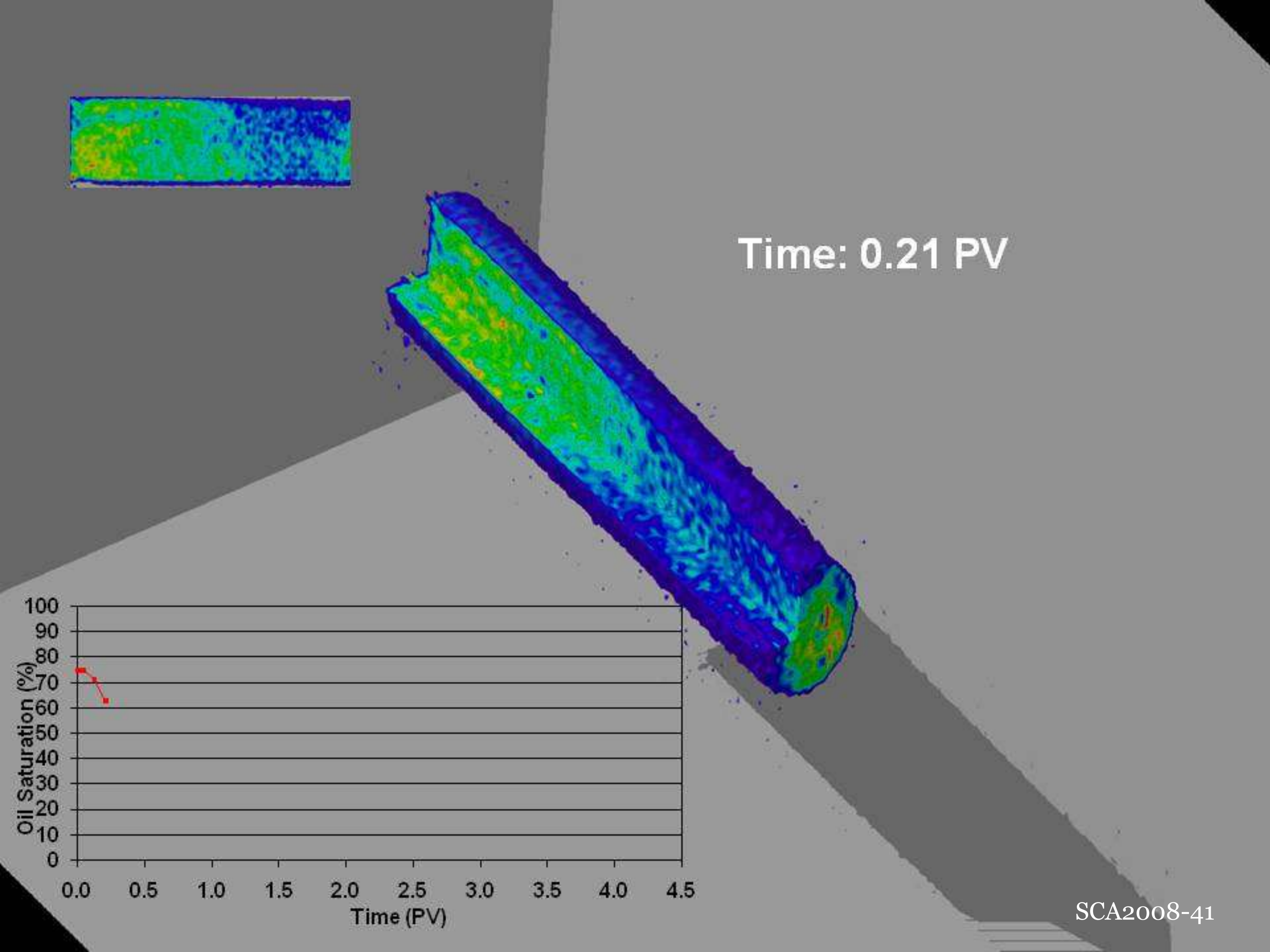
Tertiary CO_2 Injection of Less Water-Wet Chalk

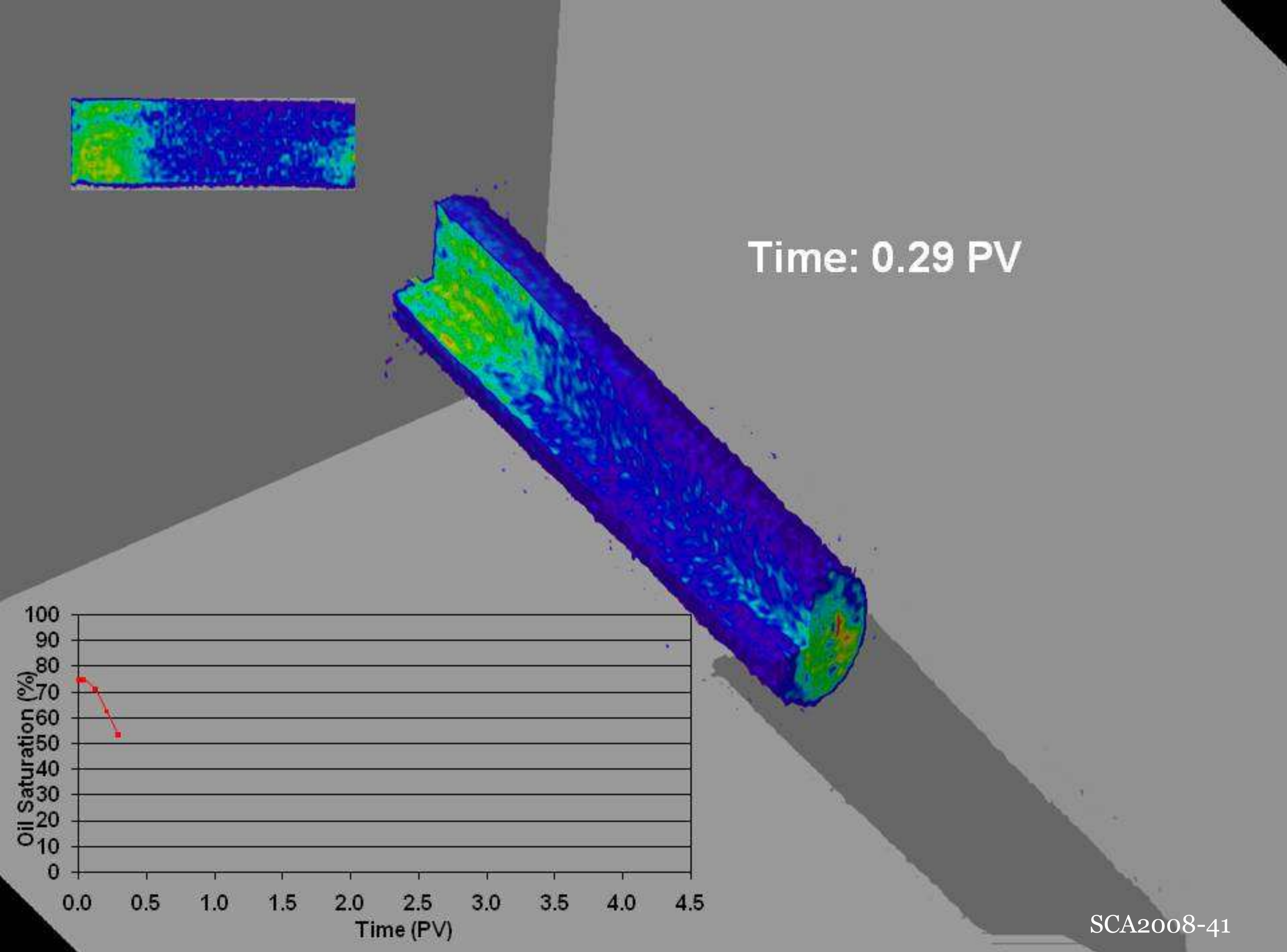


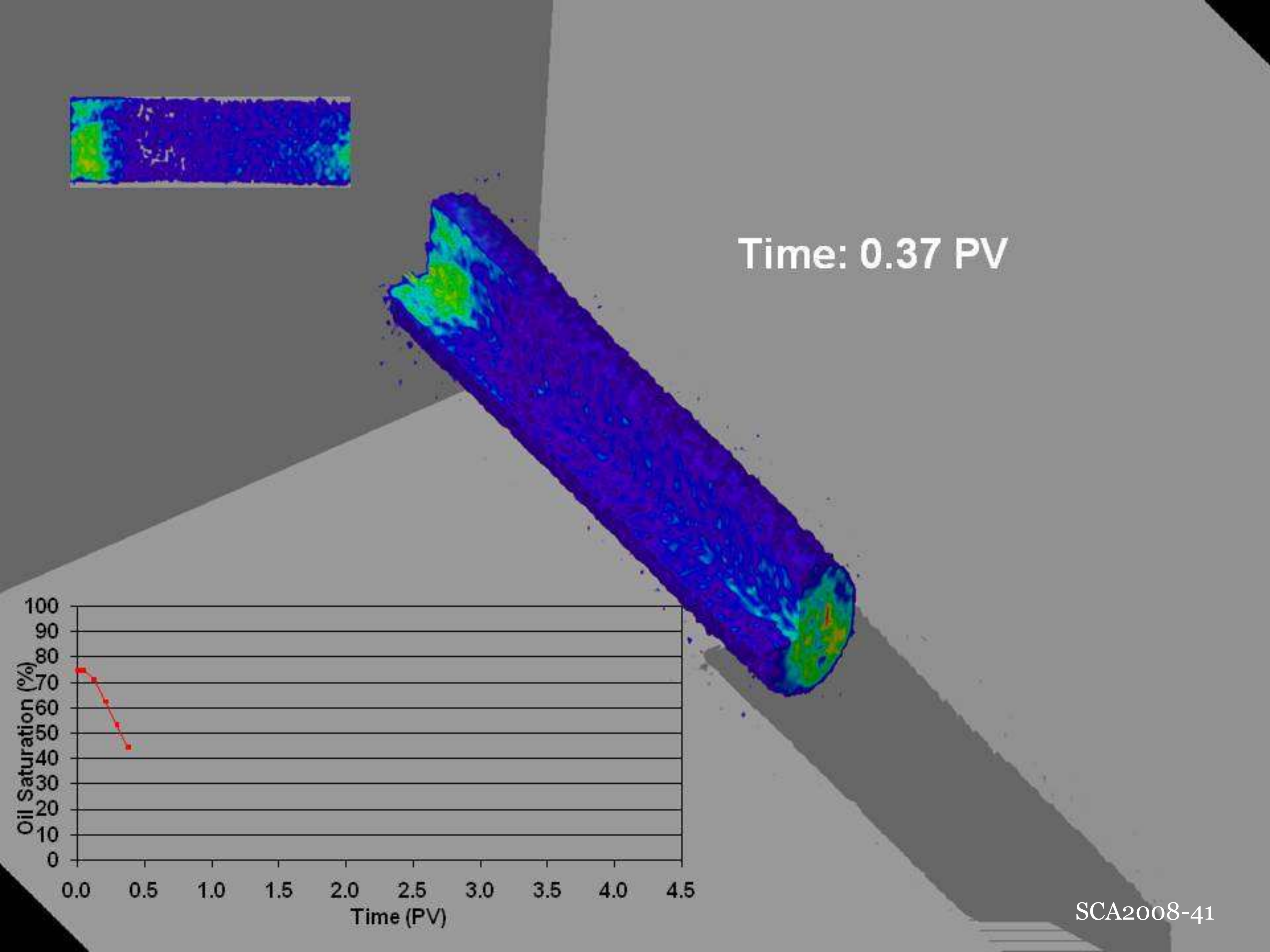

Time: 0.04 PV
$S_{o,\ wi}$ = 75.0 %
D_2O Injection
Oil Saturation (%)
0
10
20
30
40
50
60
70
80
90
100
Time (PV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

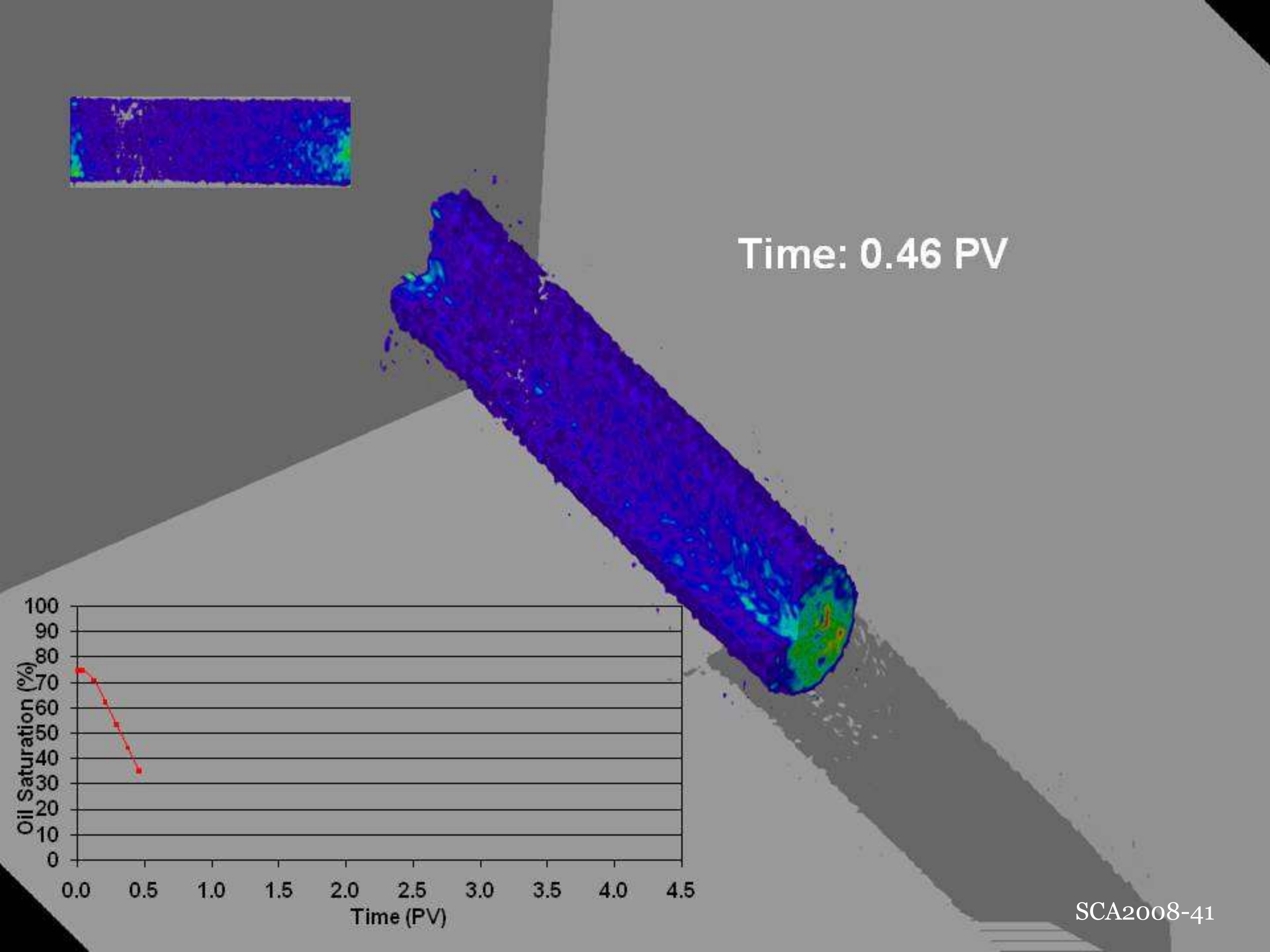

Time: 0.04 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

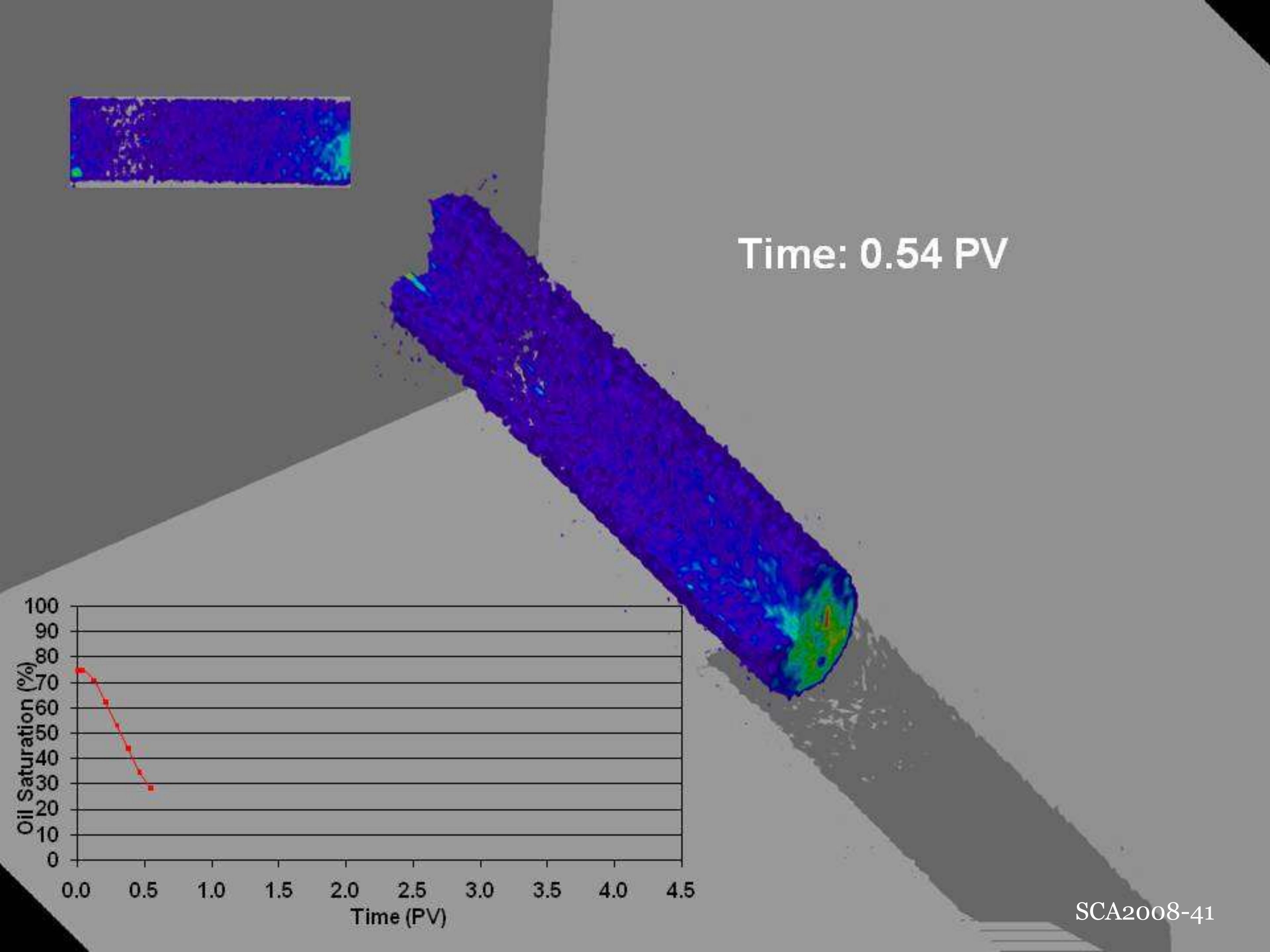

Time: 0.12 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

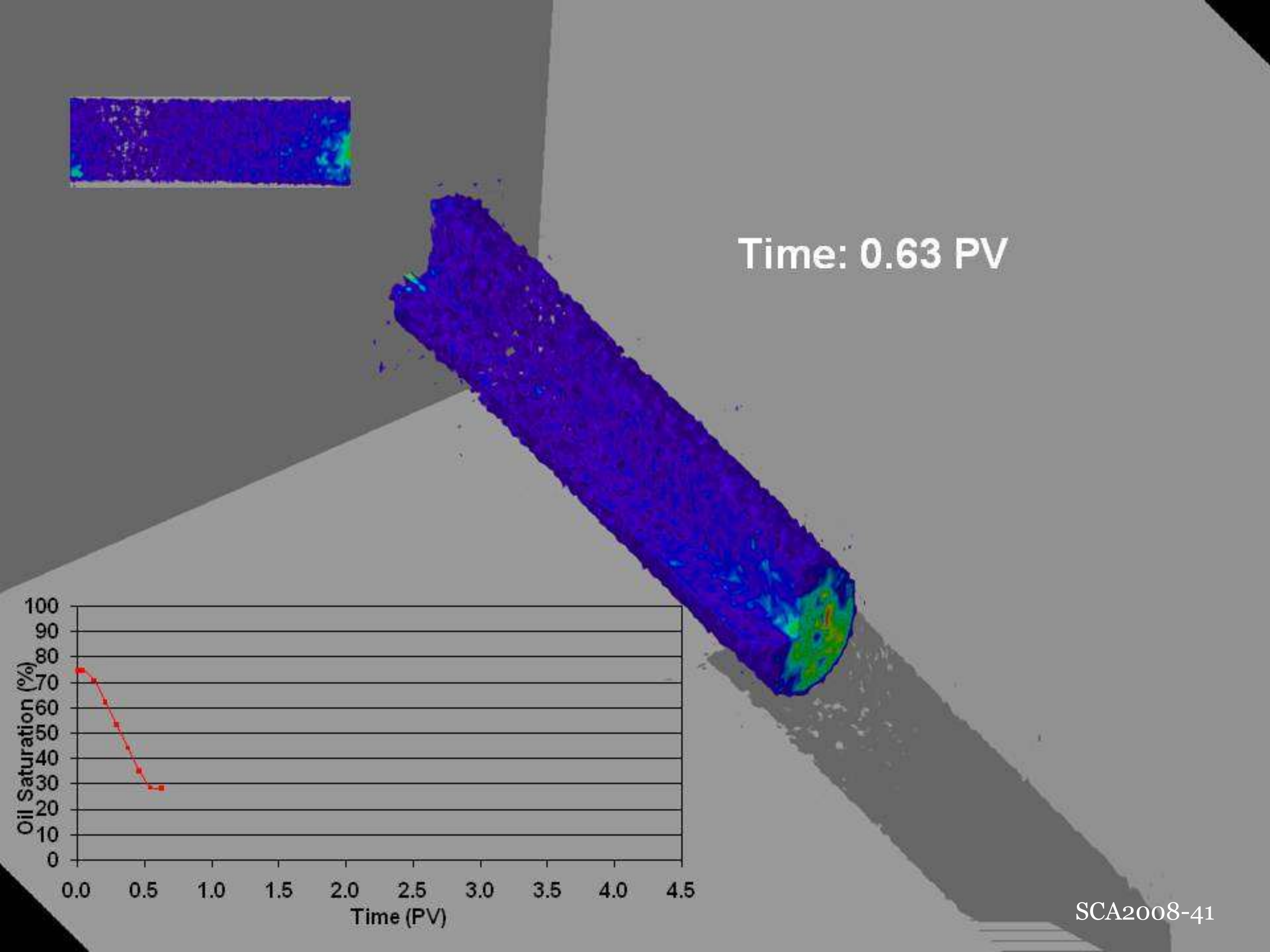

Time: 0.21 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

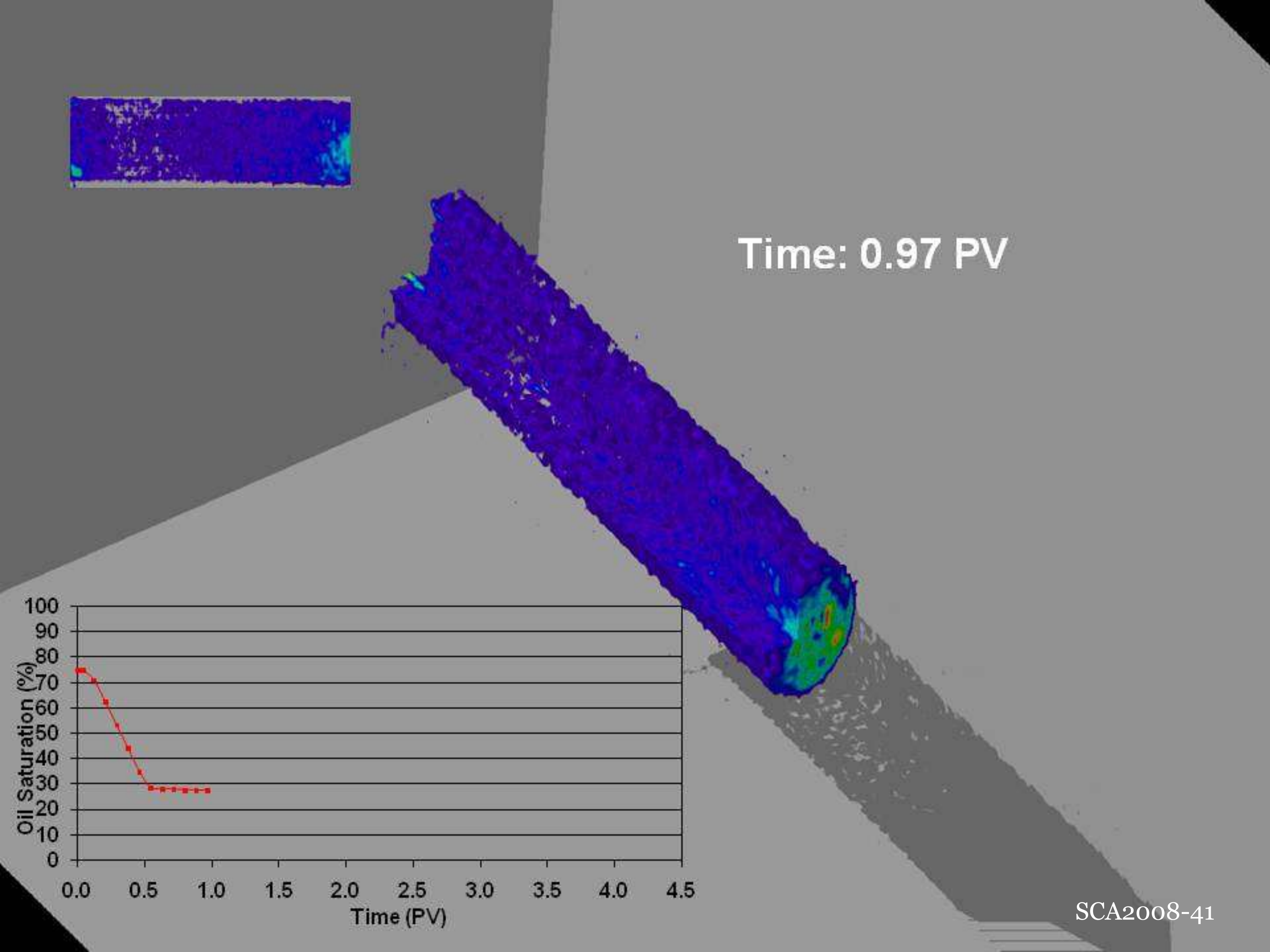

Time: 0.29 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

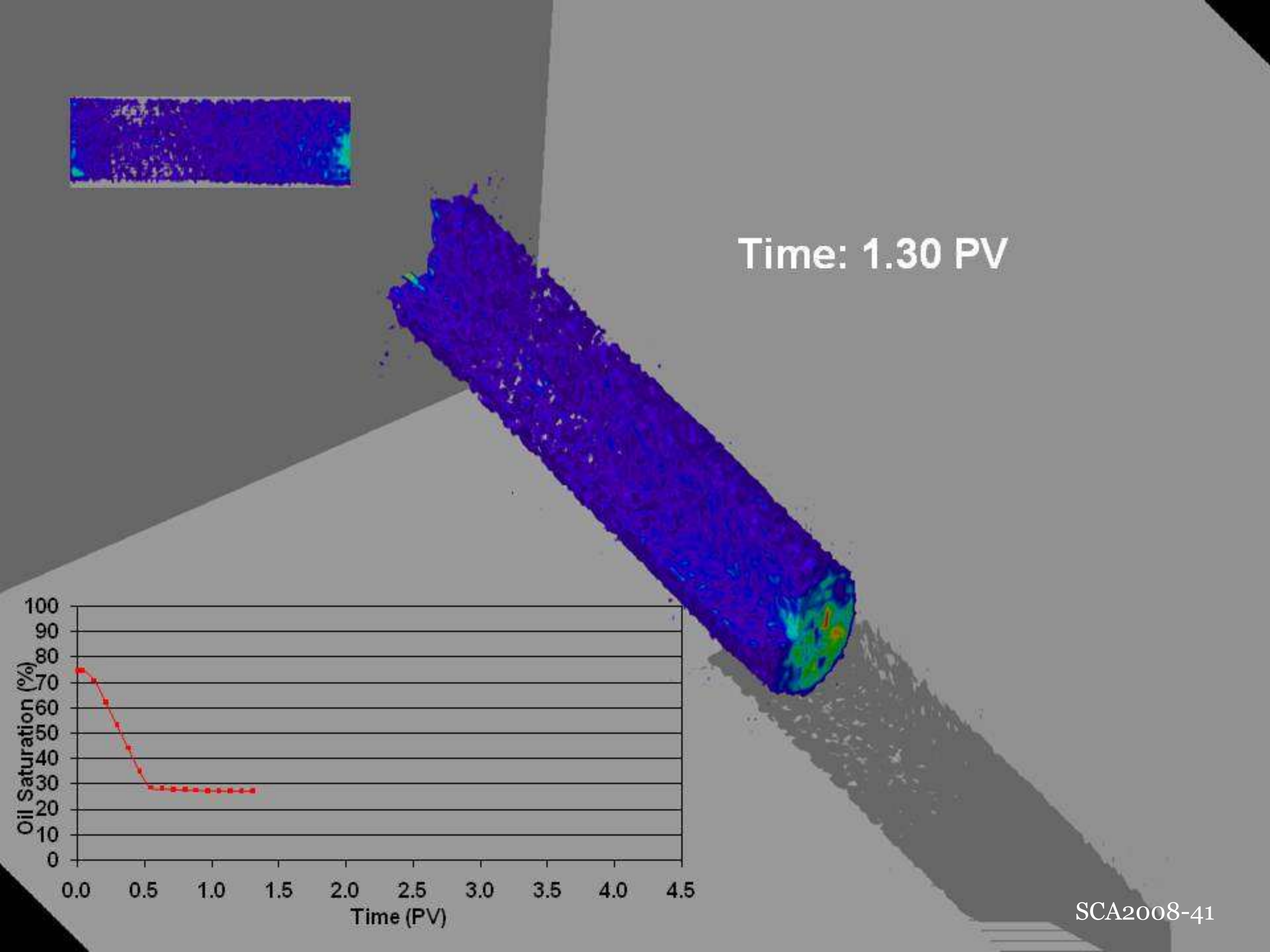

Time: 0.37 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

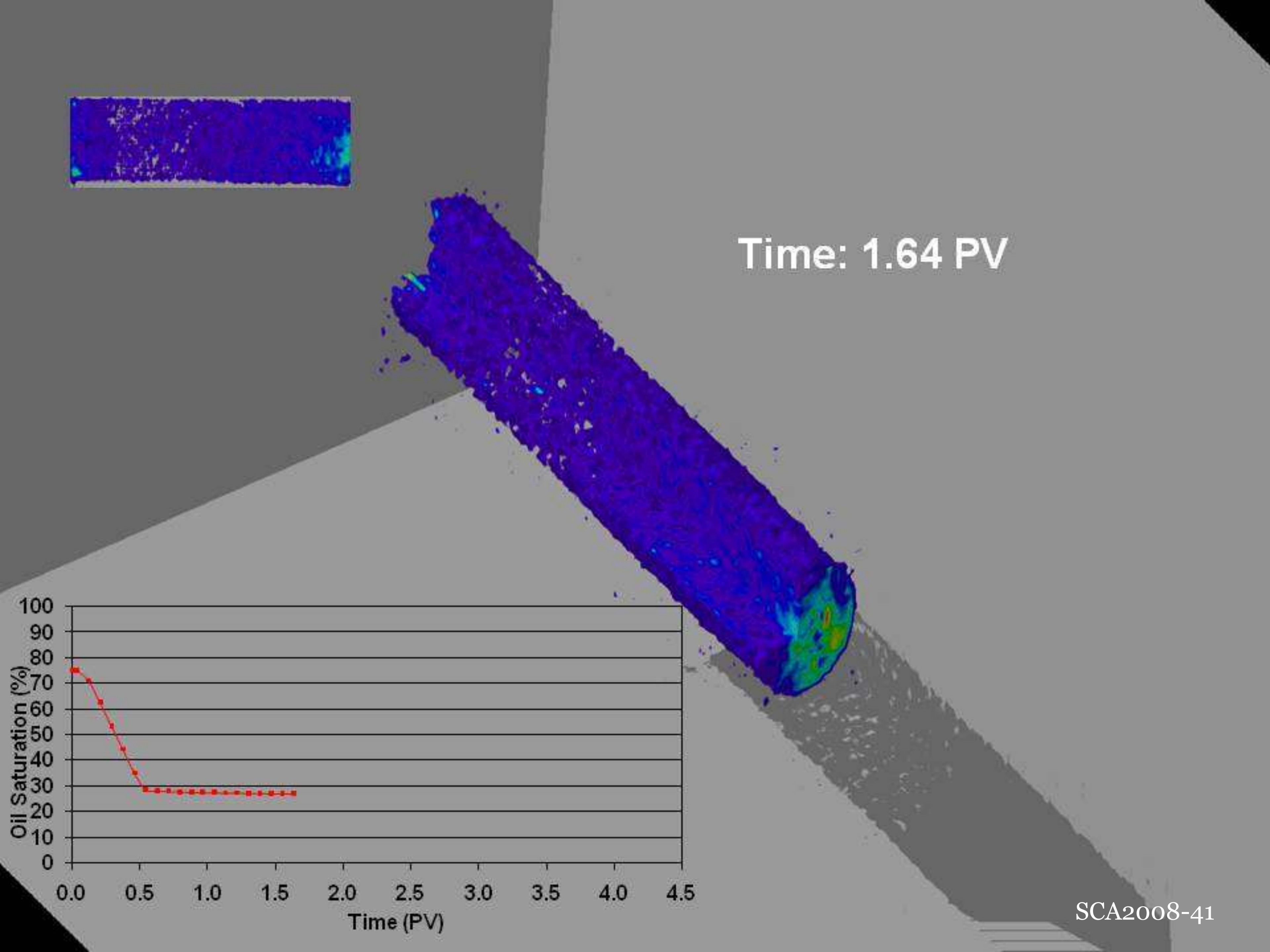

Time: 0.46 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

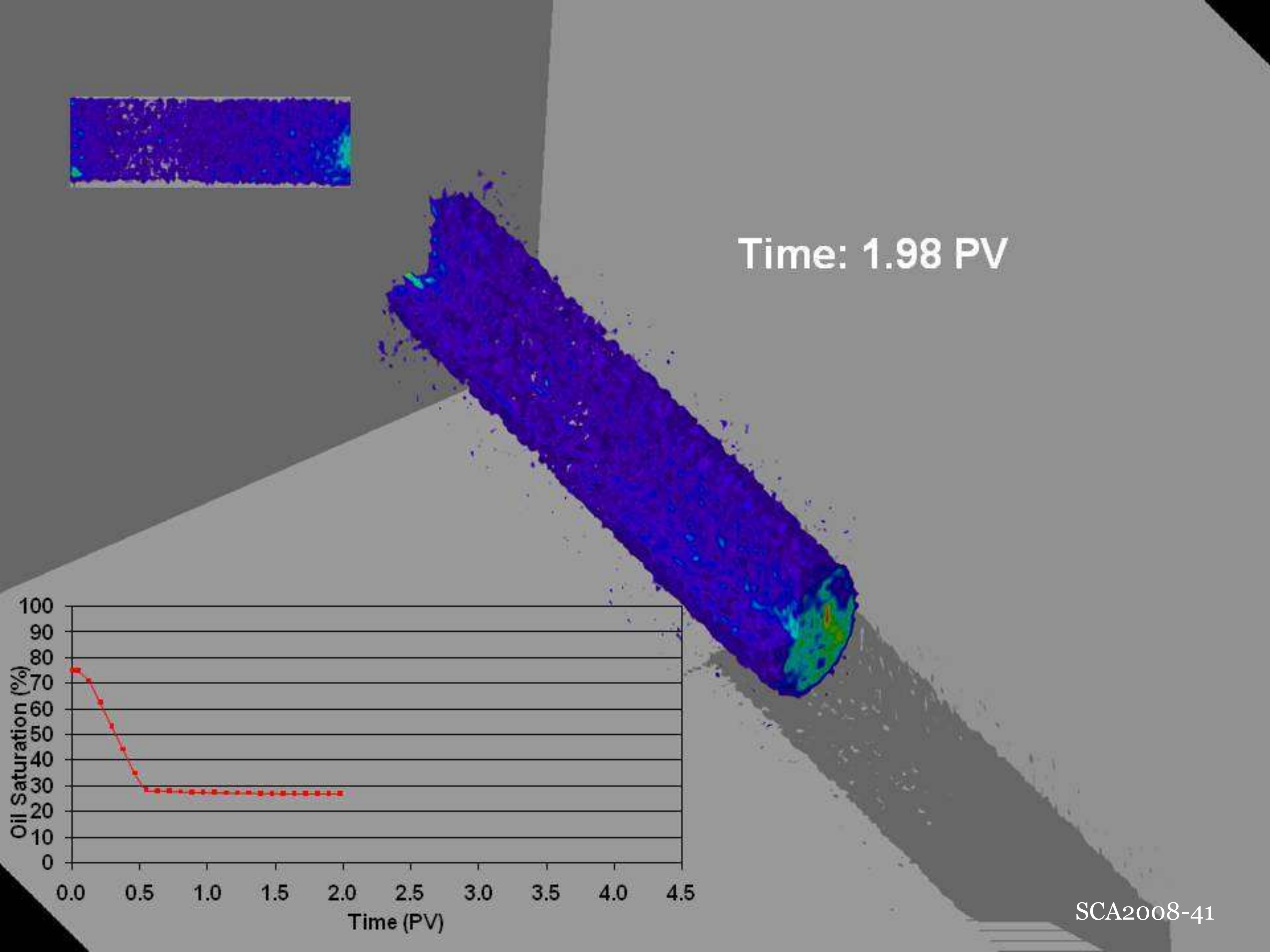

Time: 0.54 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 0.63 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

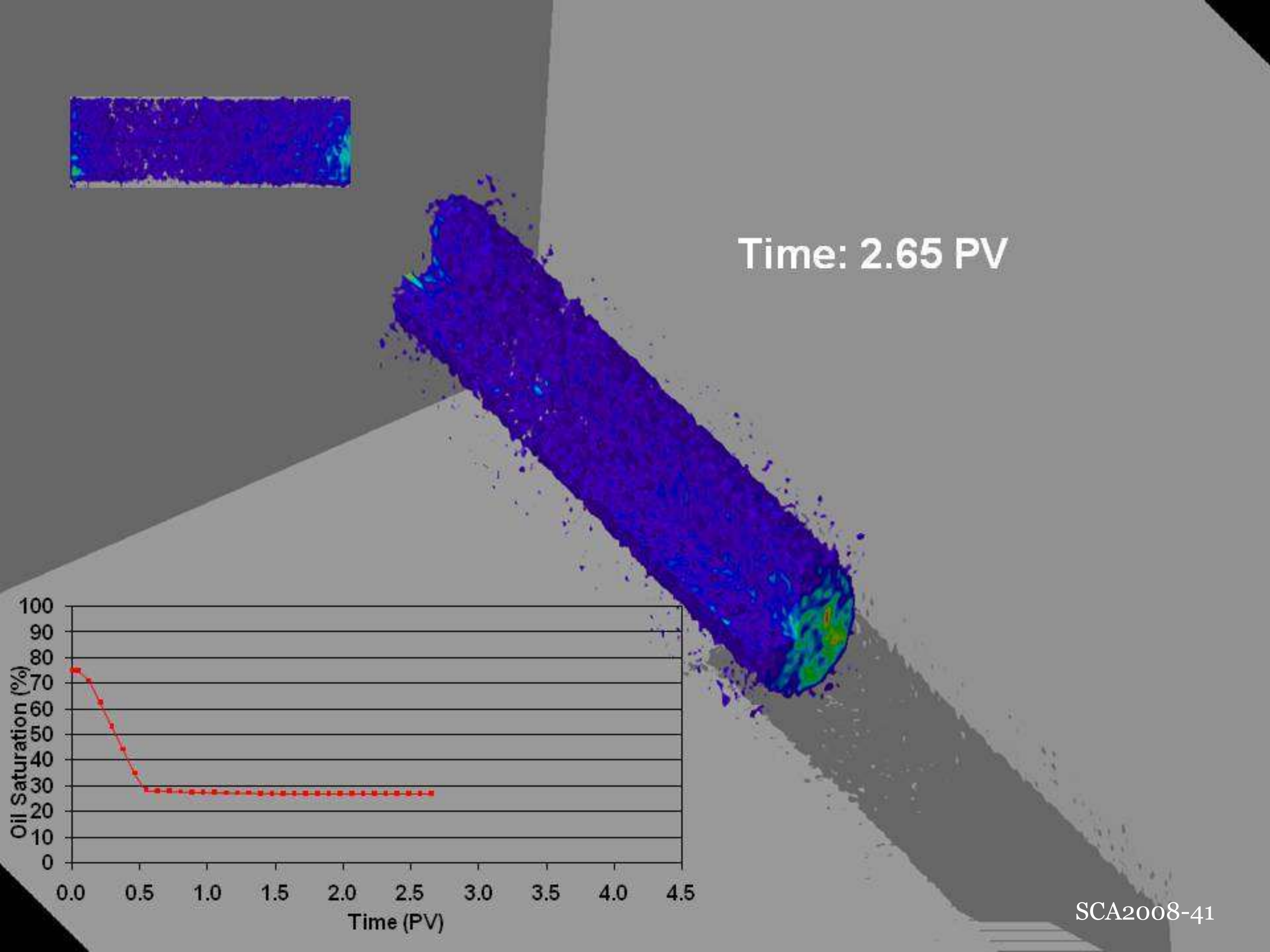

Time: 0.97 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

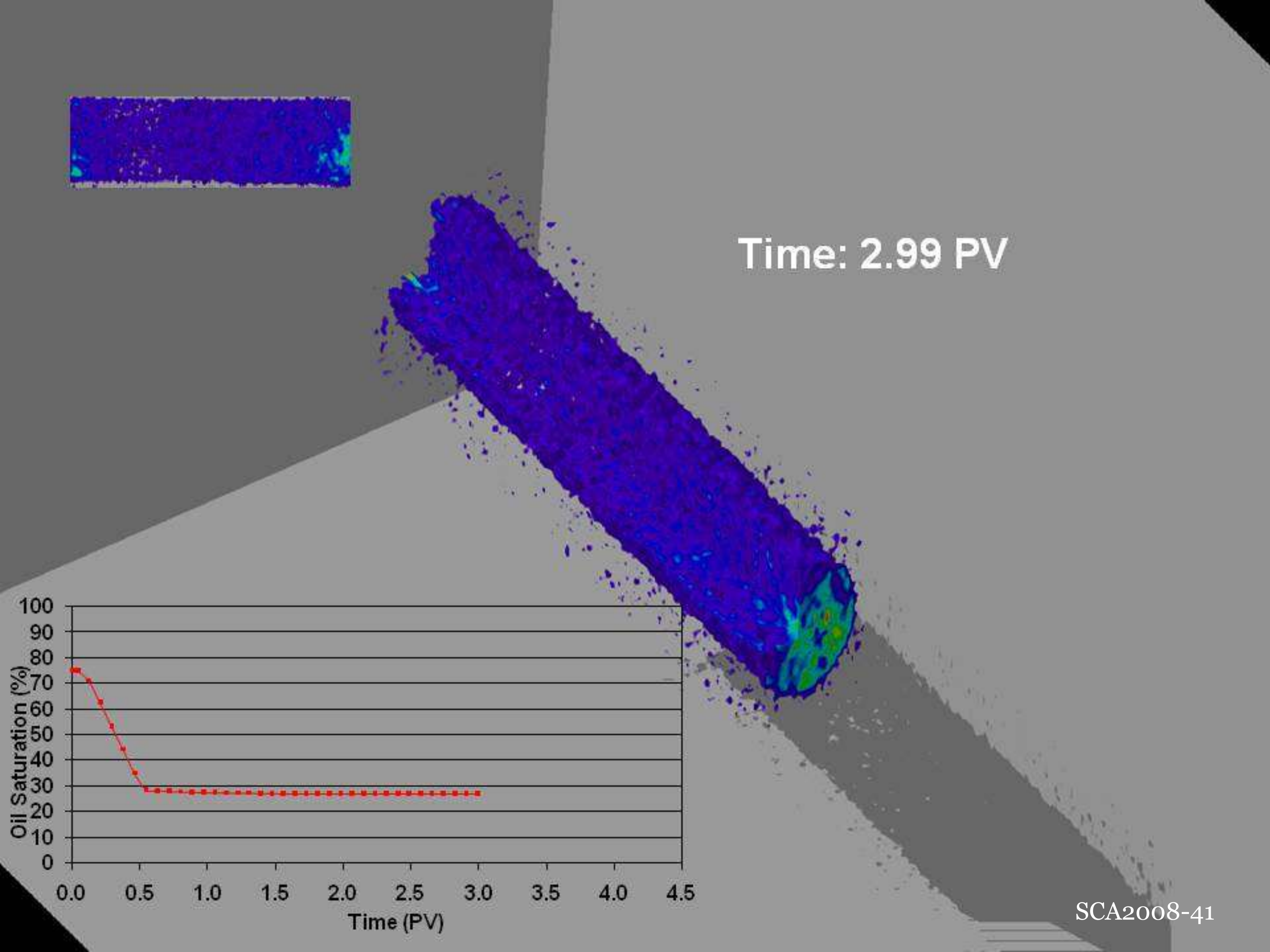

Time: 1.30 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

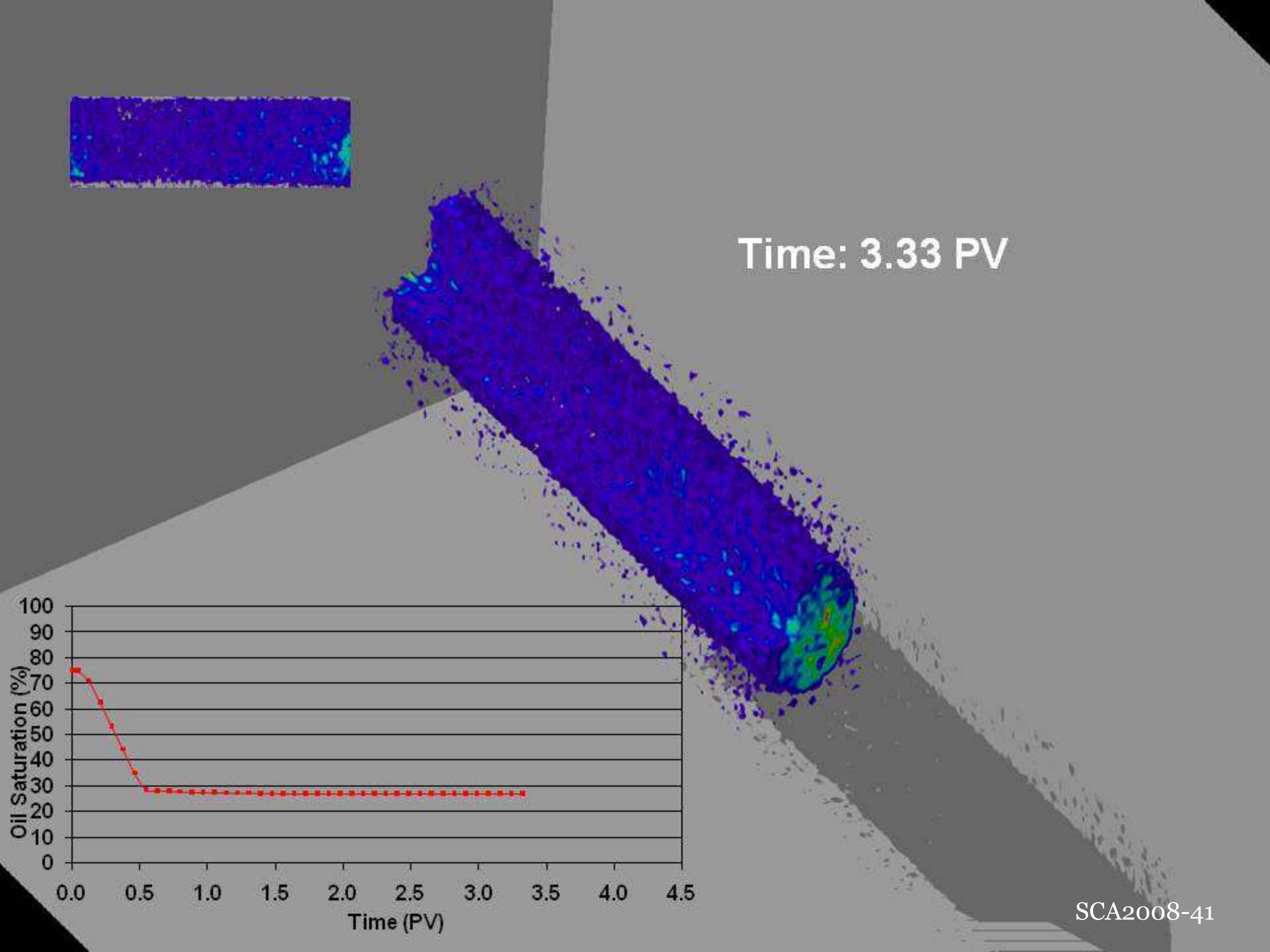

Time: 1.64 PV
Oil Saturation (%)
0
10
20
30
40
50
60
70
80
90
100
Time (PV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

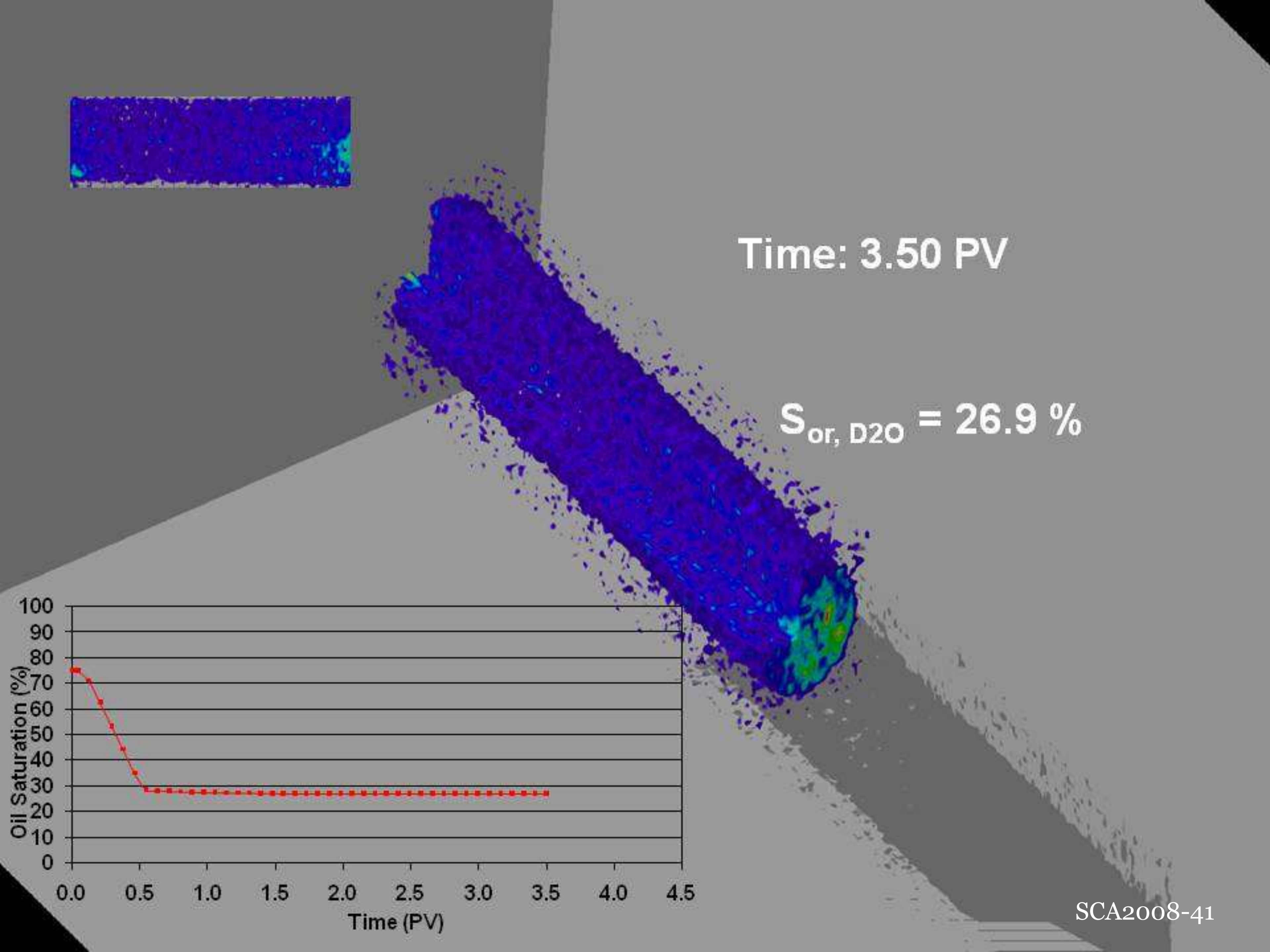


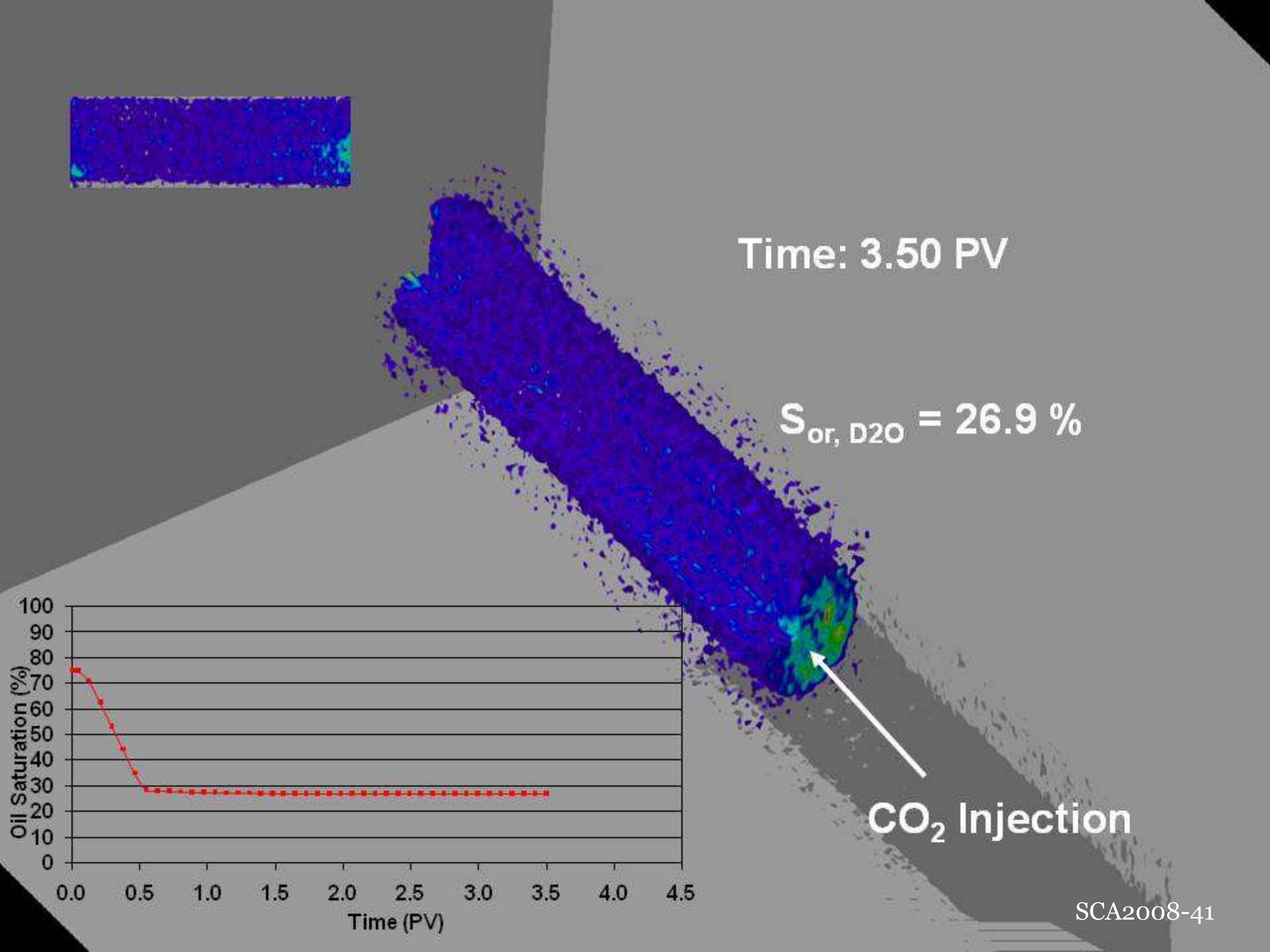
Time: 1.98 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

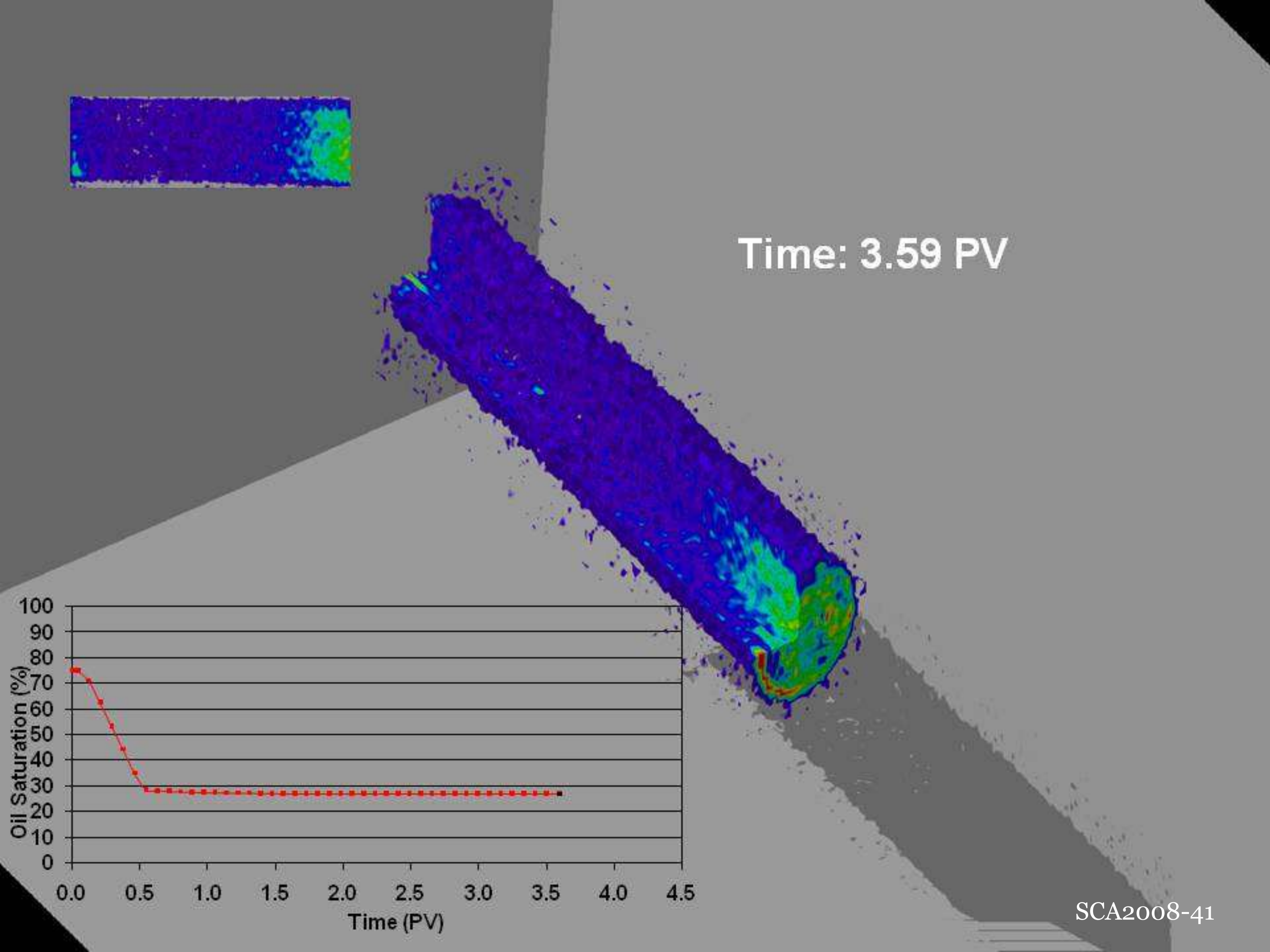

Time: 2.65 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 2.99 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

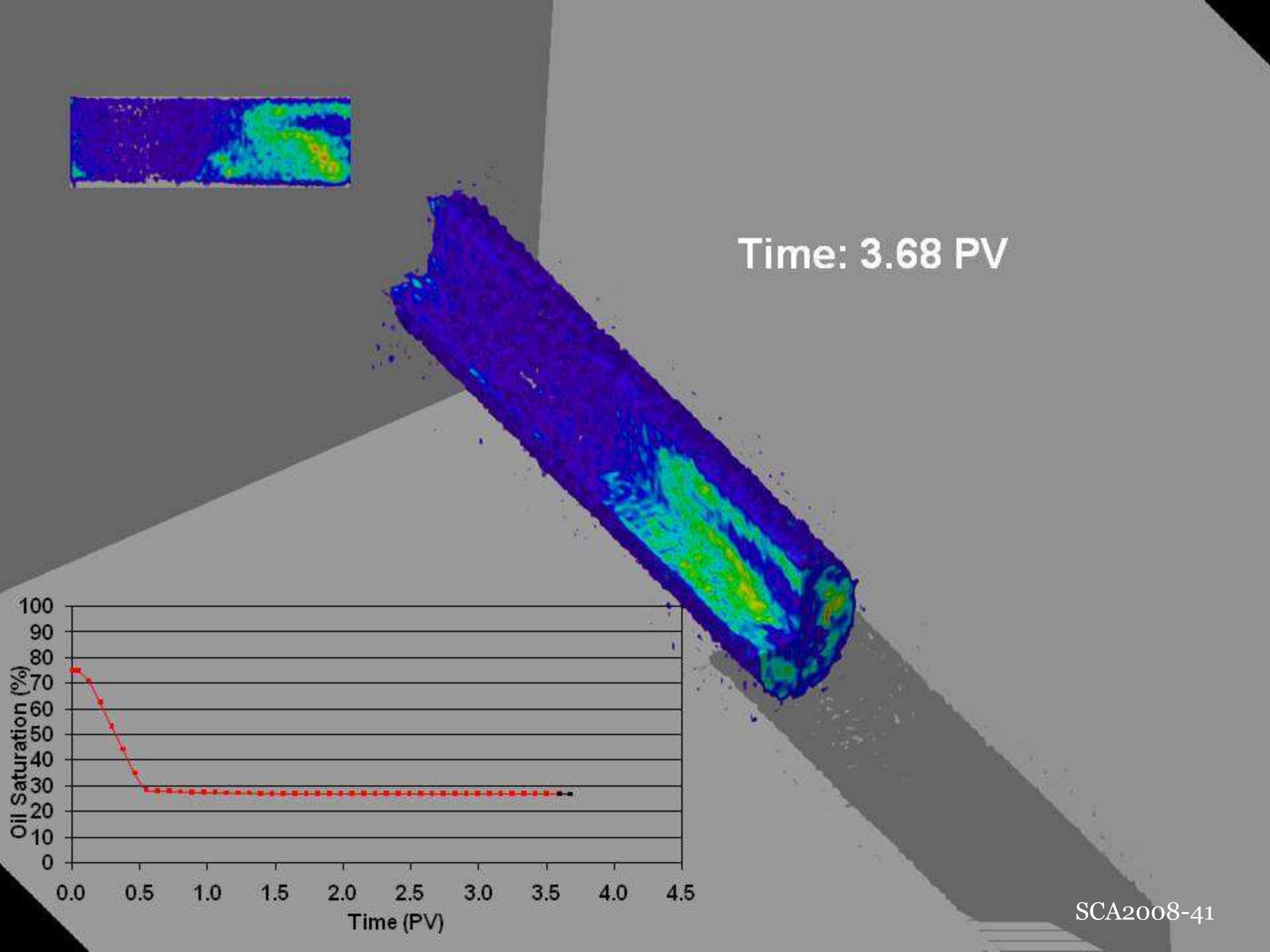

Time: 3.33 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 3.50 PV
$S_{or, D2O}$ = 26.9 %
Oil Saturation (%)
Time (PV)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5


Time: 3.50 PV
$S_{or,\ D2O}$ = 26.9 %
CO_2 Injection
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)



Time: 3.59 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 3.68 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

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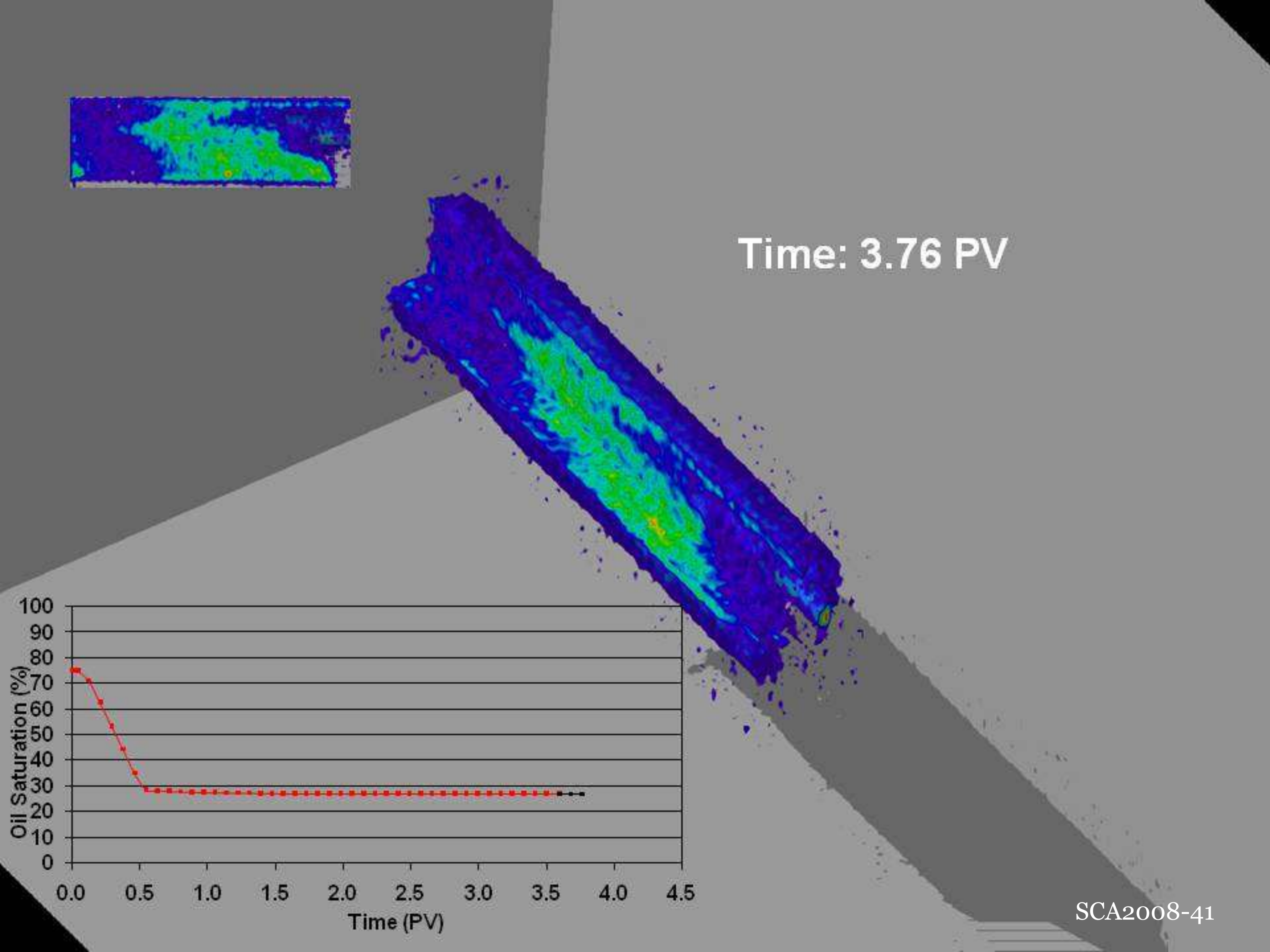
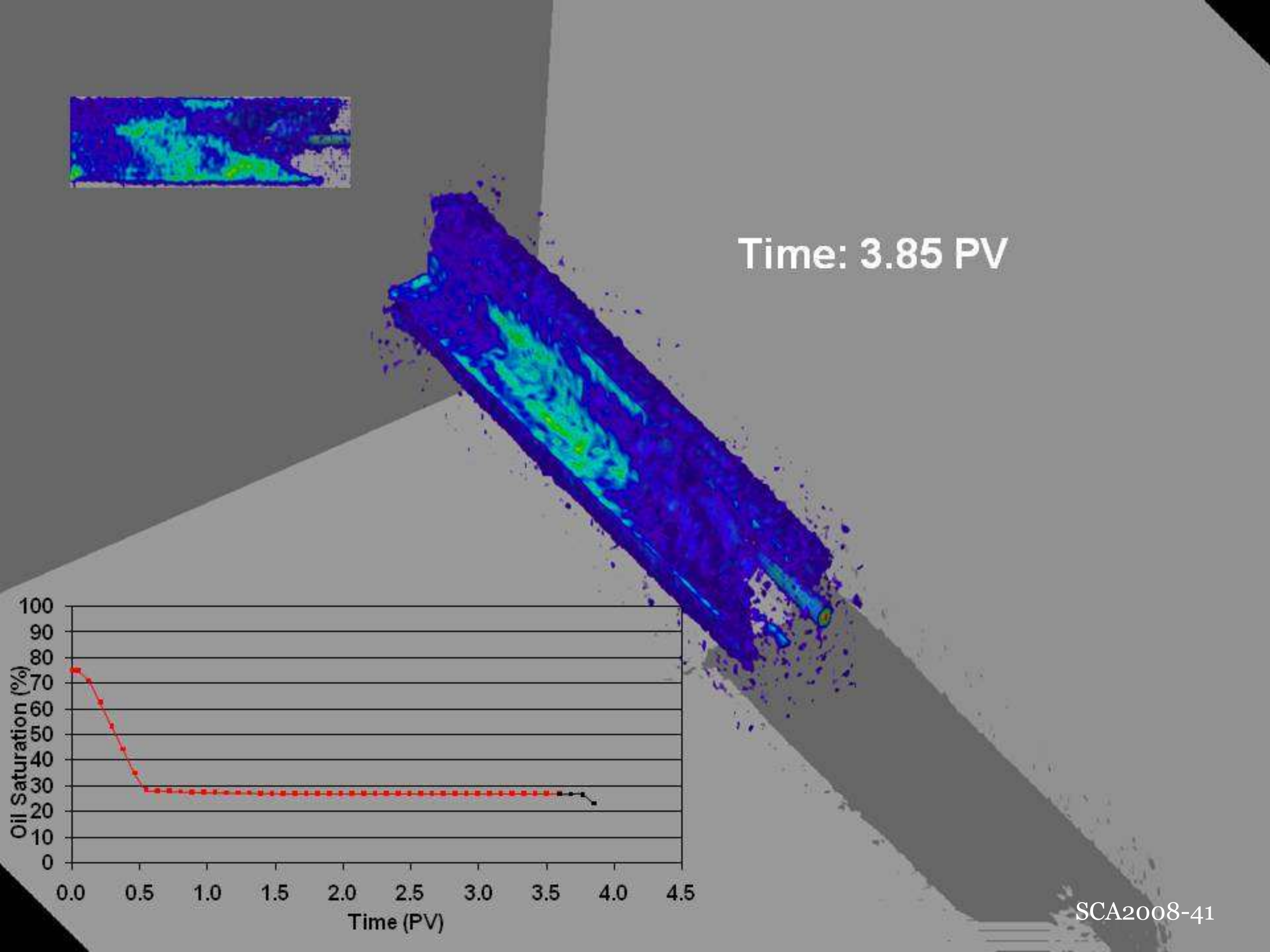
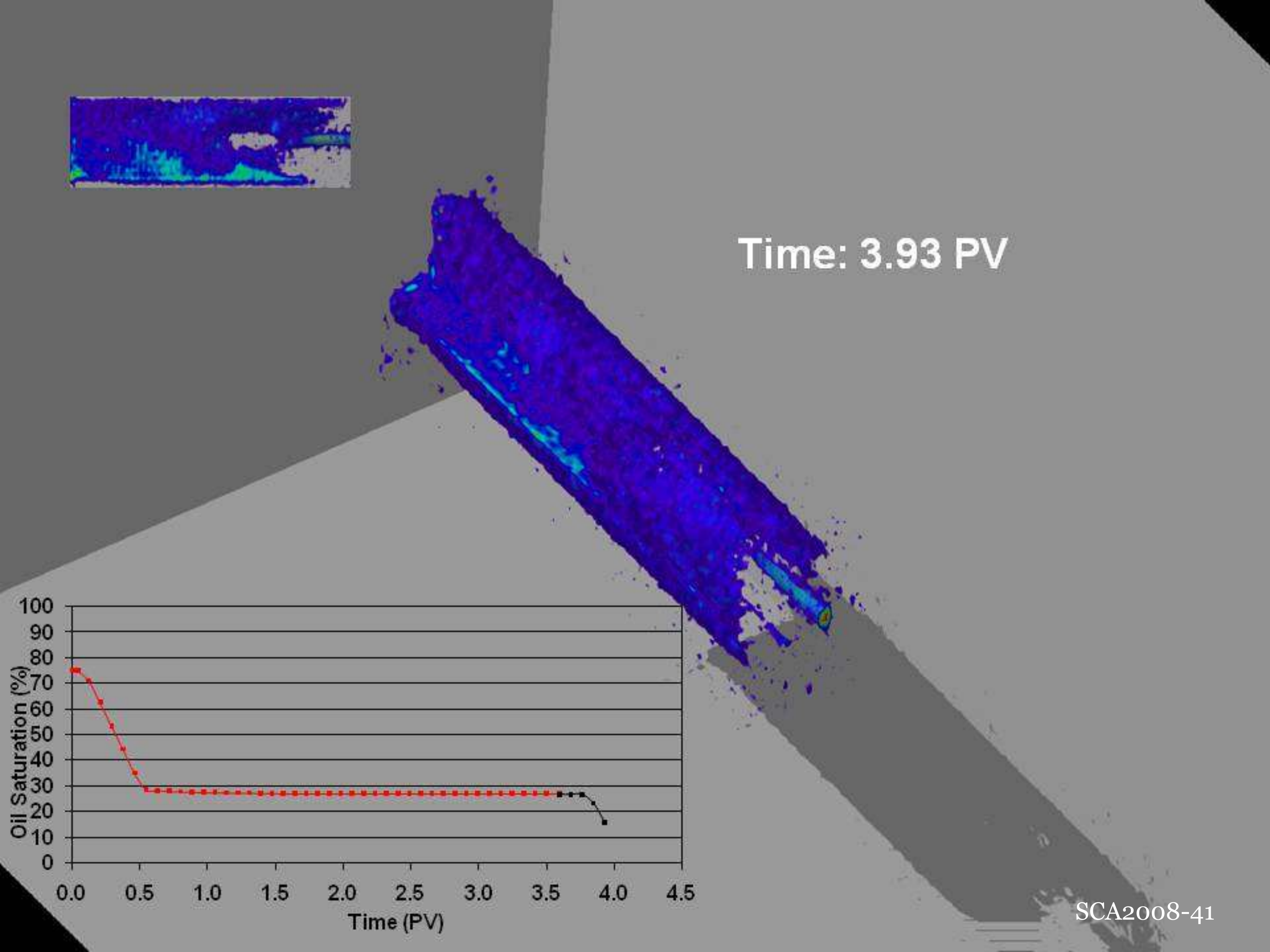
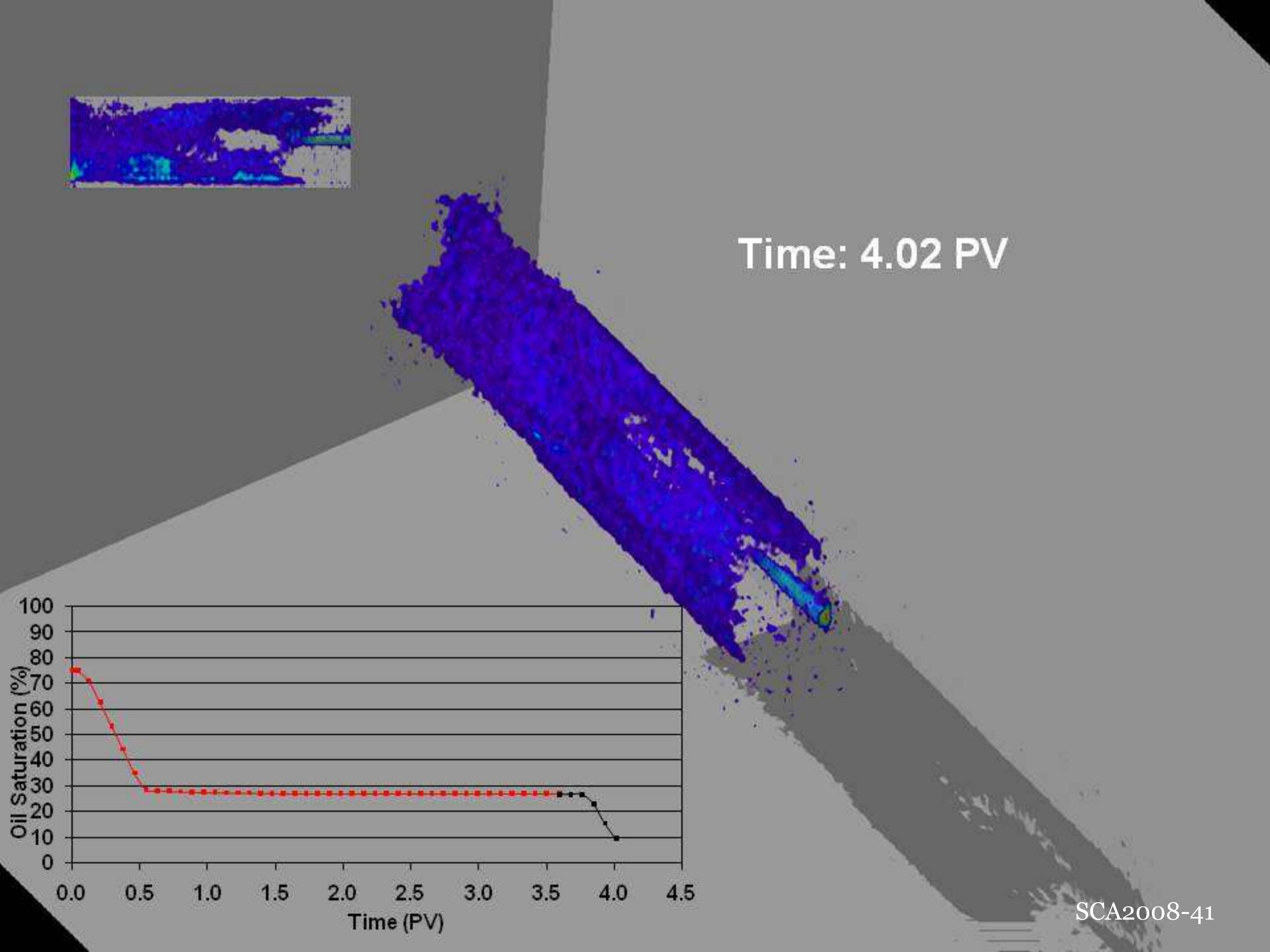
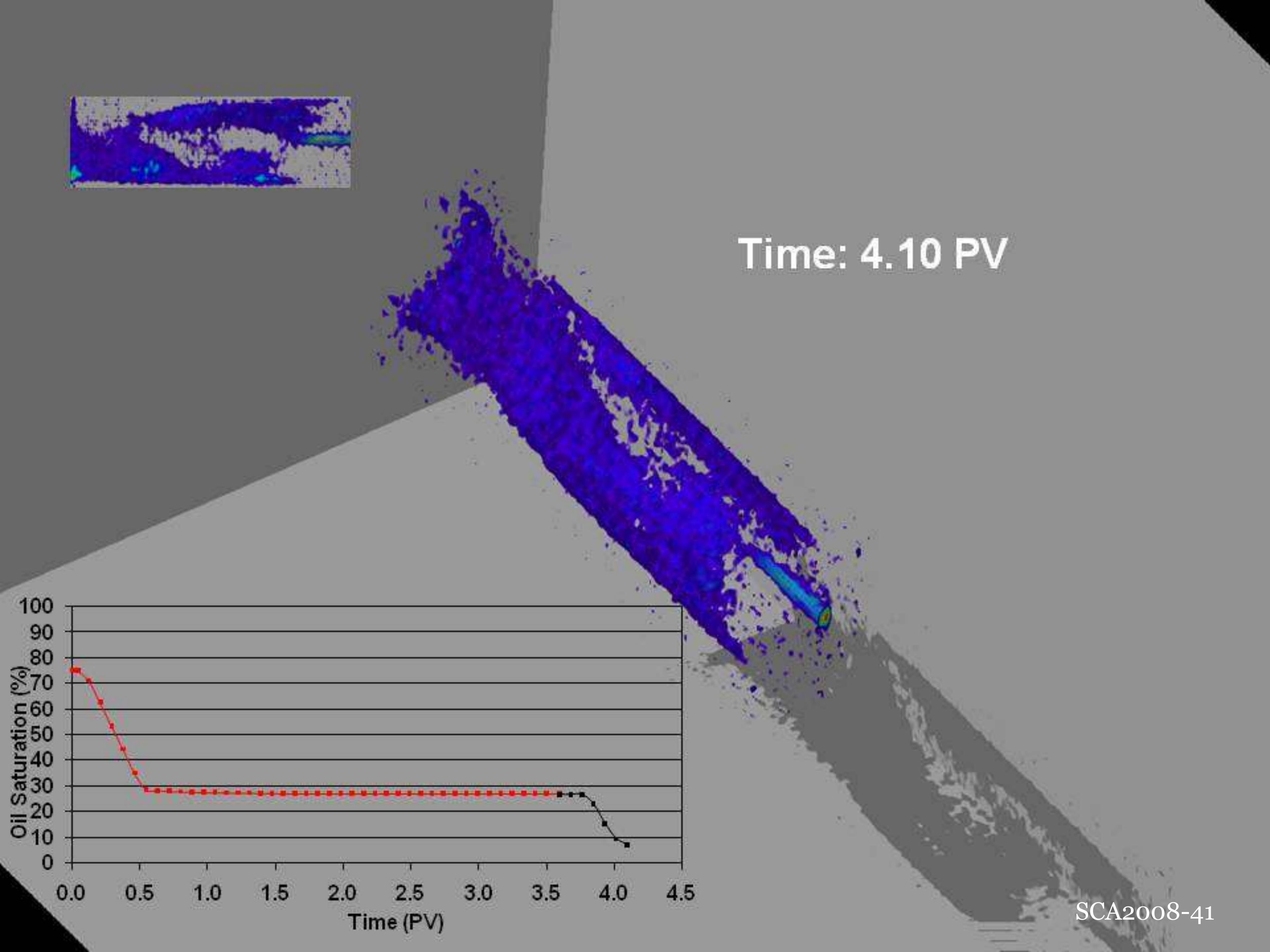

Time: 3.76 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 3.85 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

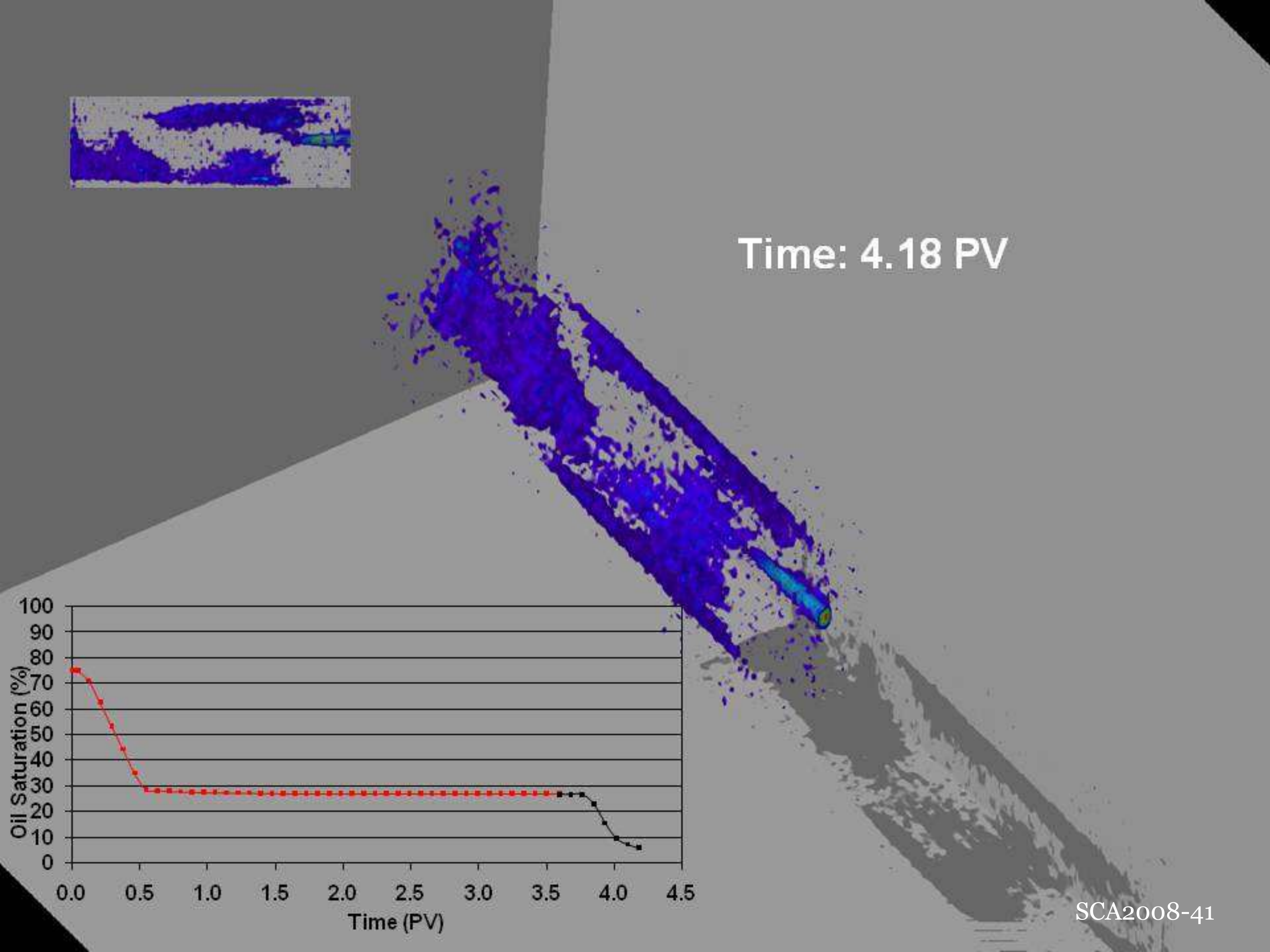


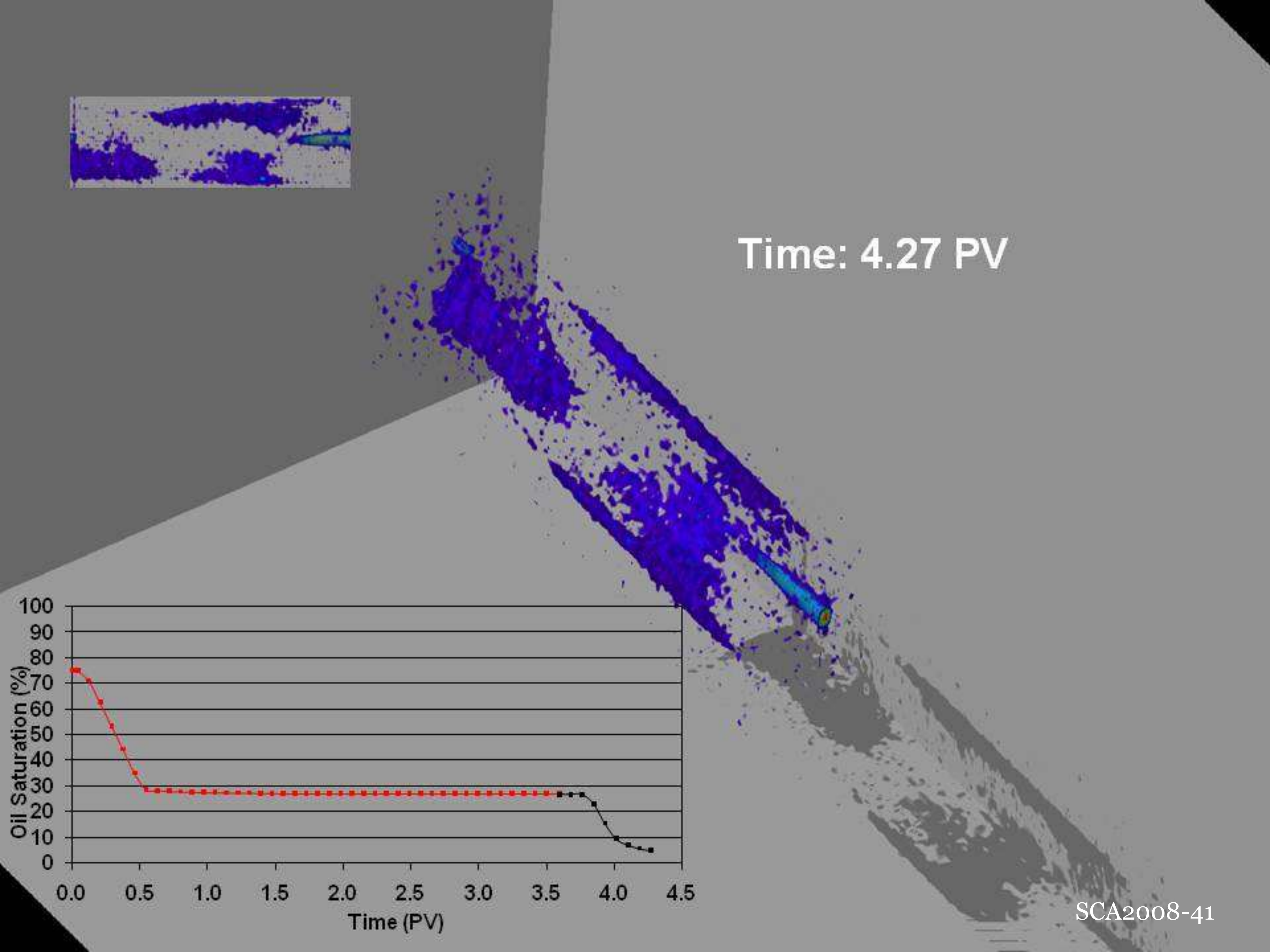
Time: 3.93 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 4.02 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

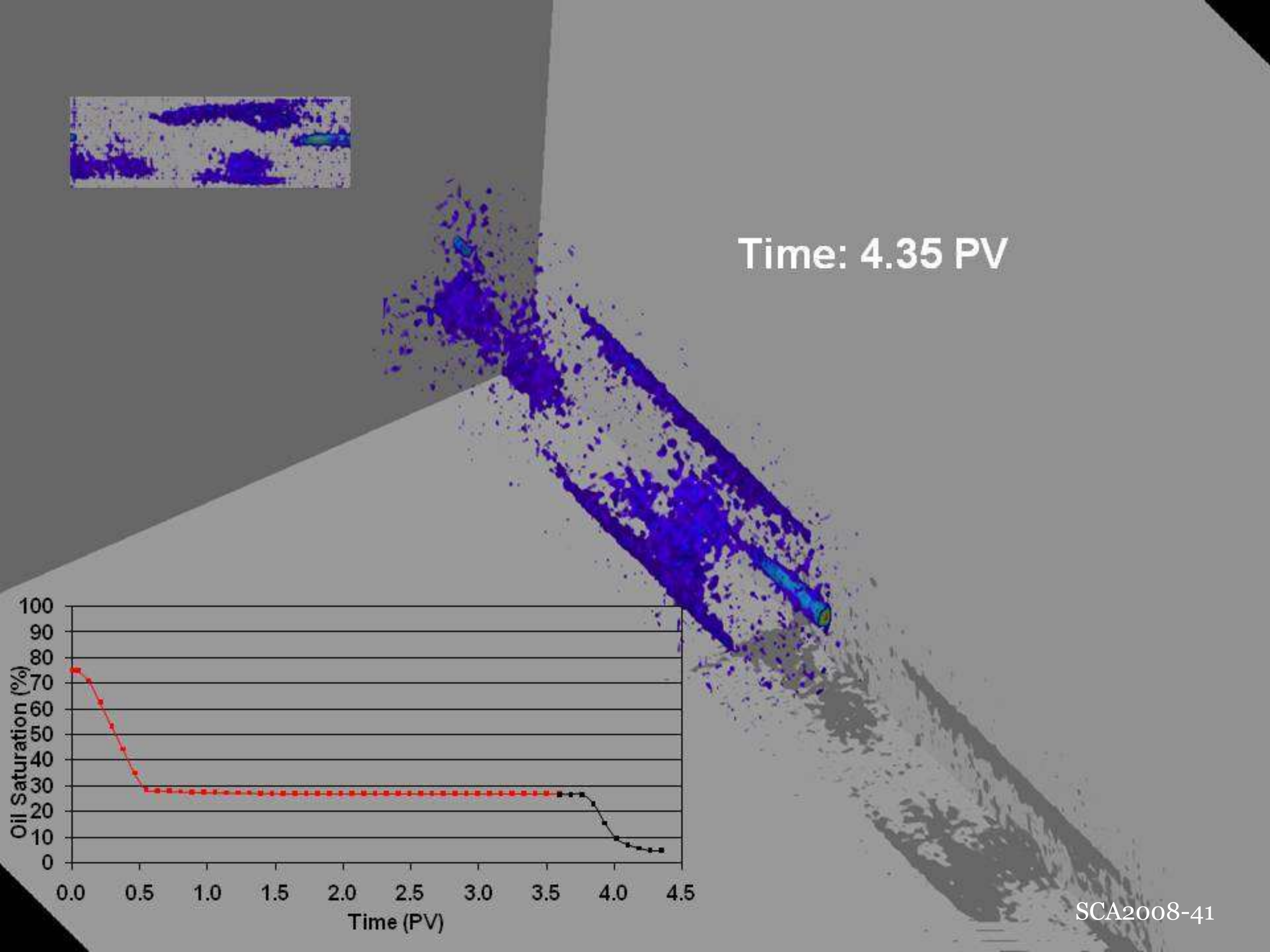


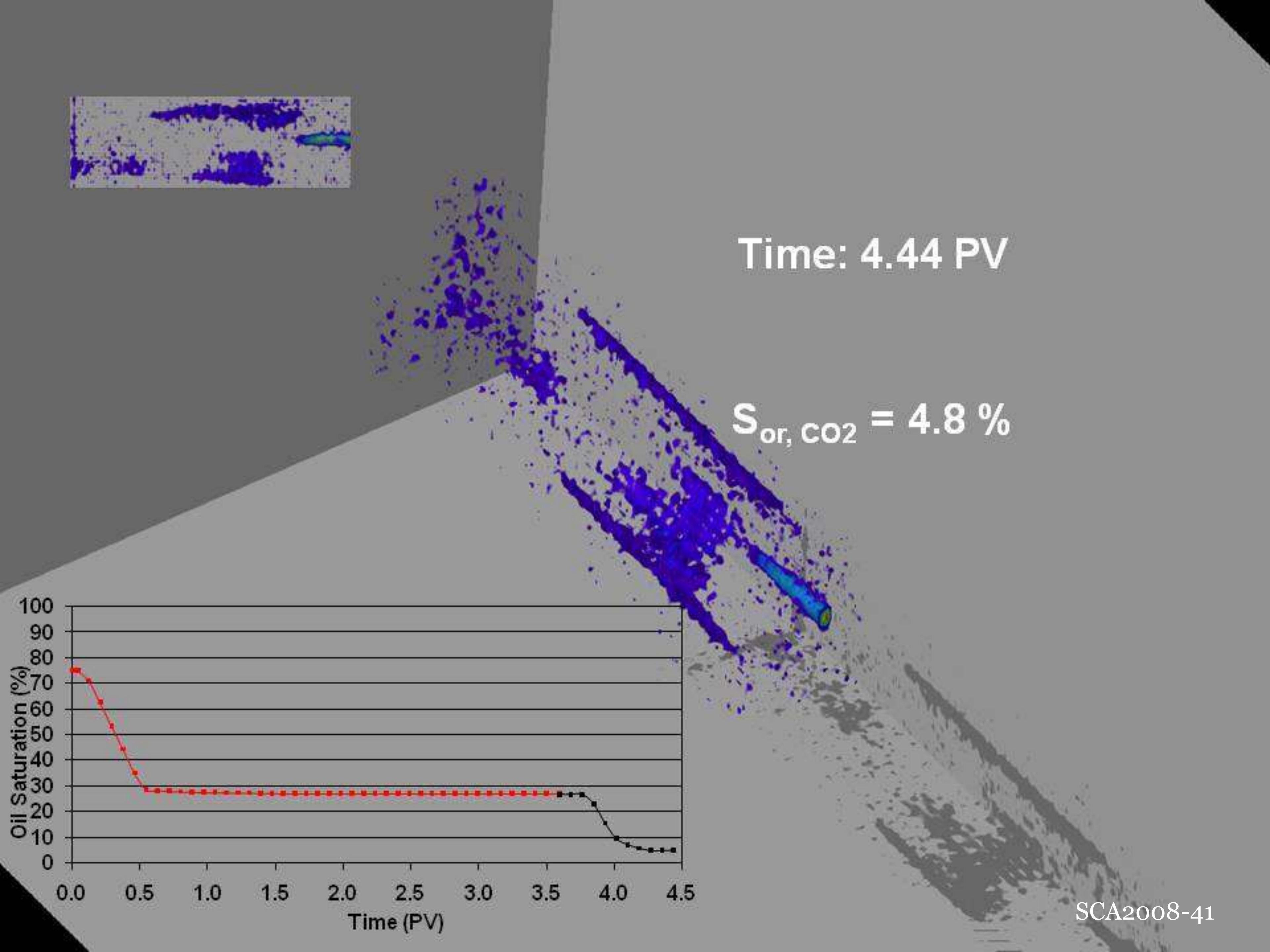
Time: 4.10 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)


Time: 4.18 PV
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)



Time: 4.27 PV
100
90
80
70
60
50
40
30
20
10
0
Oil Saturation (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

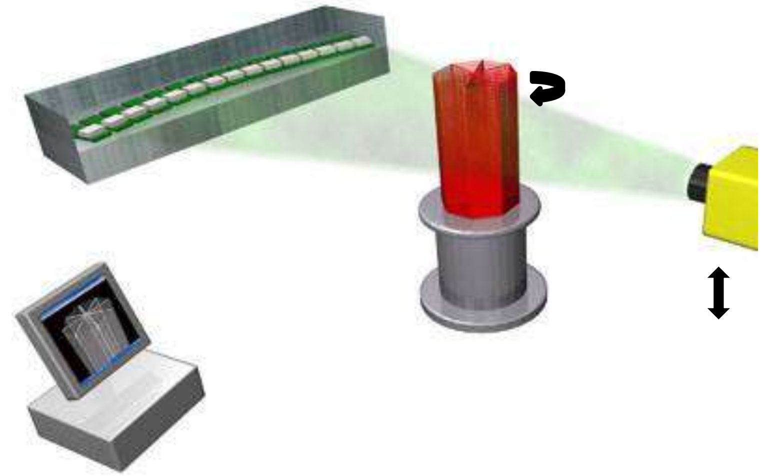

Time: 4.35 PV
Oil Saturation (%)
Time (PV)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5



Time: 4.44 PV
$S_{or,\ CO2}$ = 4.8 %
Oil Saturation (%)
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time (PV)

Industrial CT

- Consists of a sample rotator, an x-ray source and a detector
- The detector measures the absorption of x-rays when they pass through the sample
- The sample rotates, creating a 2D image of each layer, and by moving either the sample or the detector system vertically, a 3D image is made

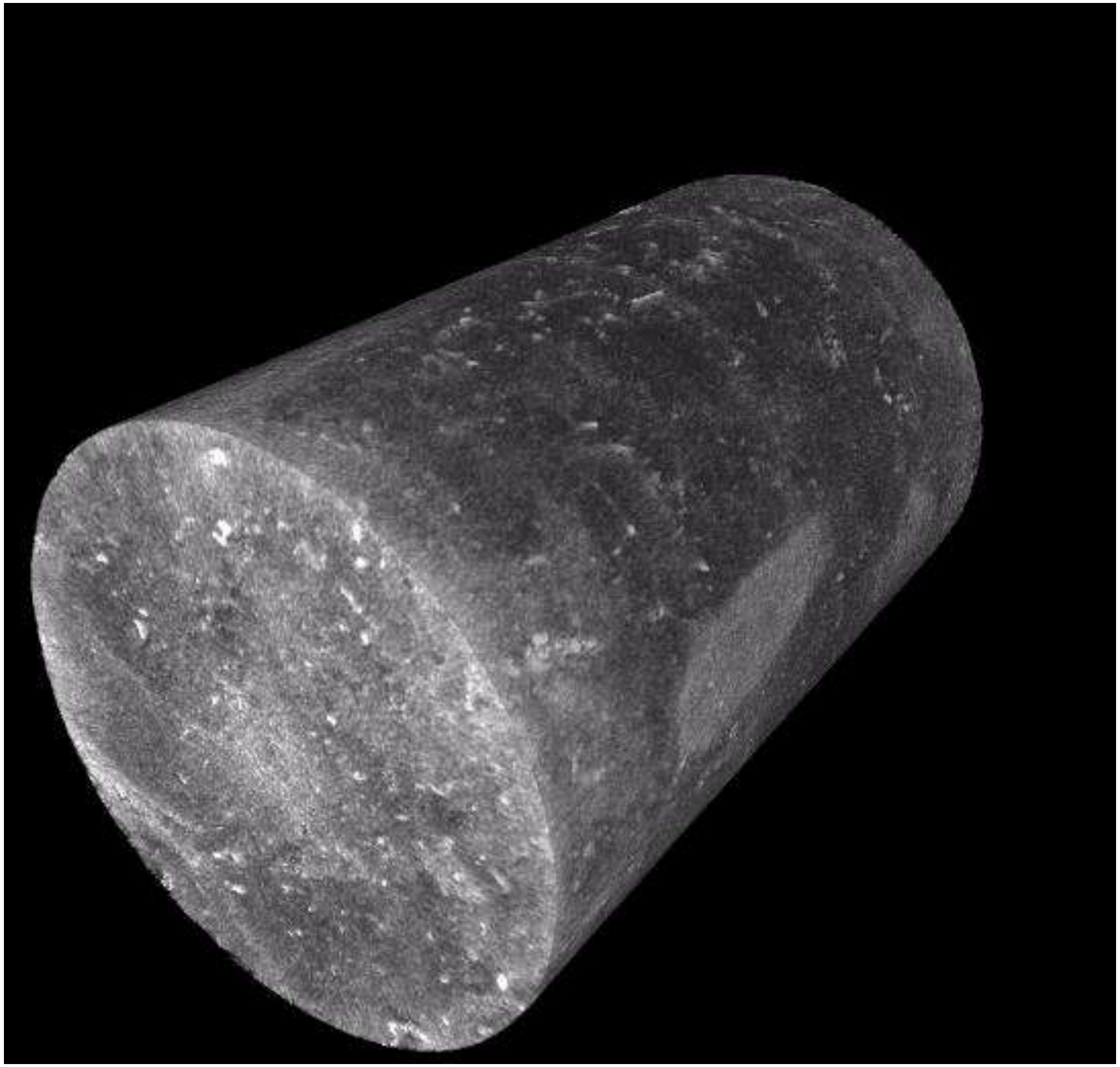


From www.deetee.com

- Can be moved closer to the source then a medical CT, and thus has larger resolution
- Much higher resolution then other imaging techniques
  - MRI ≈ 1000 microns
  - Medical CT ≈ 250 microns
  - Industrial CT ≈ 5 microns
- Runs at high voltage, meaning more energetic and penetrating x-rays, which again leads to higher resolution, but also lower contrast images
- Runs at low power
- Following images taken at 160 keV, with a resolution of 40 microns per voxel, with 1024*1024*1400 voxels

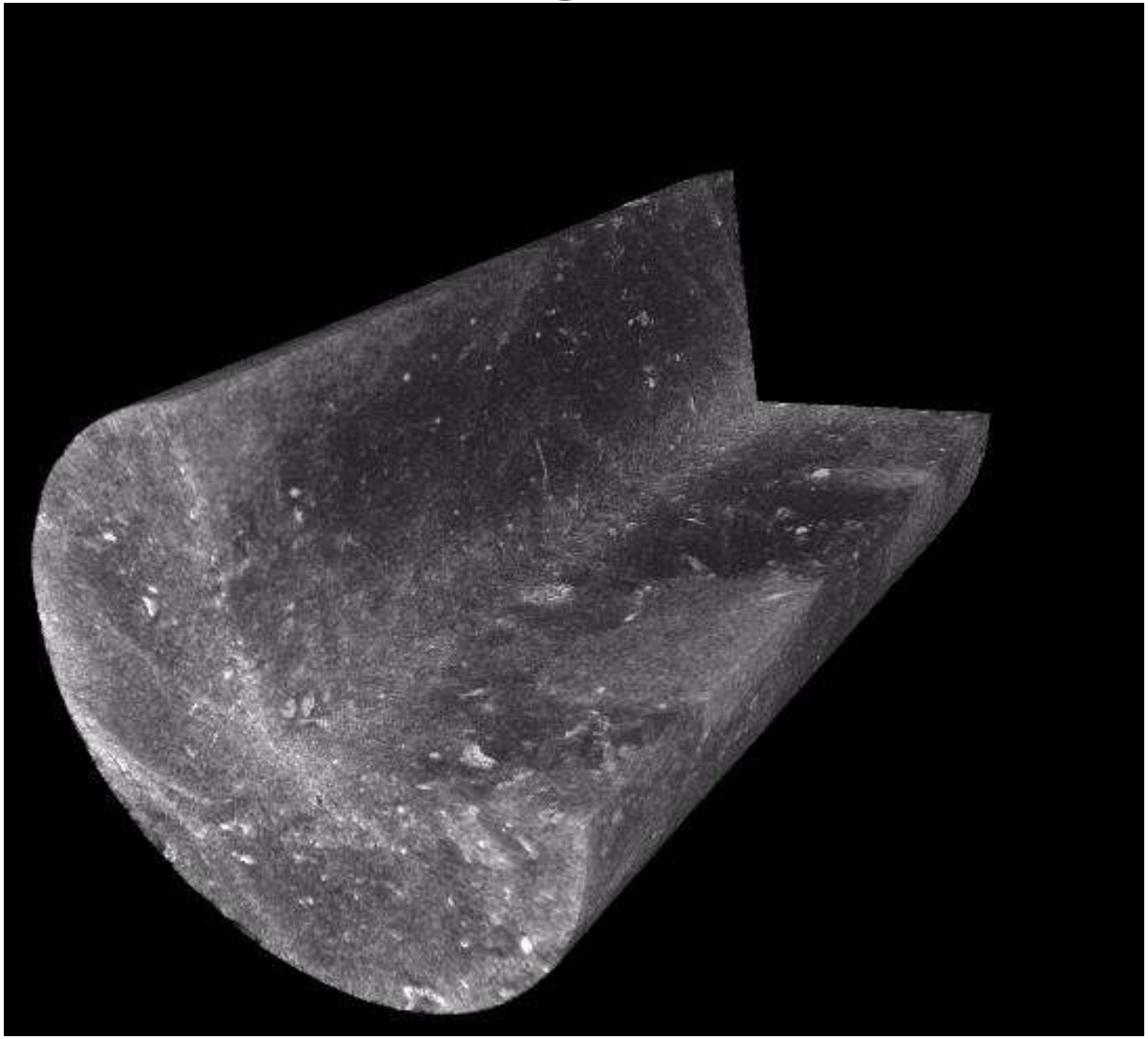
Results:
Rock characterization using CT

- 40 x 40 x 42 microns resolution
- 1.5“ Portland chalk



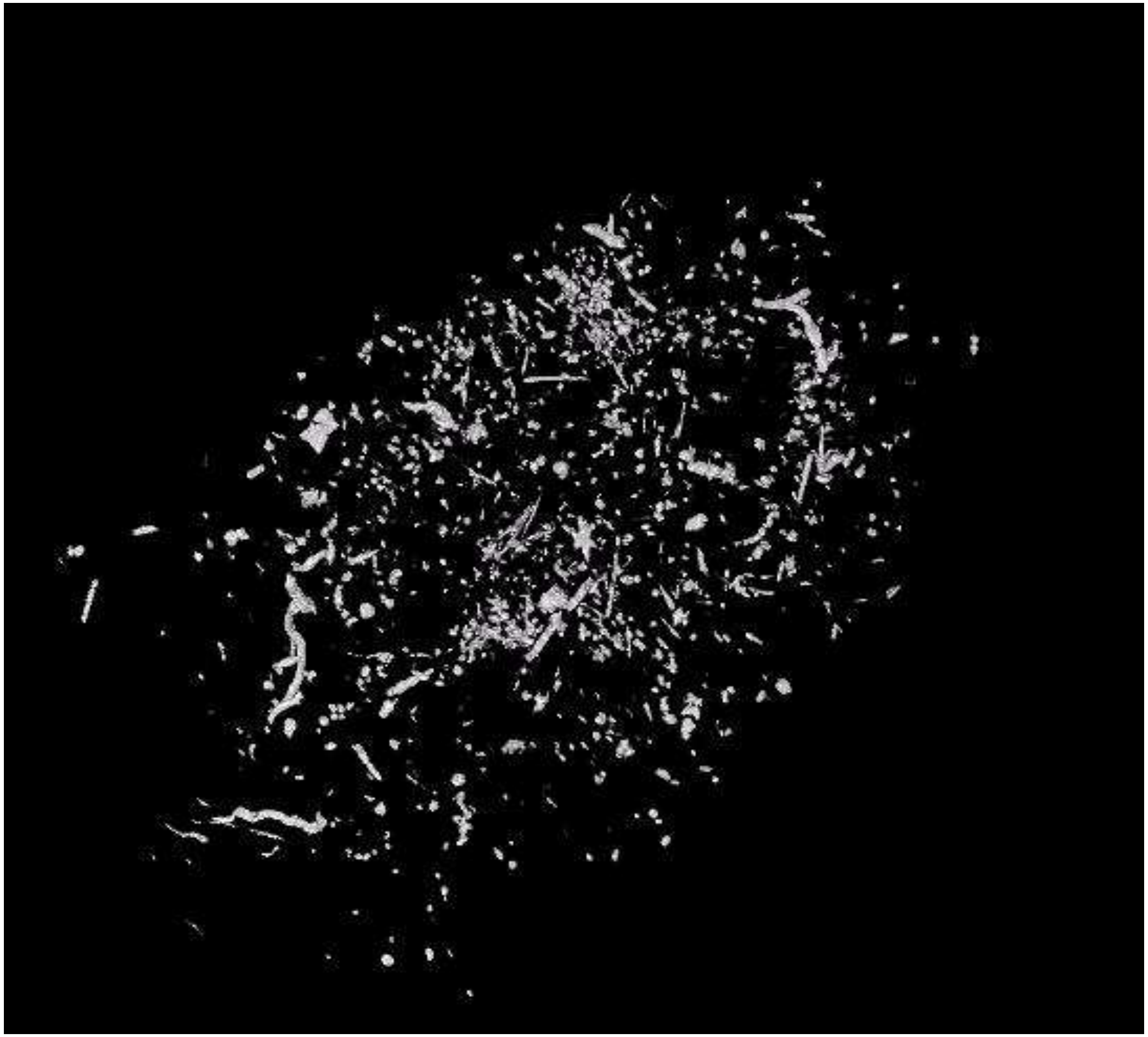
Results:
Rock characterization using CT

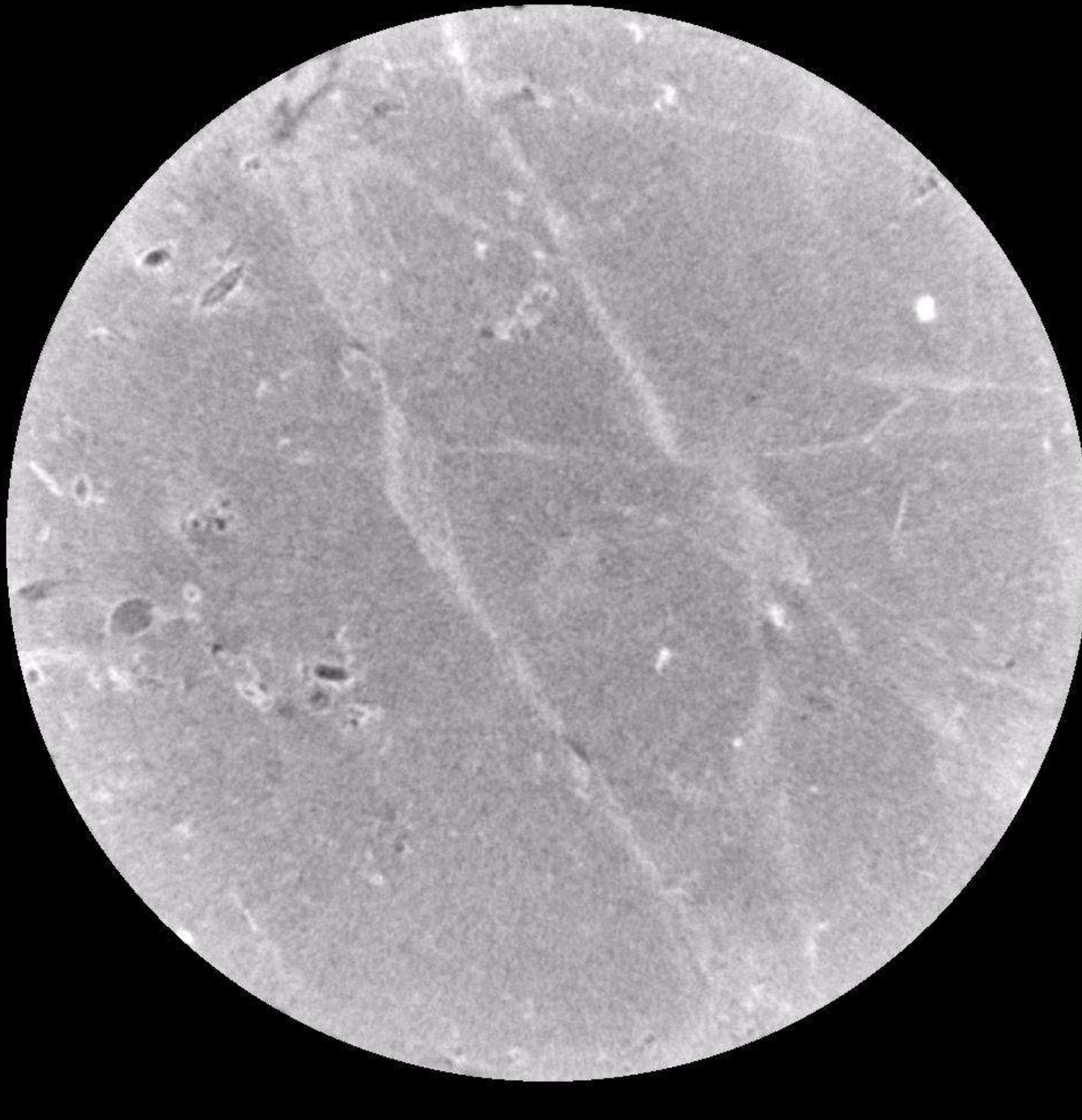
- 40 x 40 x 42 microns resolution
- 1.5" Portland chalk

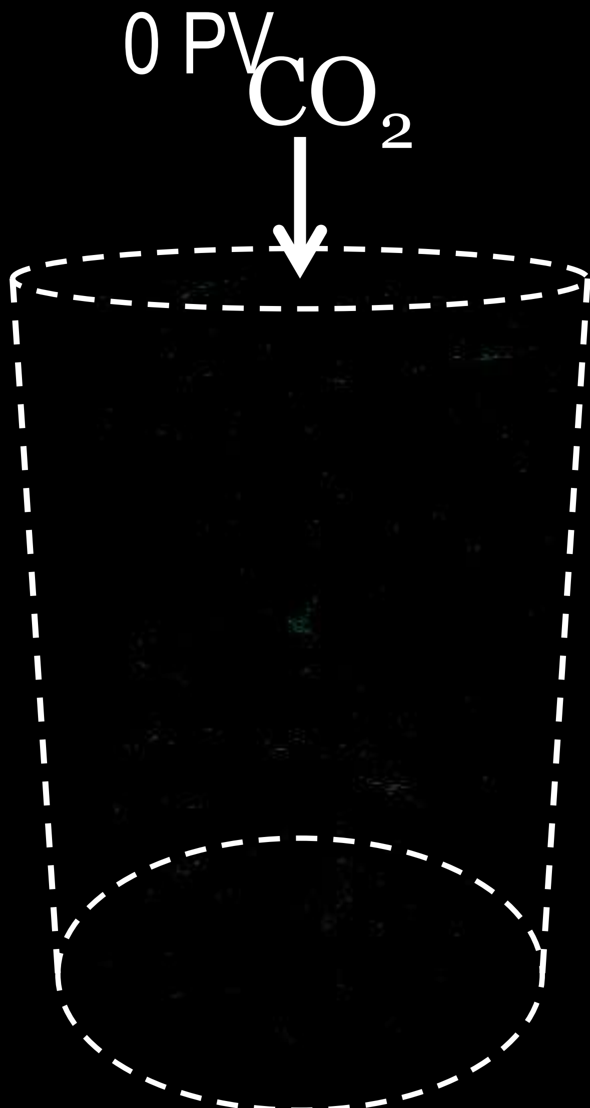


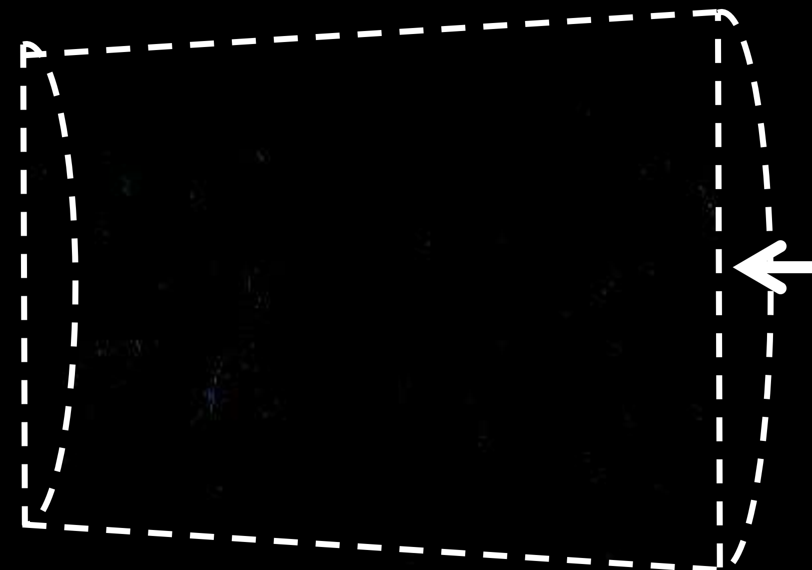
Results: Rock characterization using CT

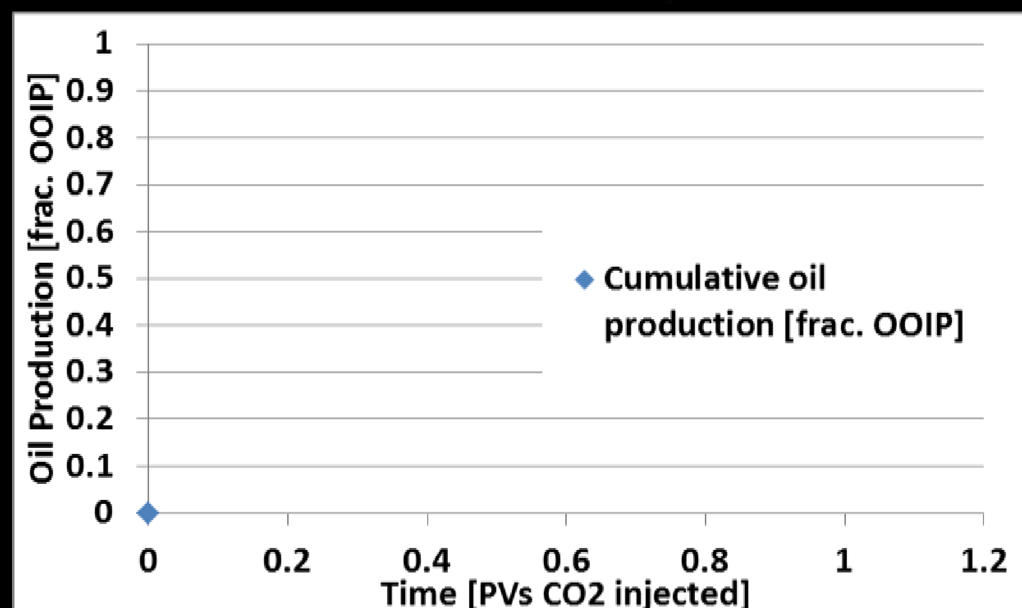
- 40 x 40 x 42 microns resolution
- 1.5“ Portland chalk



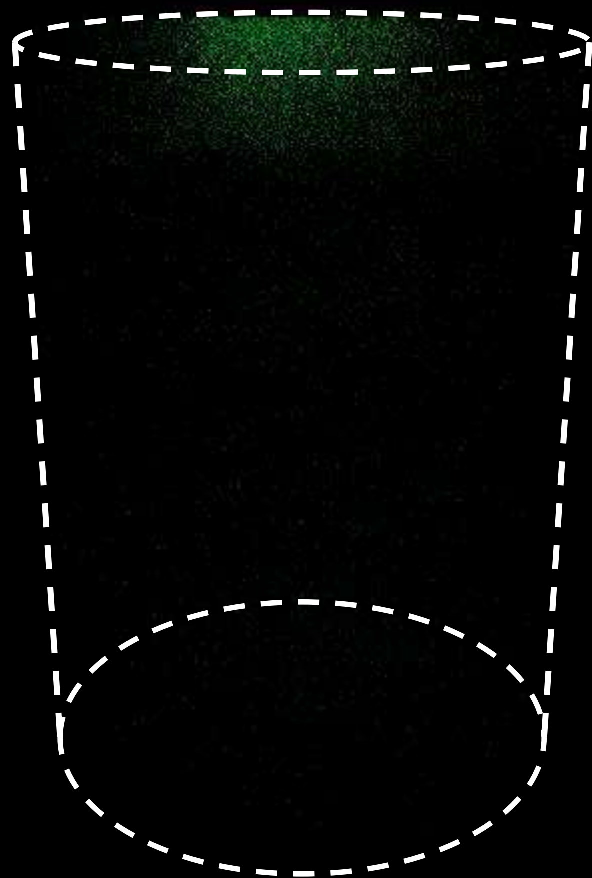


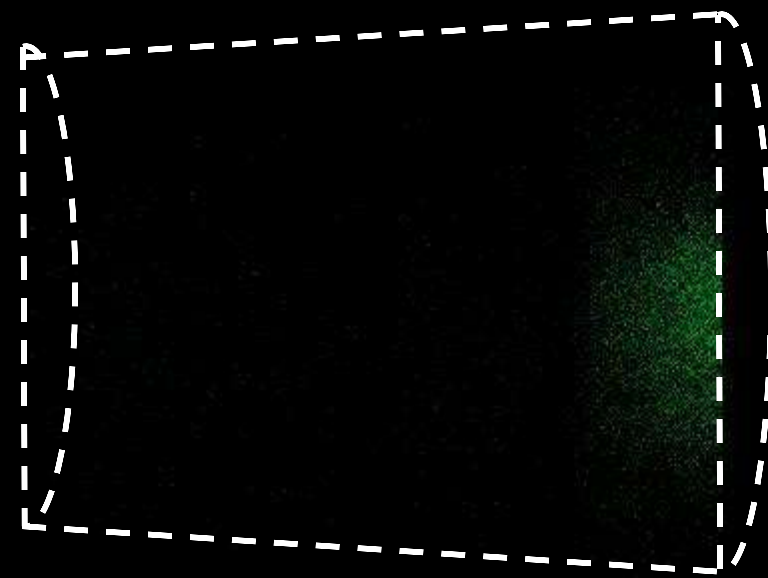

0 PV
CO_2

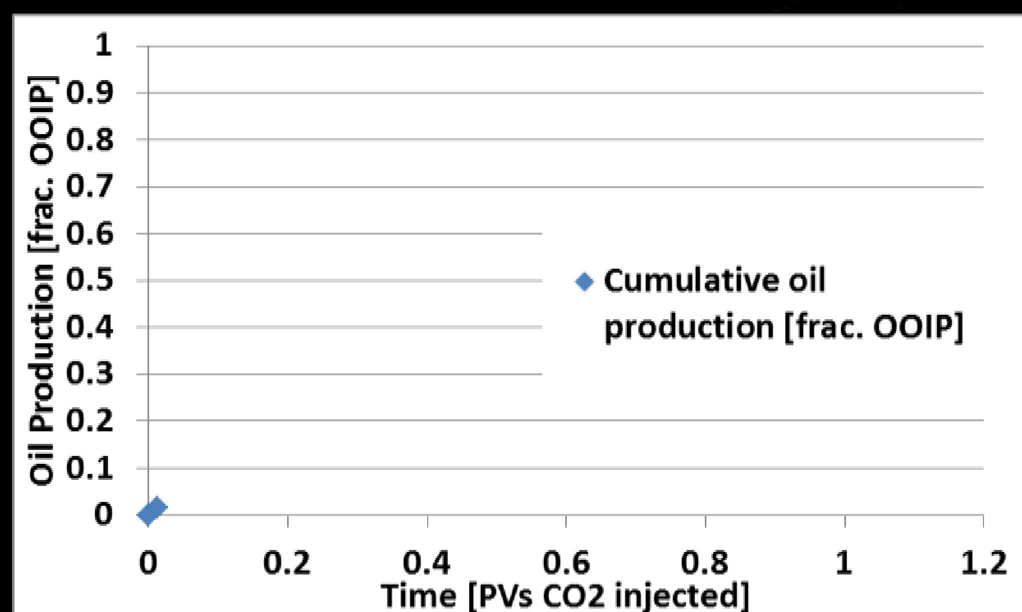



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

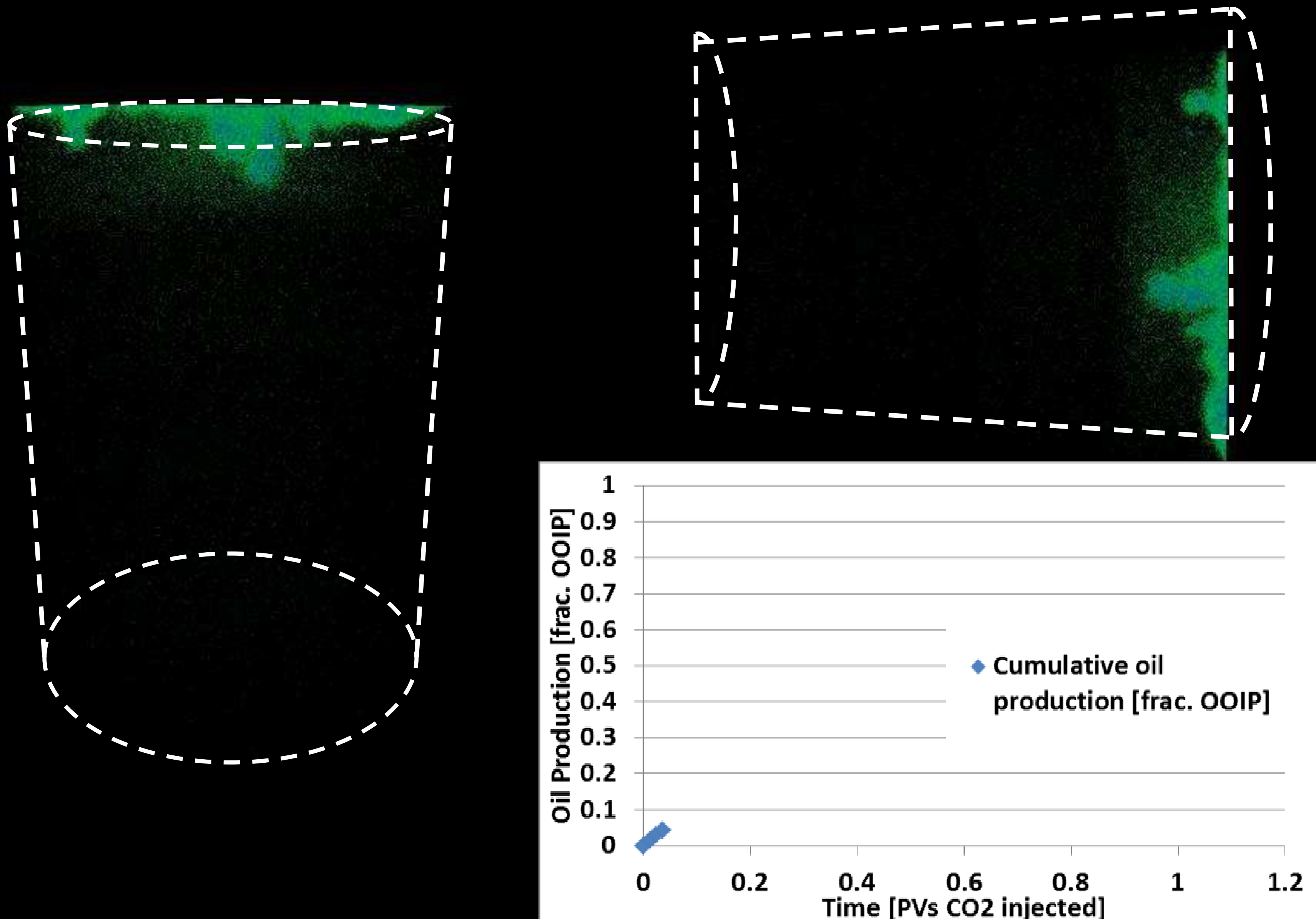
0.01 PV



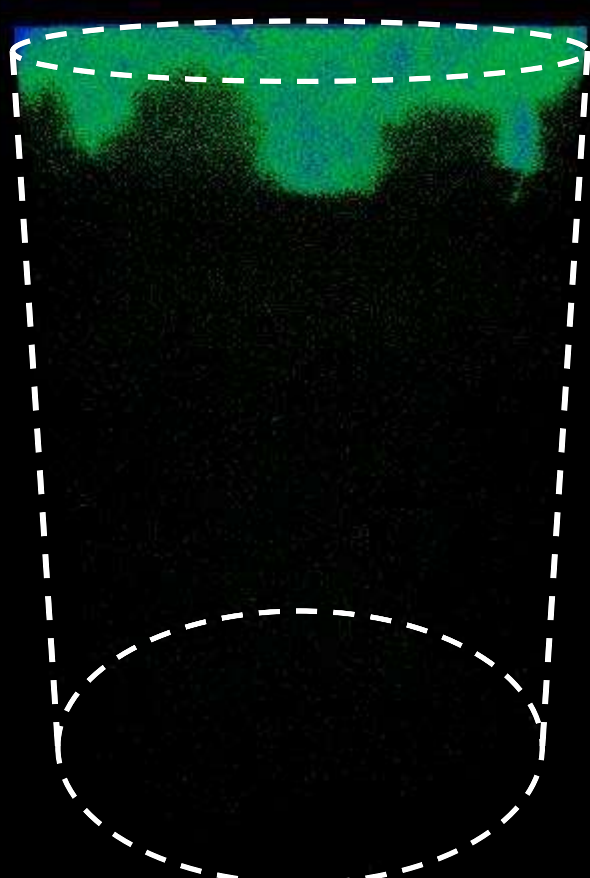


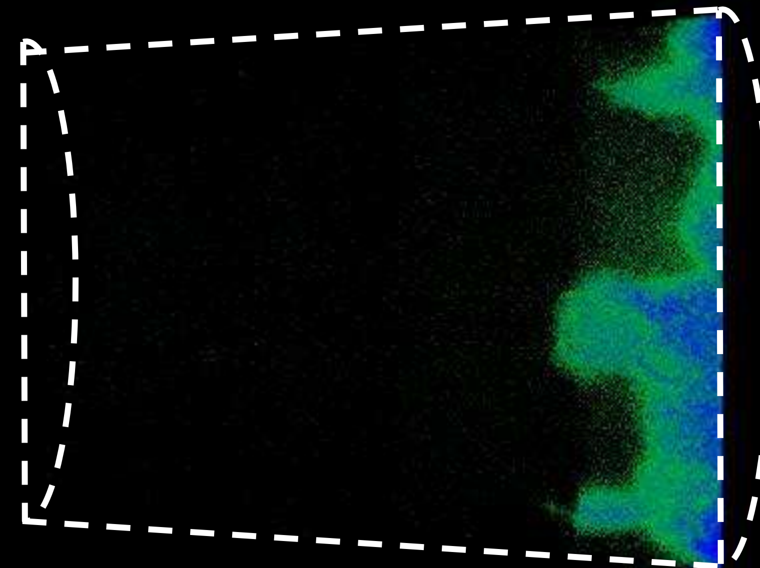

Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

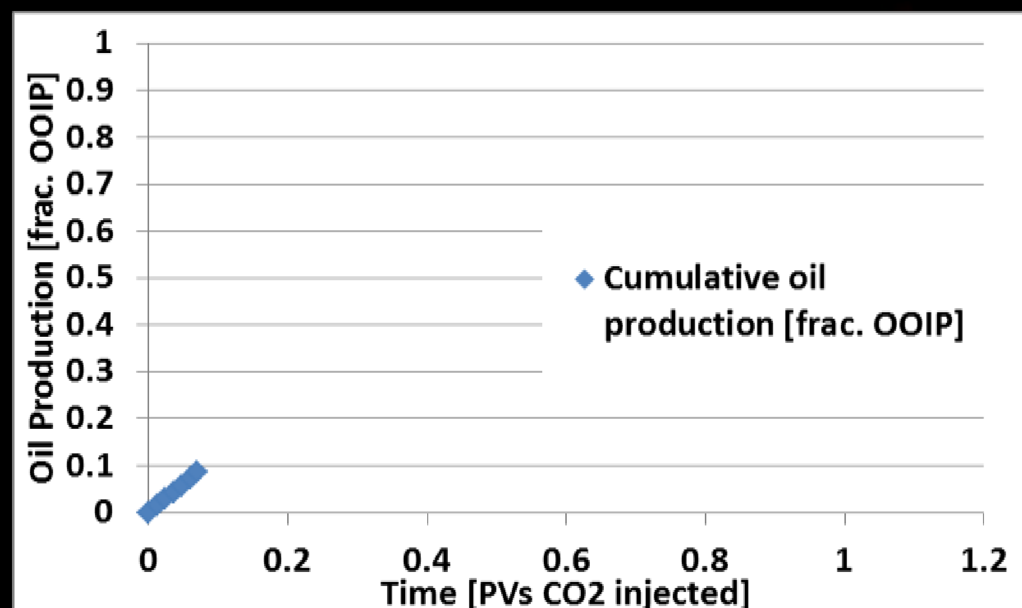
0.04 PV


Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

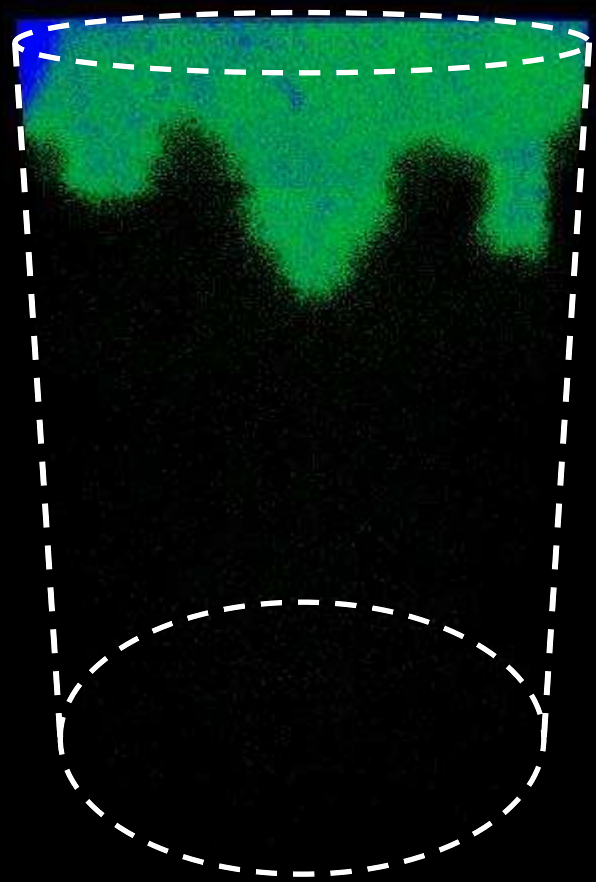
0.07 PV

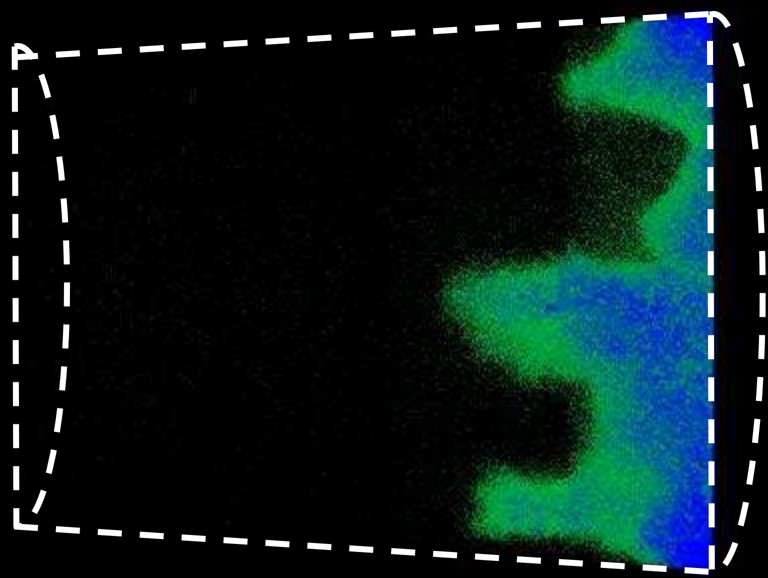


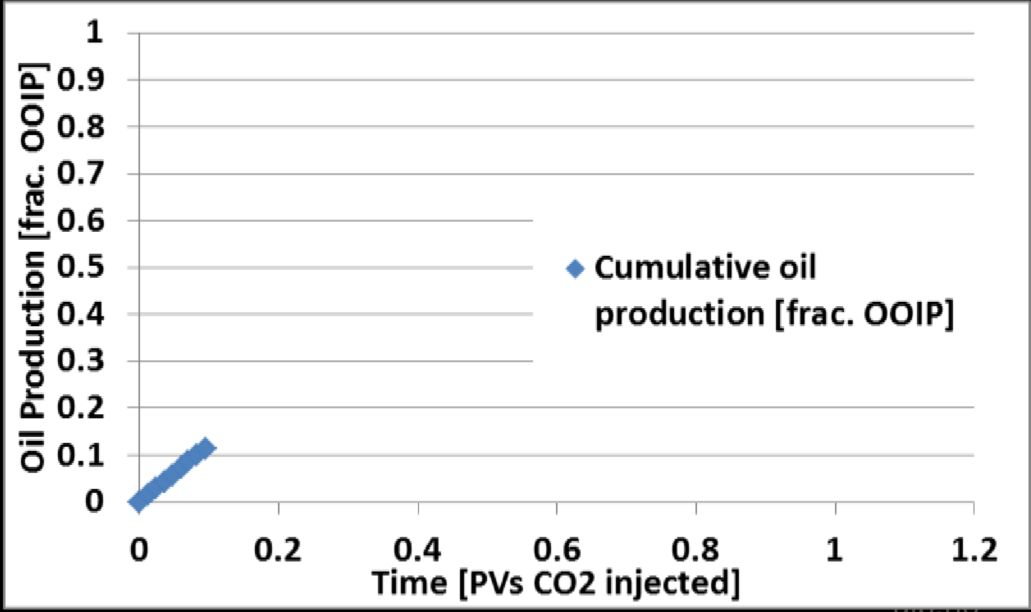



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

0.10 PV

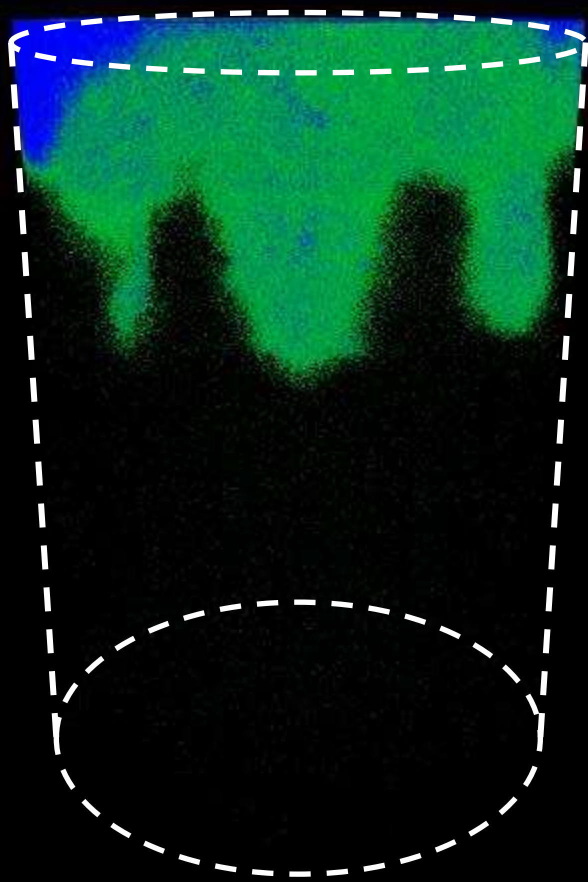


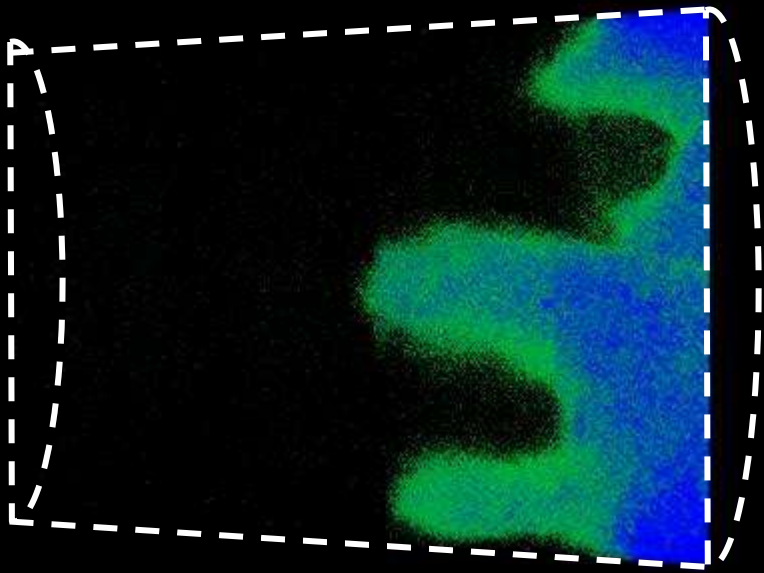


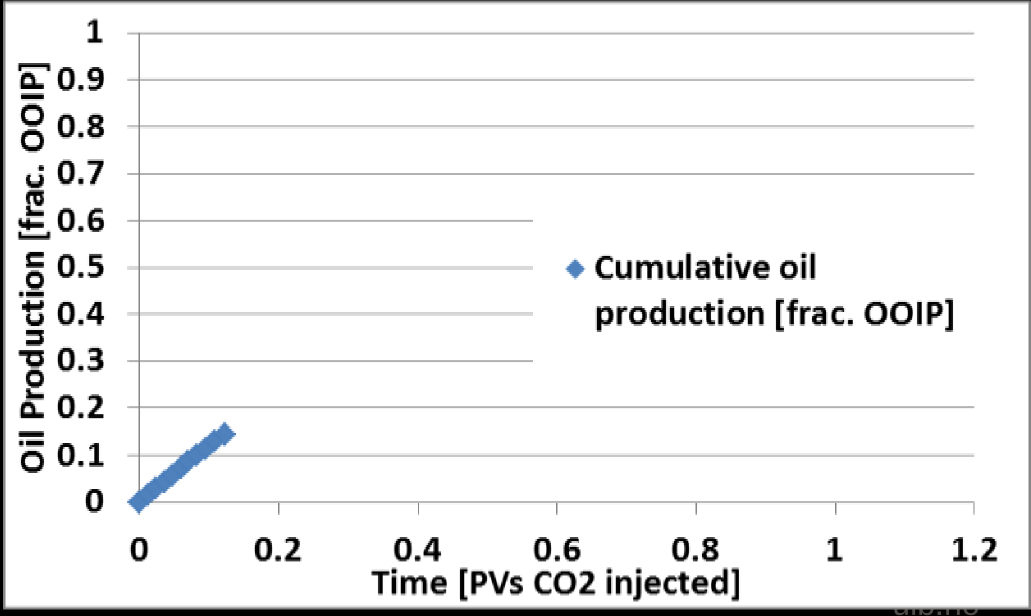


Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

0.12 PV

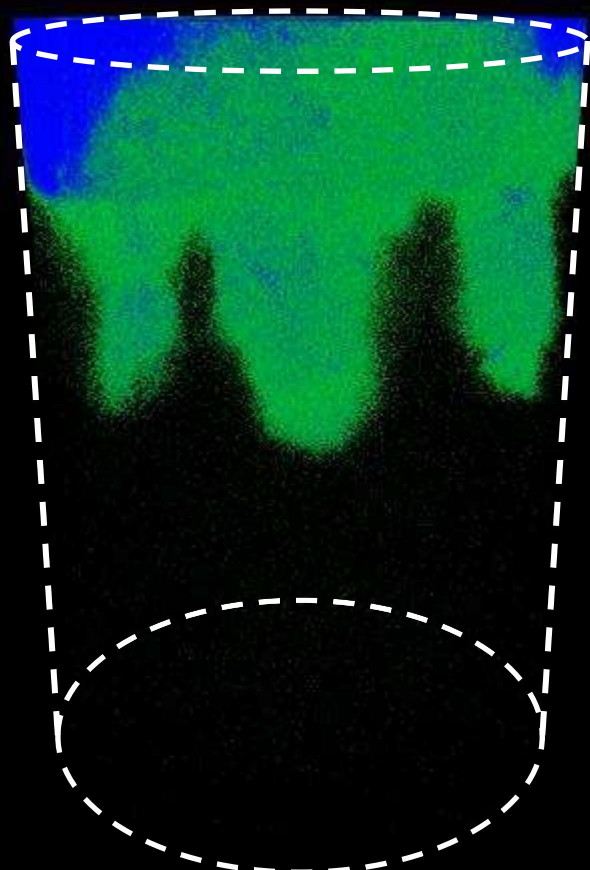


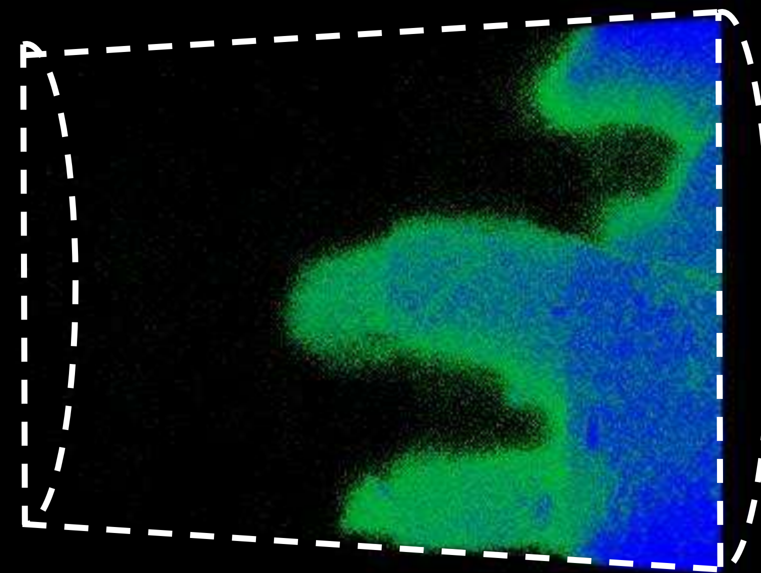


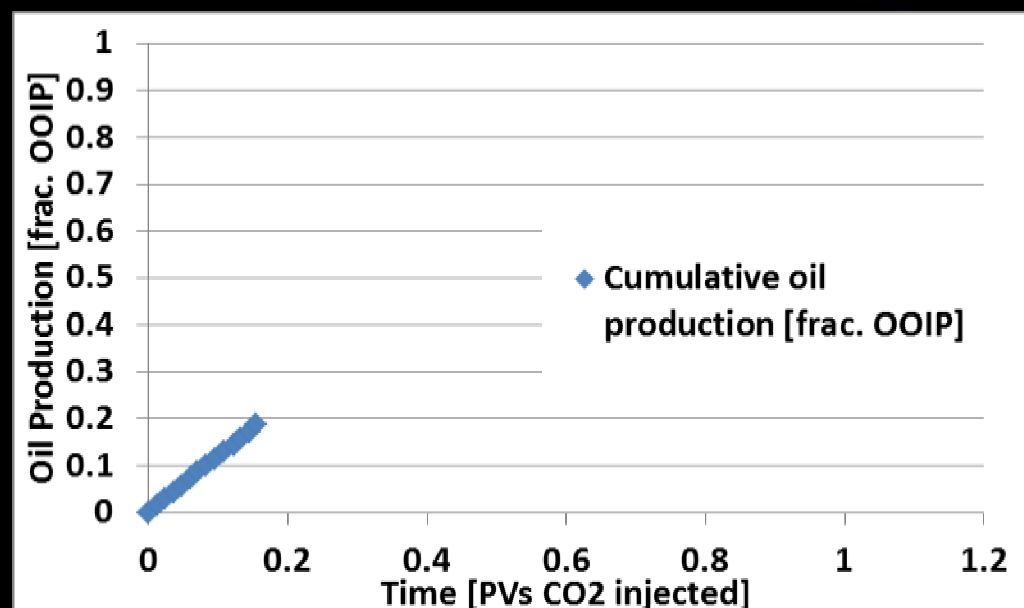


Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative oil production [frac. OOIP]
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]

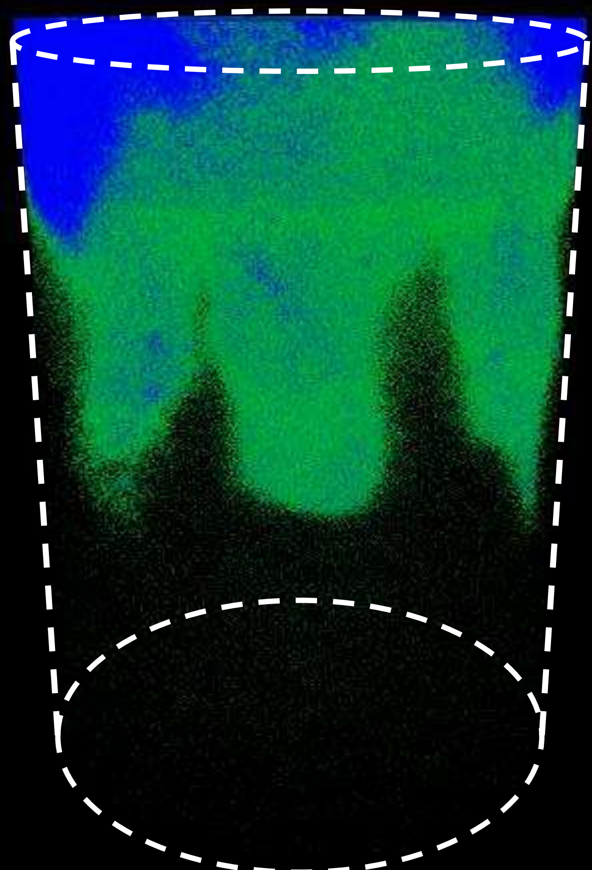
0.15 PV

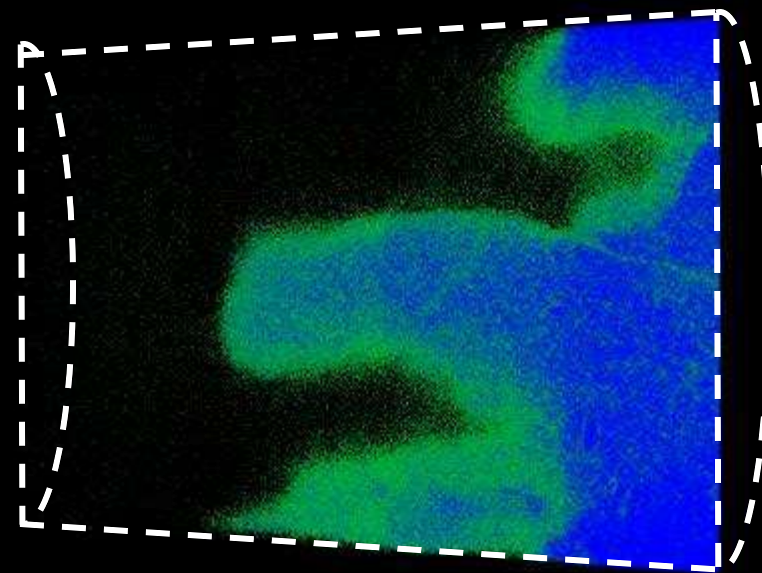


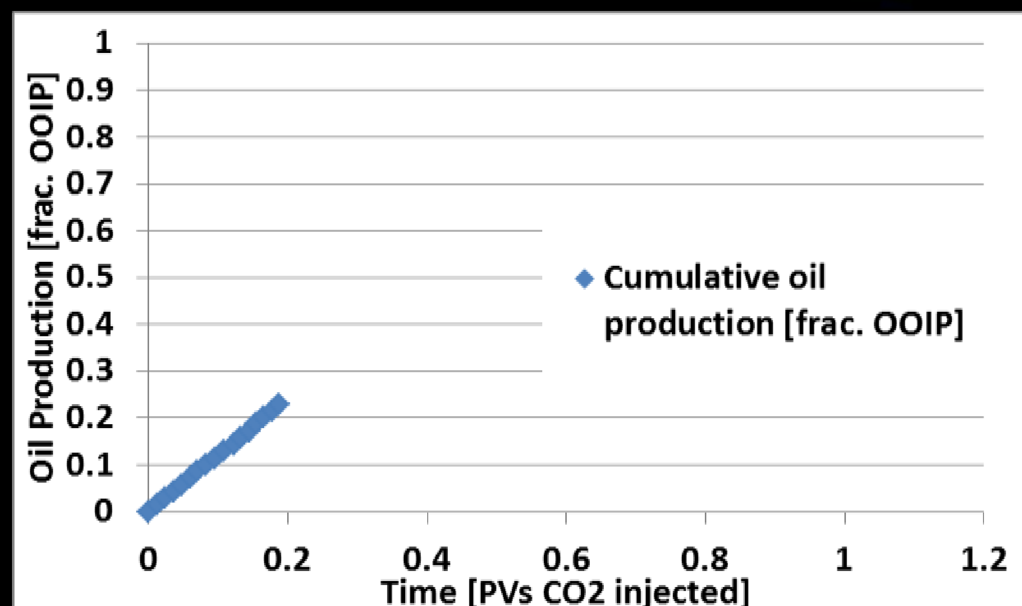



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

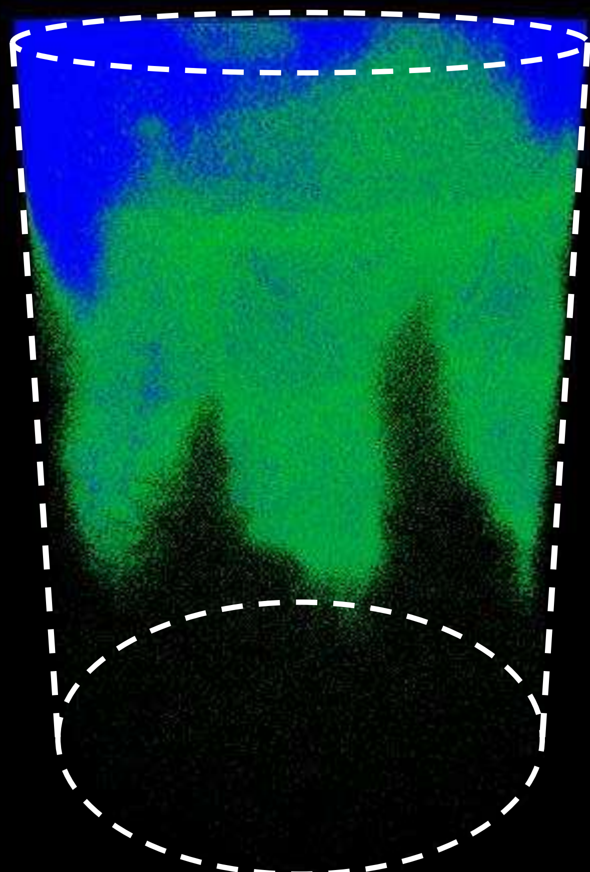
0.18 PV

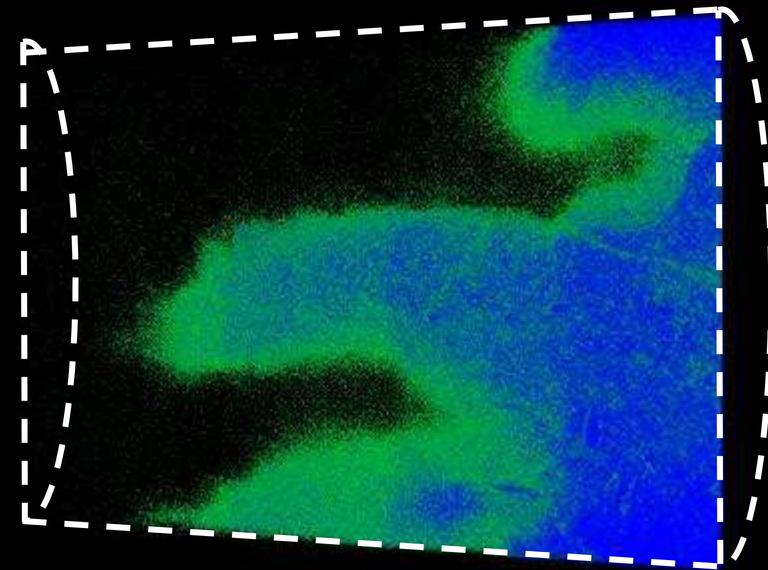


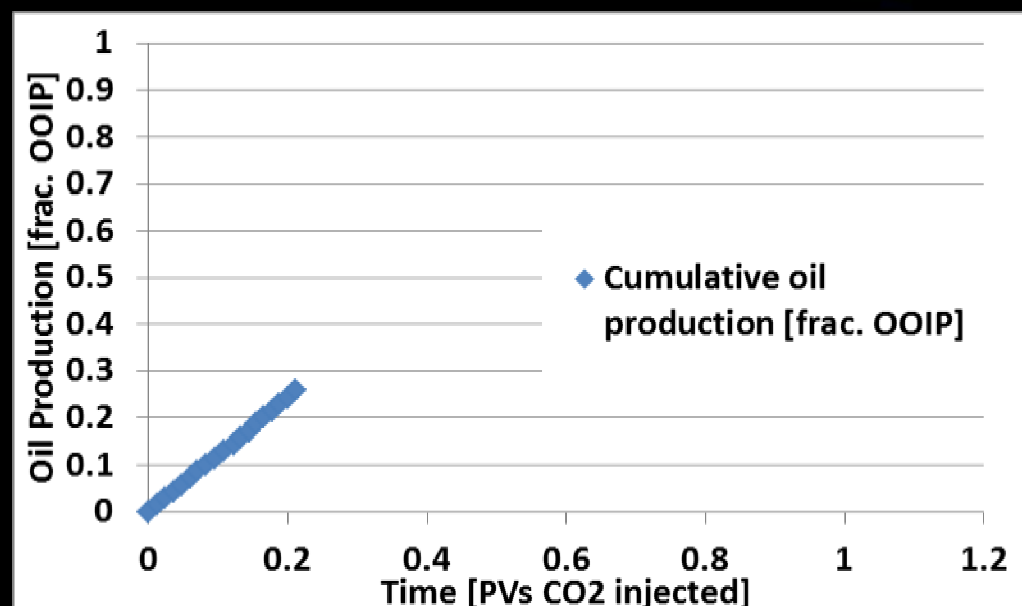



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

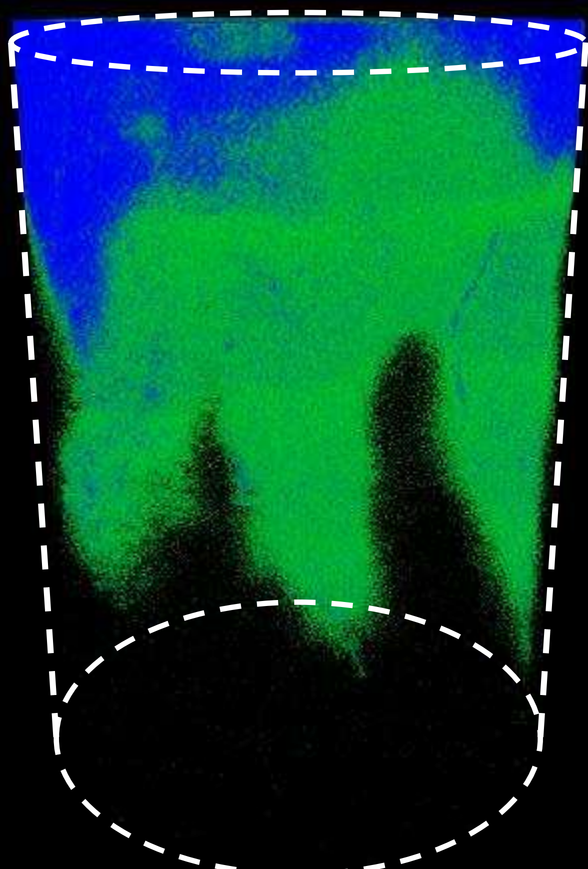
0.21 PV

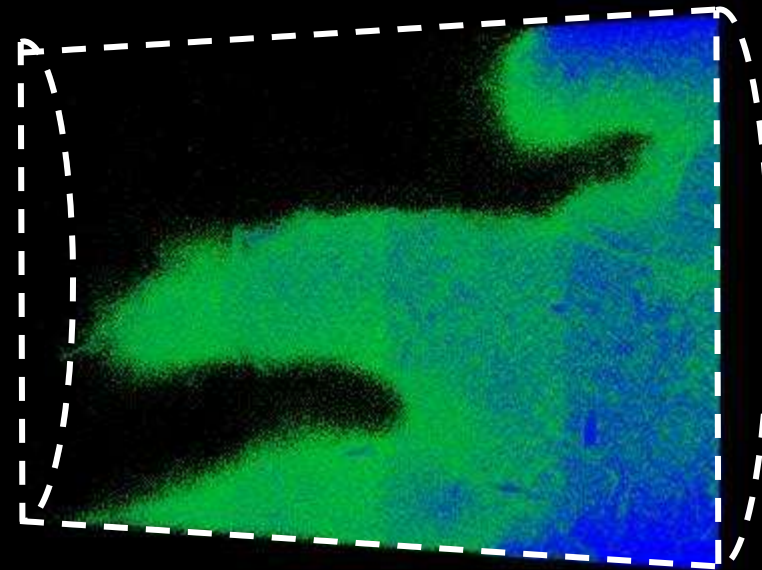


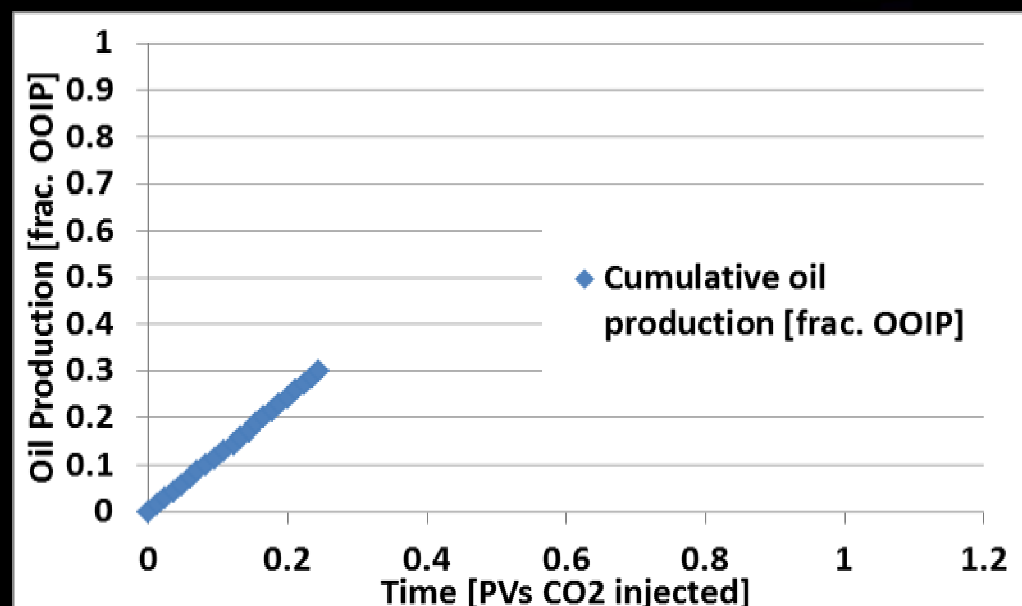



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

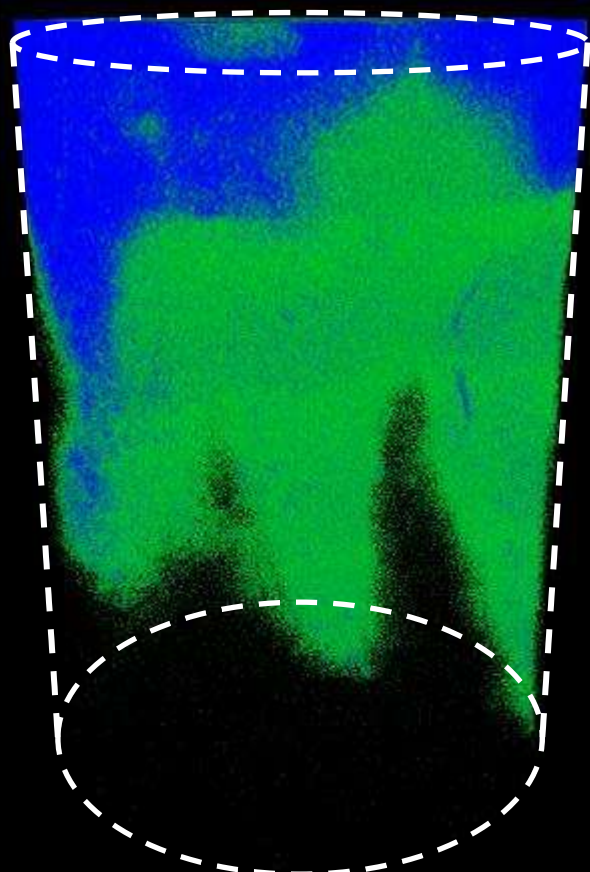
0.24 PV

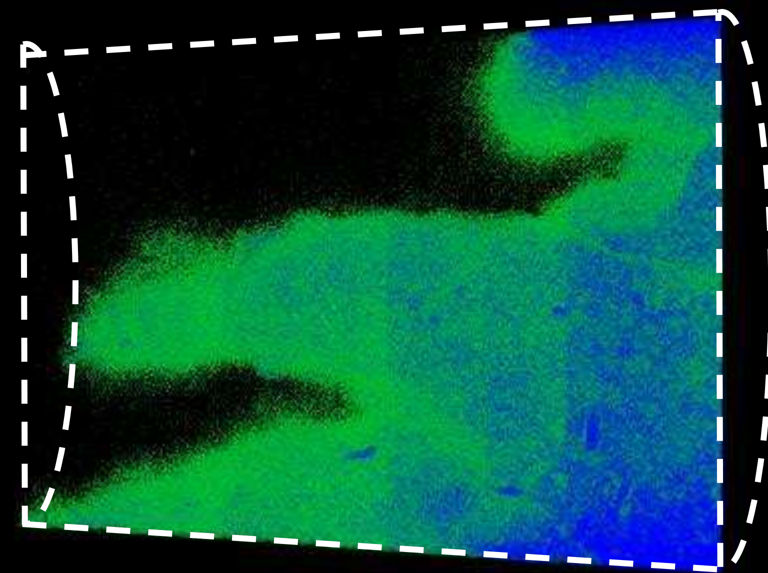


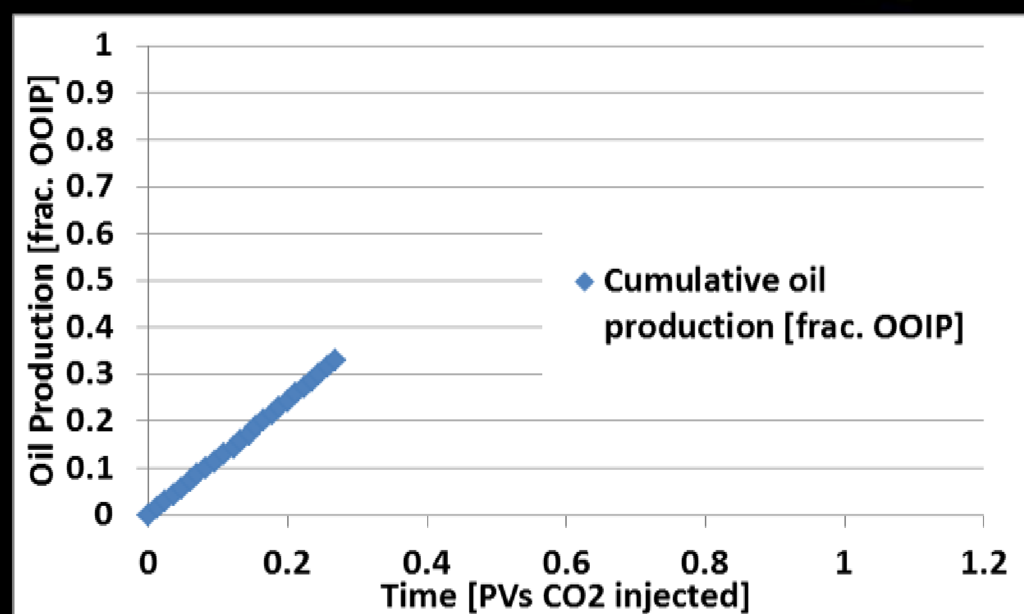



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

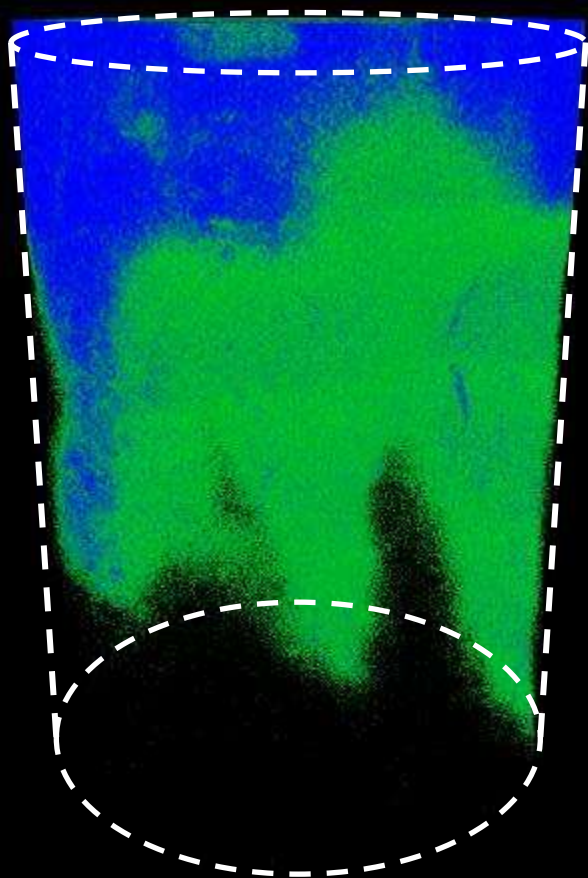
0.27 PV

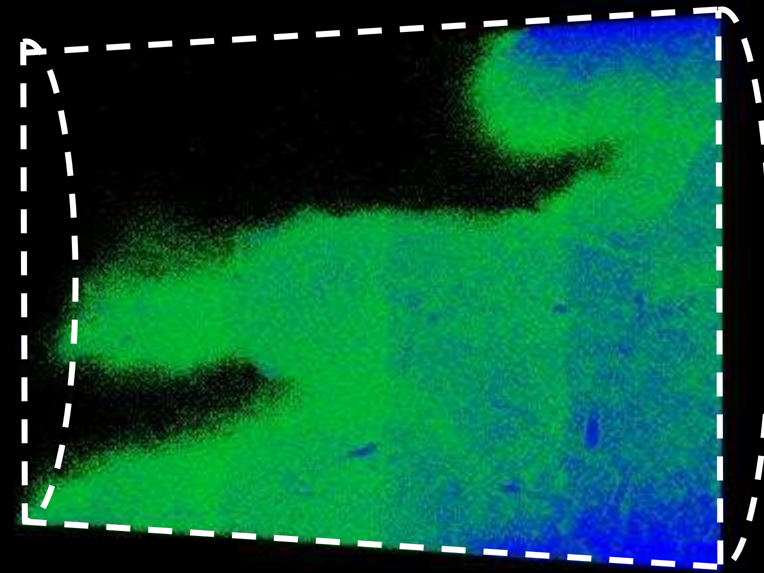


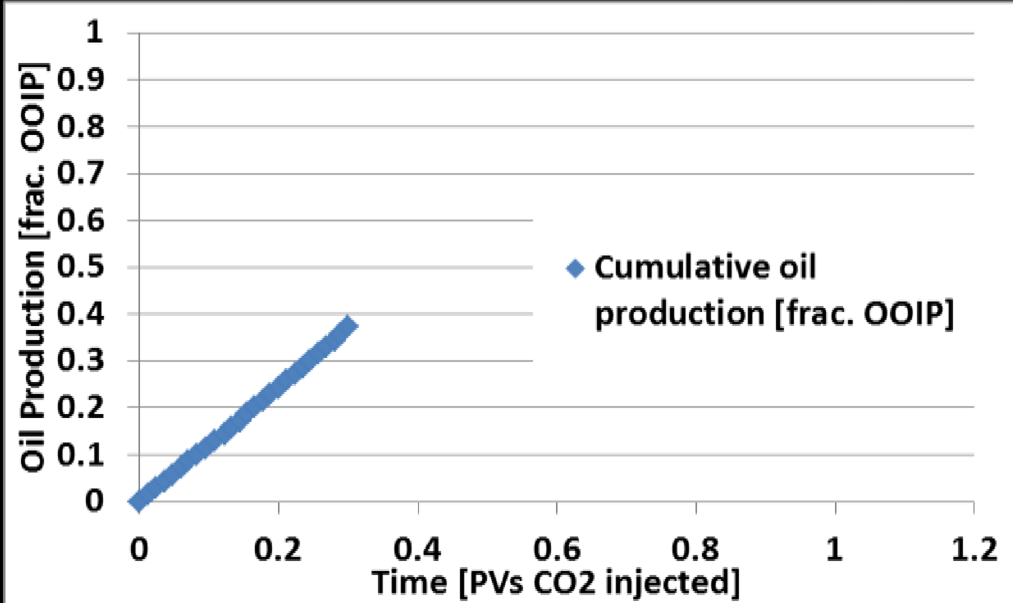



Oil Production [frac. OOIP]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

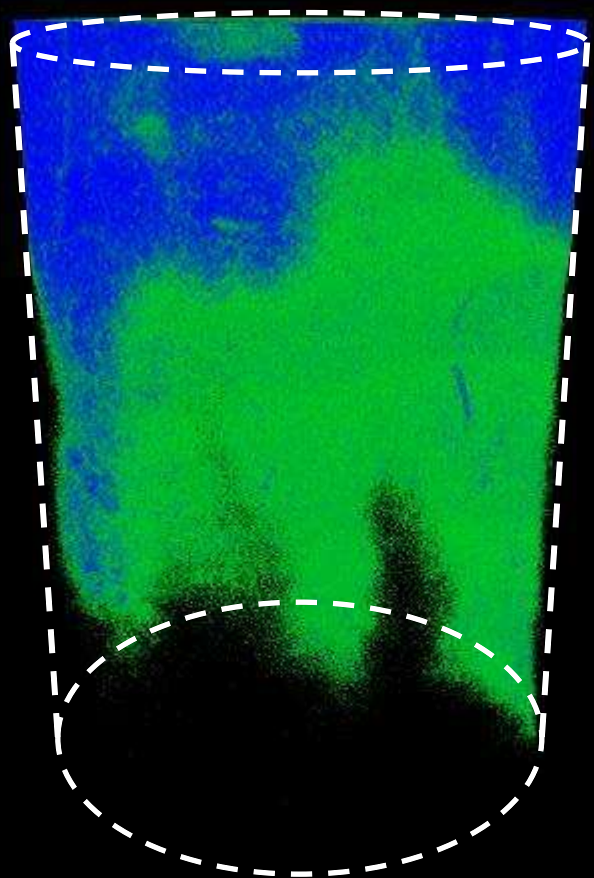
0.30 PV

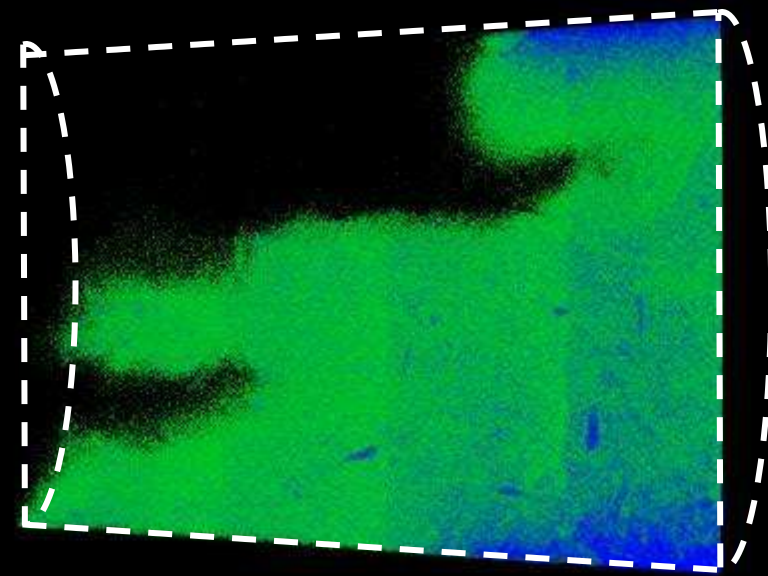


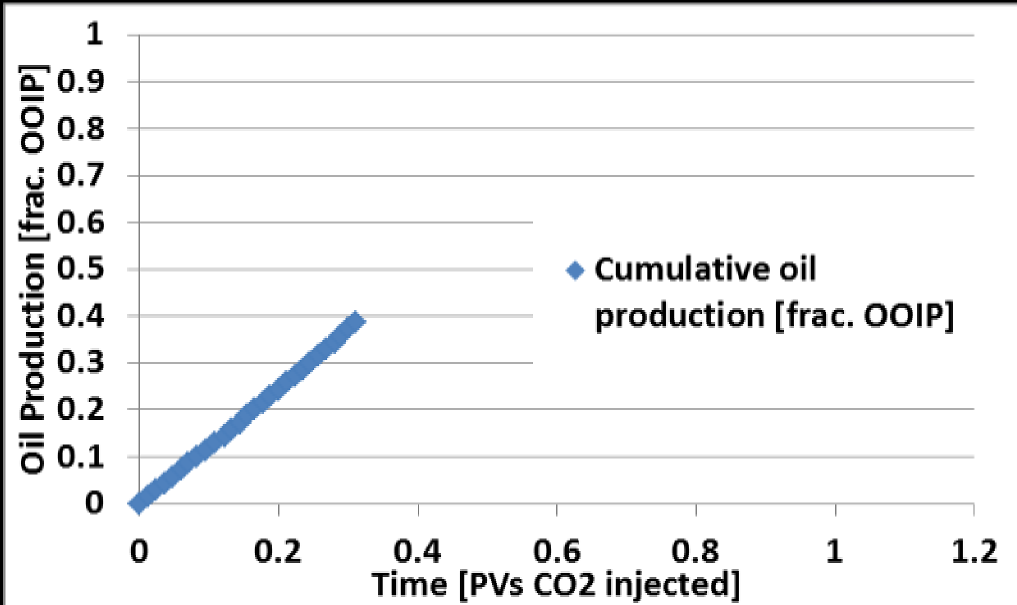



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

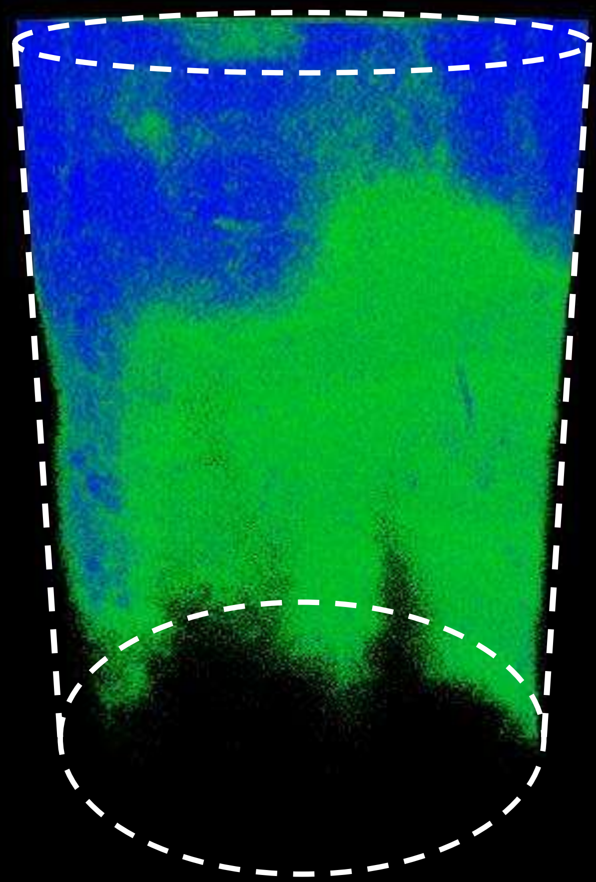
0.33 PV

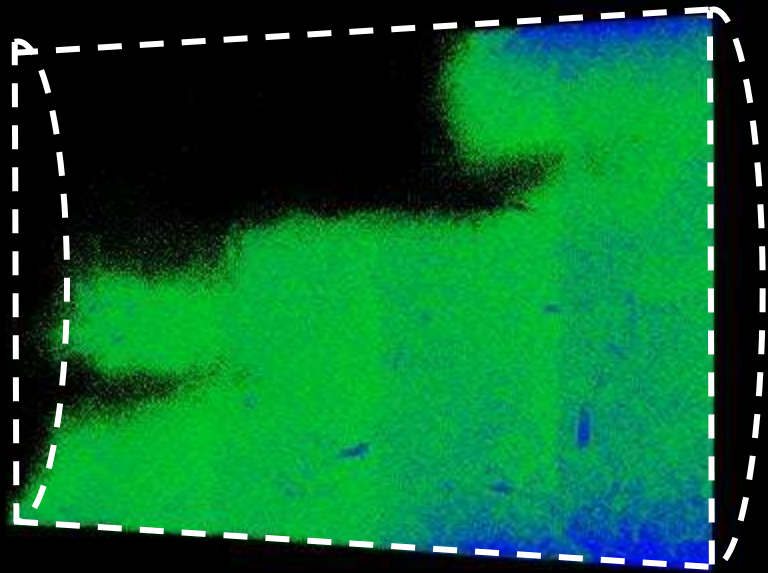


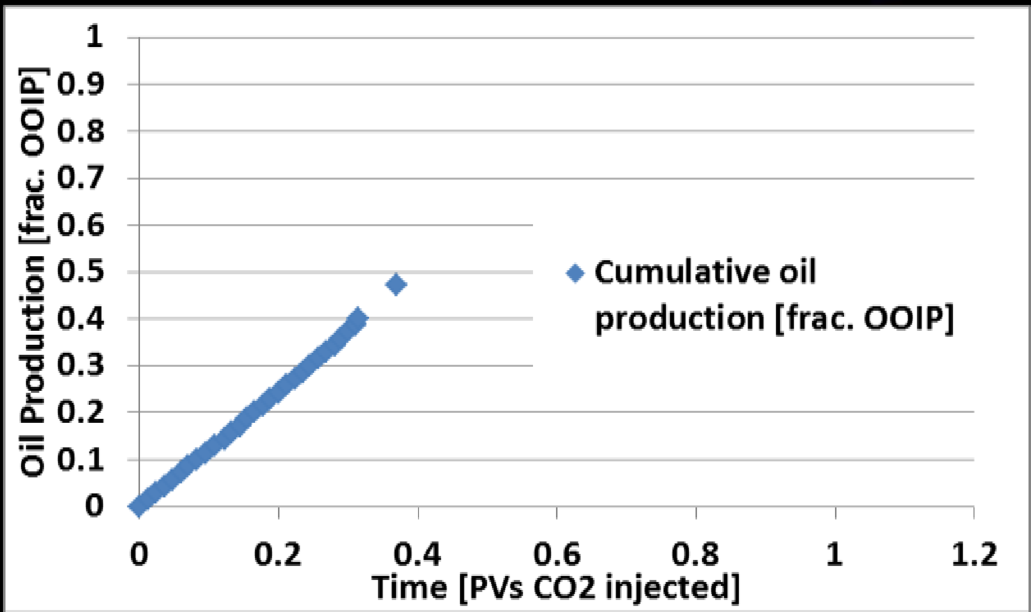



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

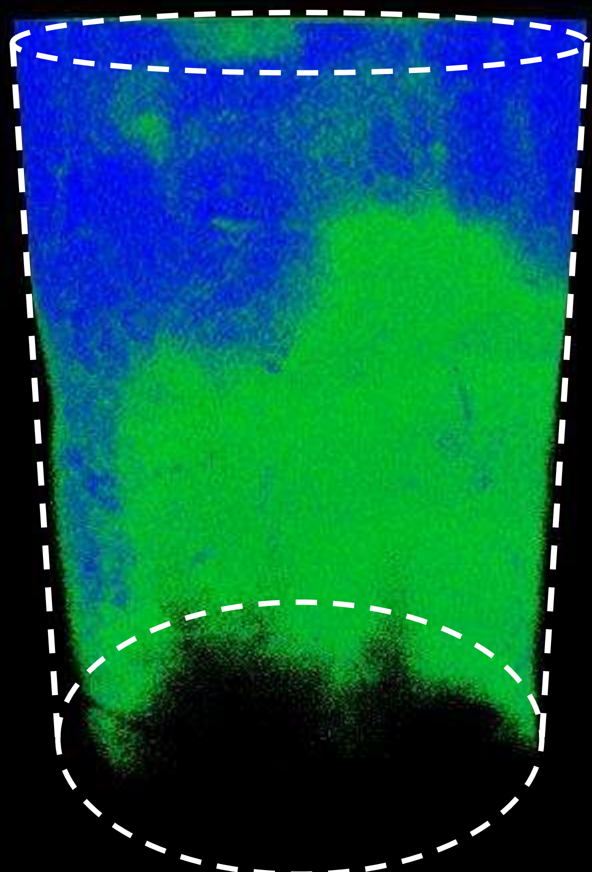
0.36 PV

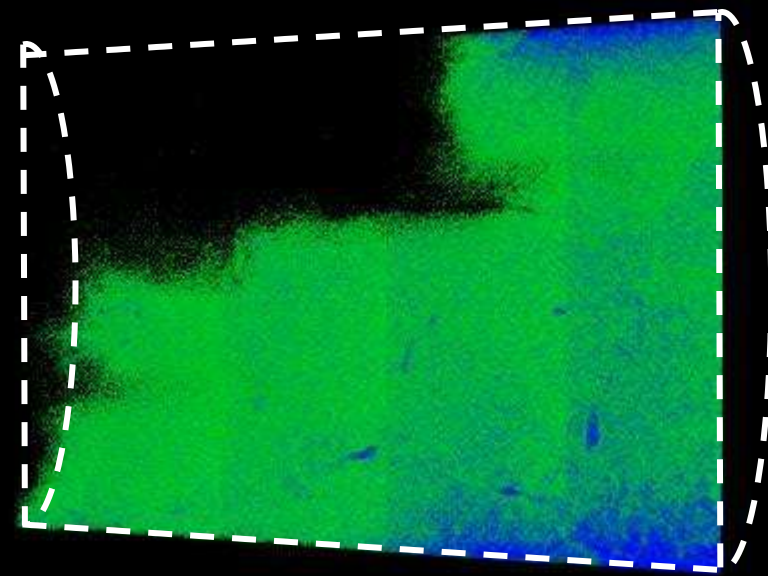


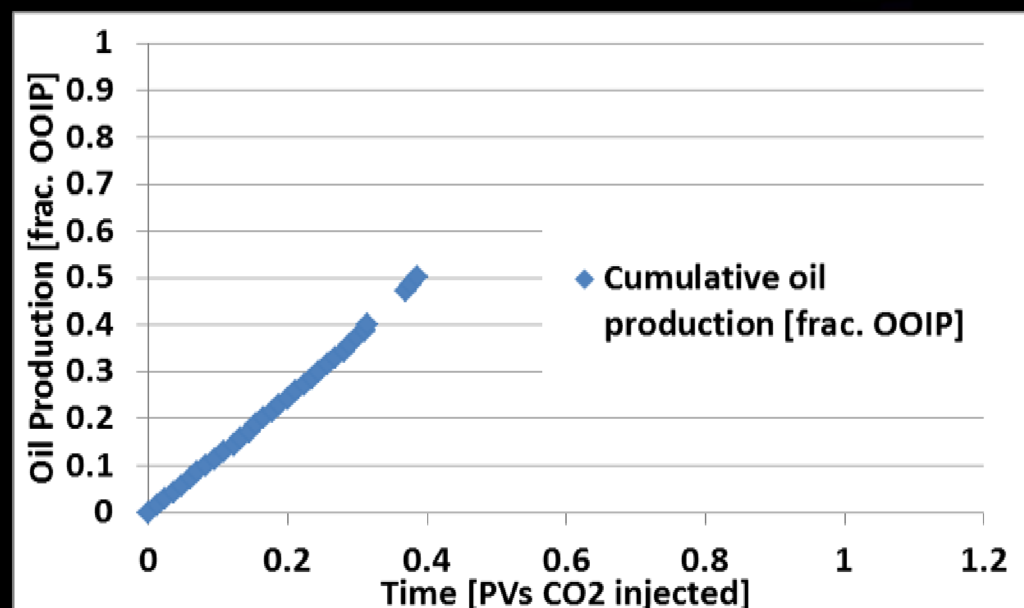



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

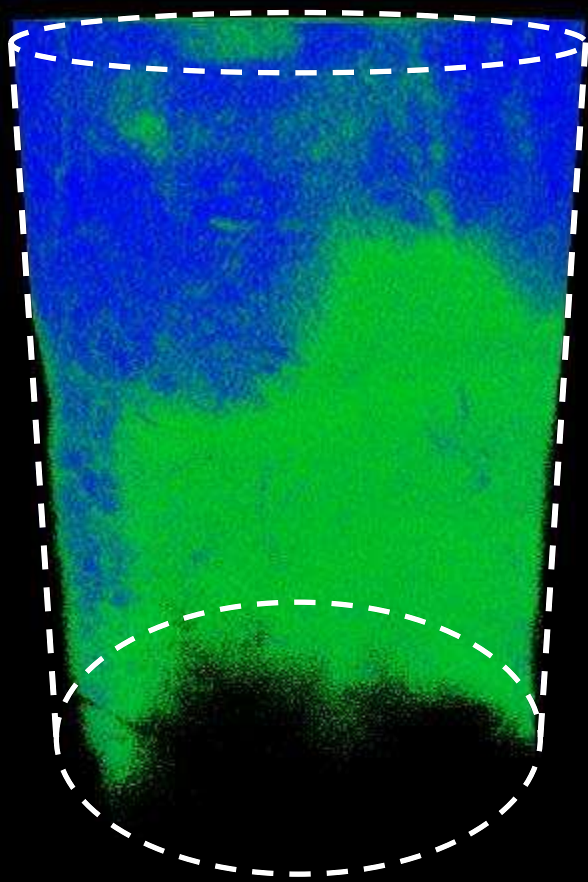
0.38 PV

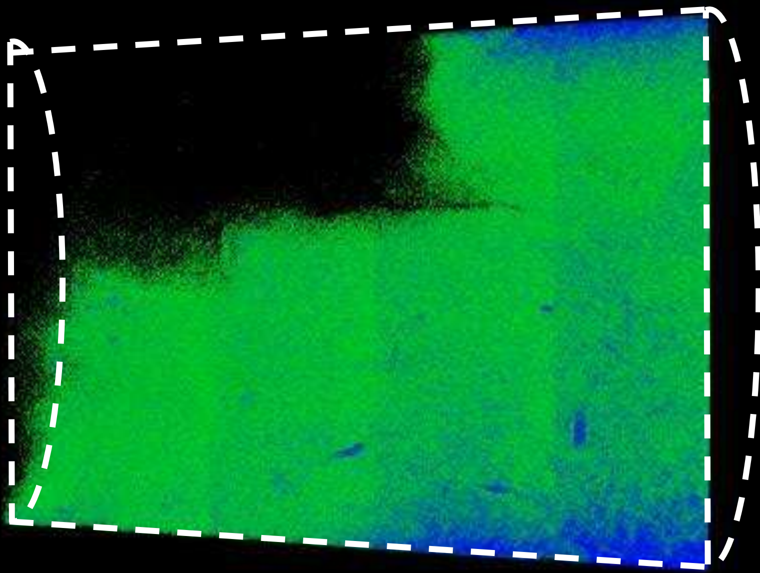


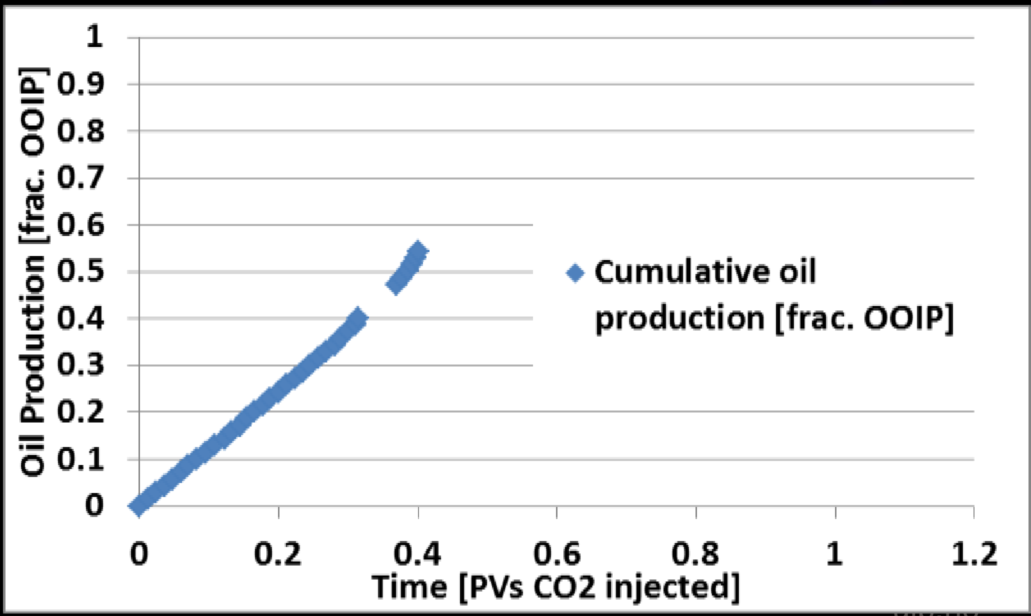



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

0.41 PV

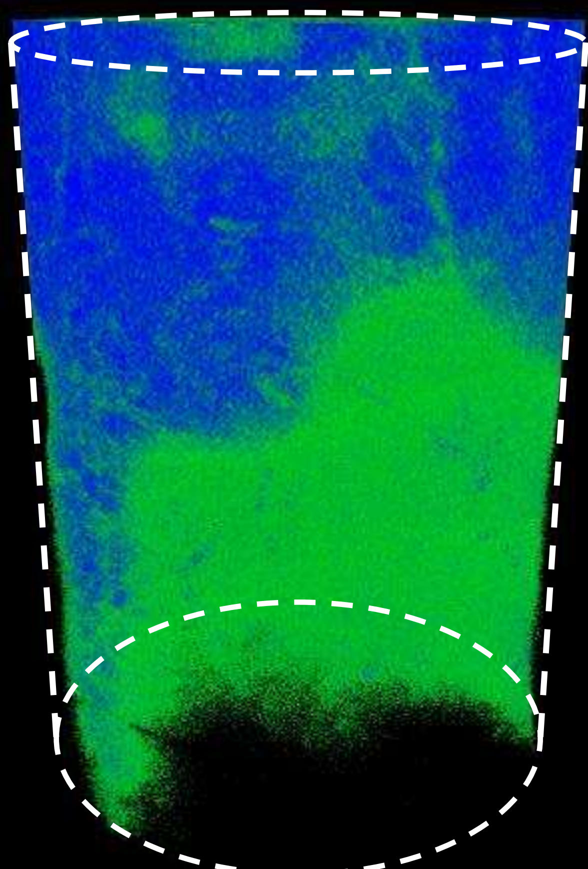


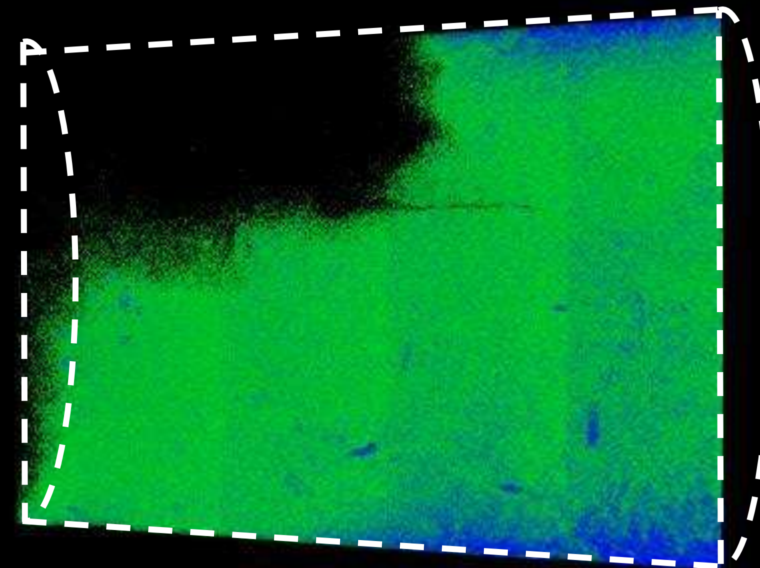


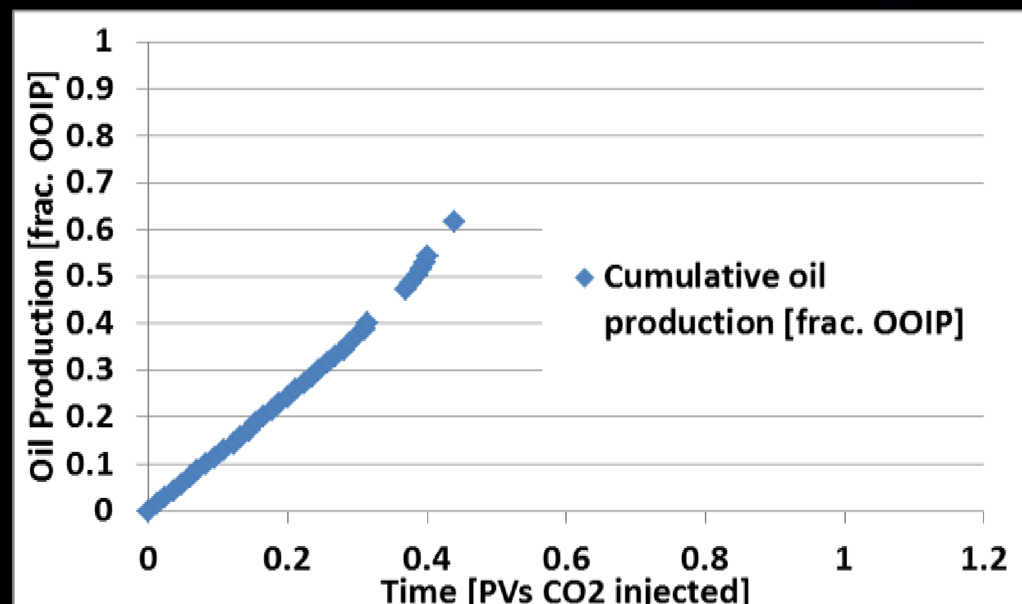


Oil Production [frac. OOIP]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

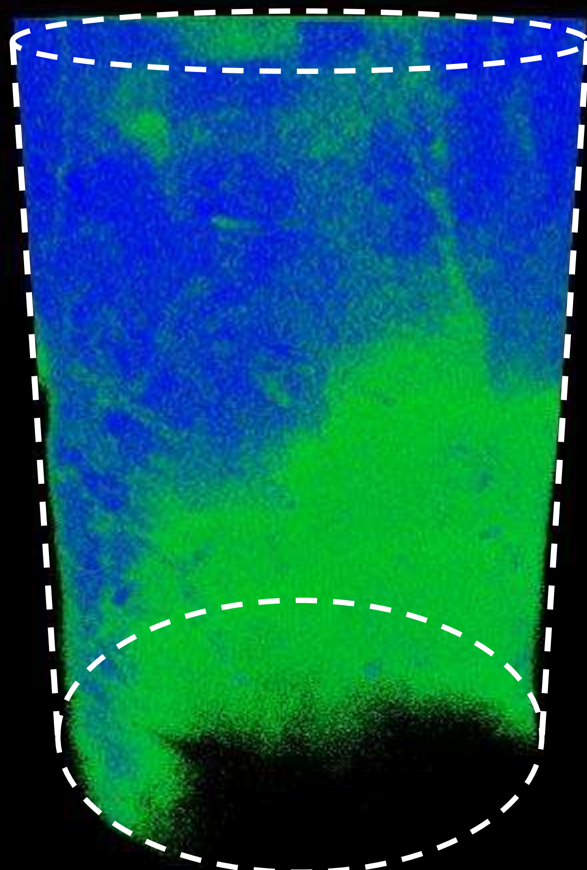
0.44 PV

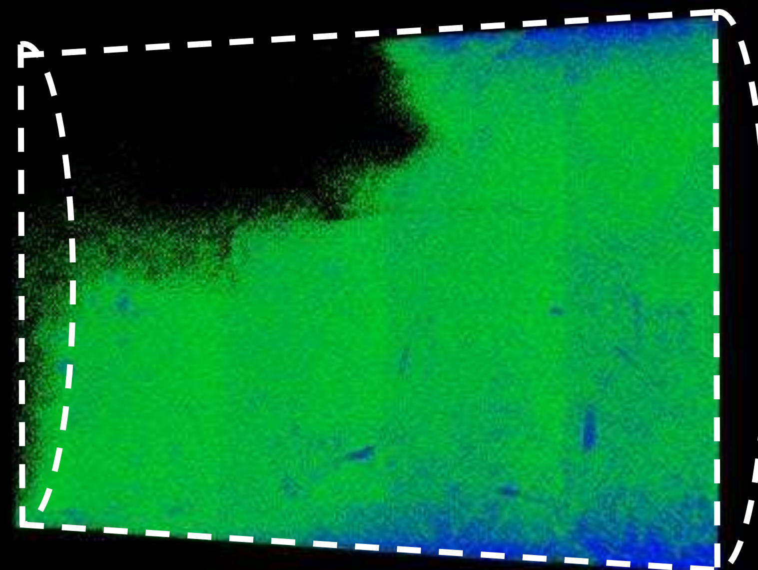


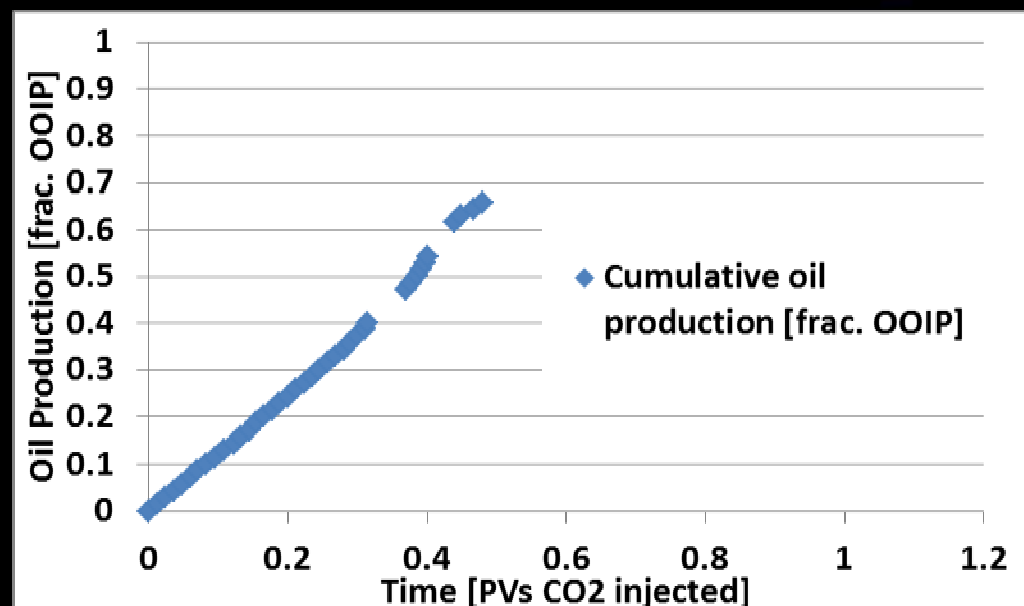



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

0.48 PV

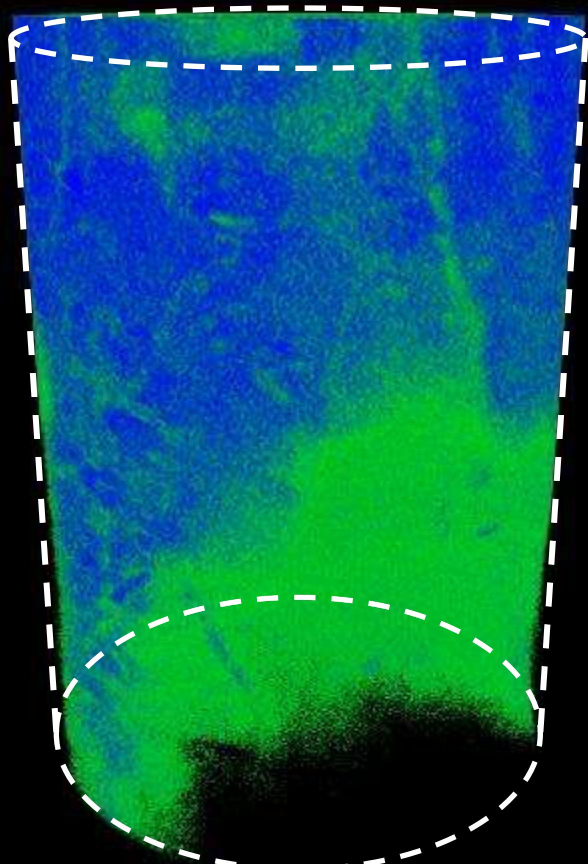


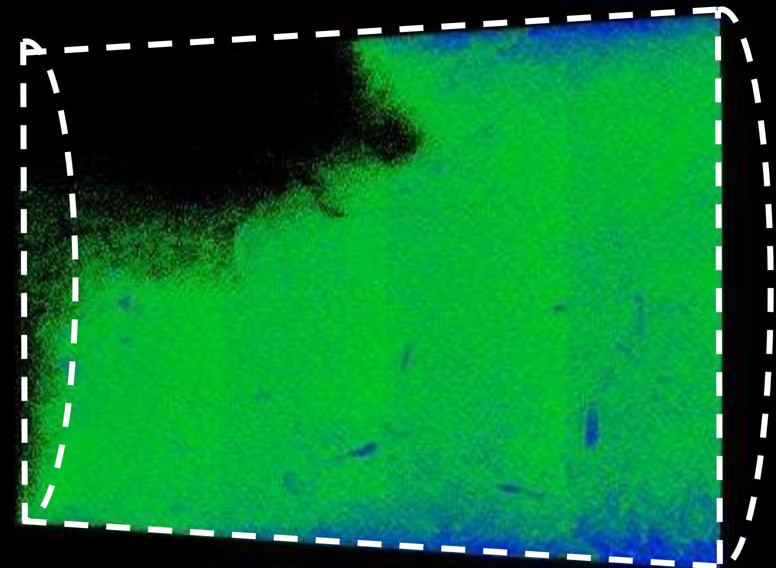


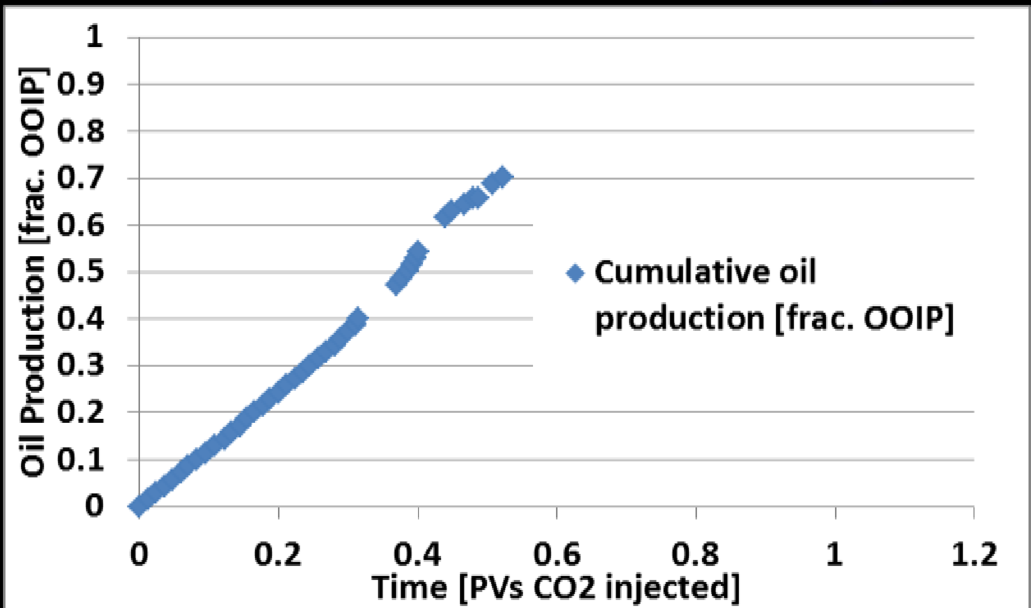


Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

0.53 PV

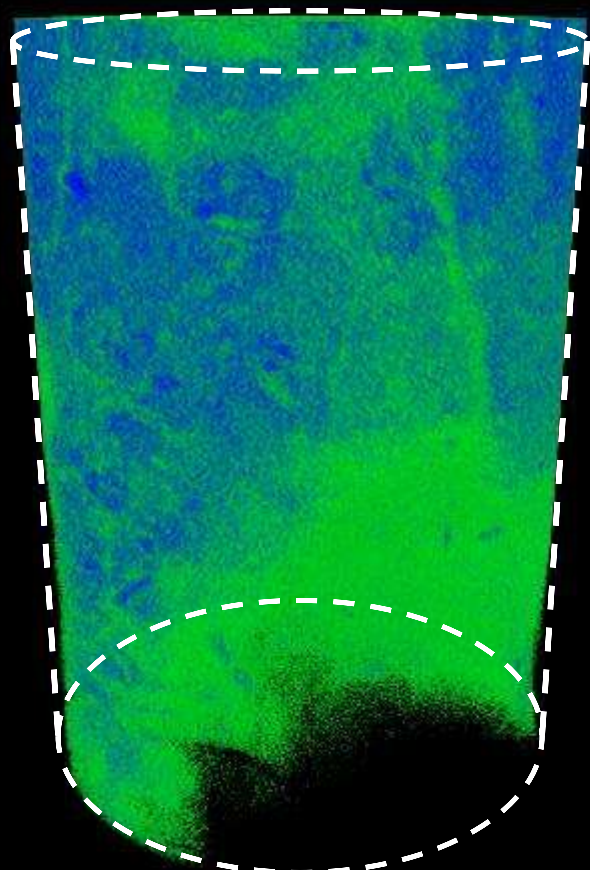


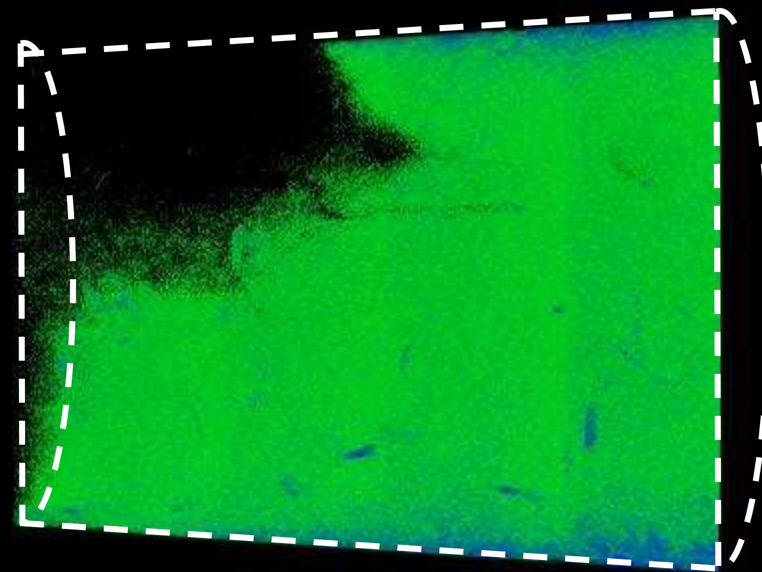


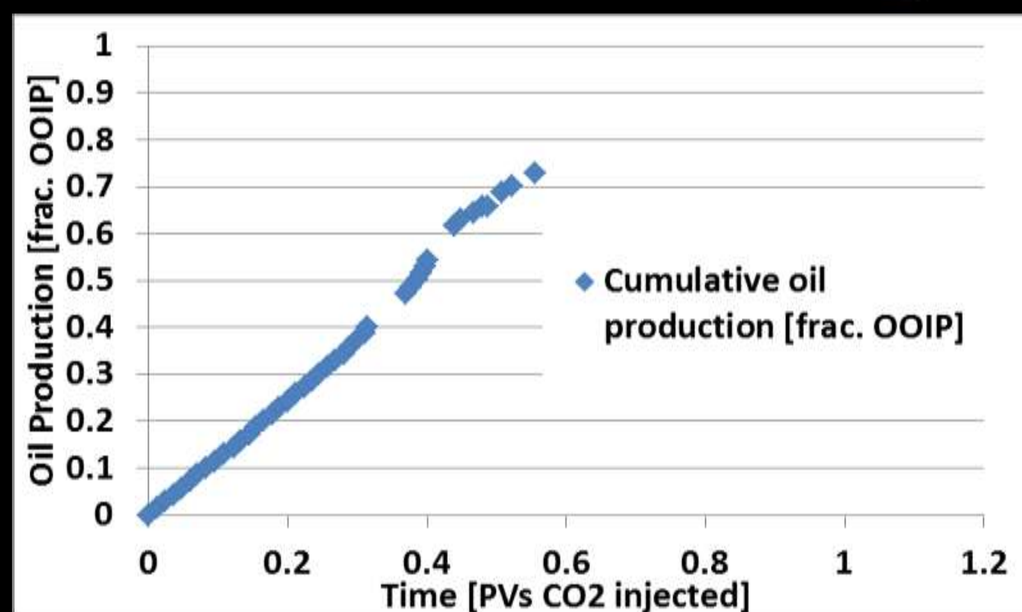


Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

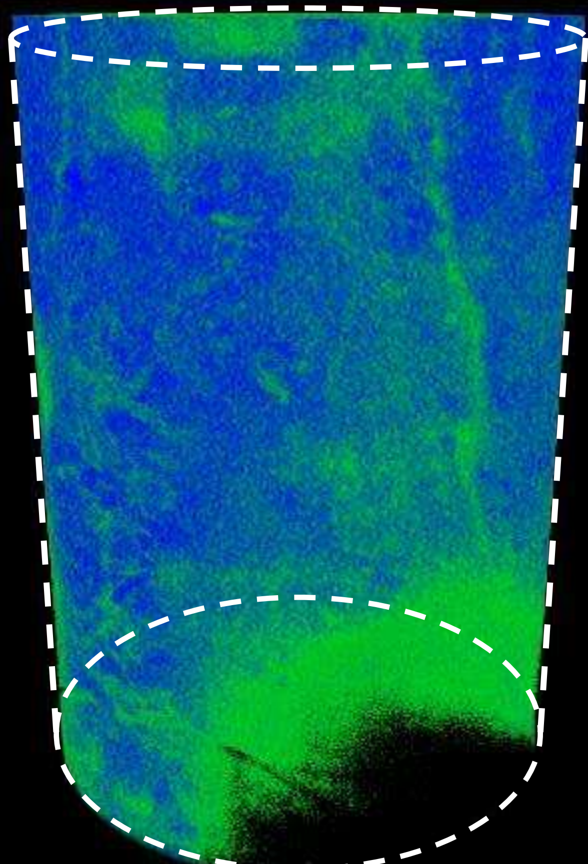
0.59 PV

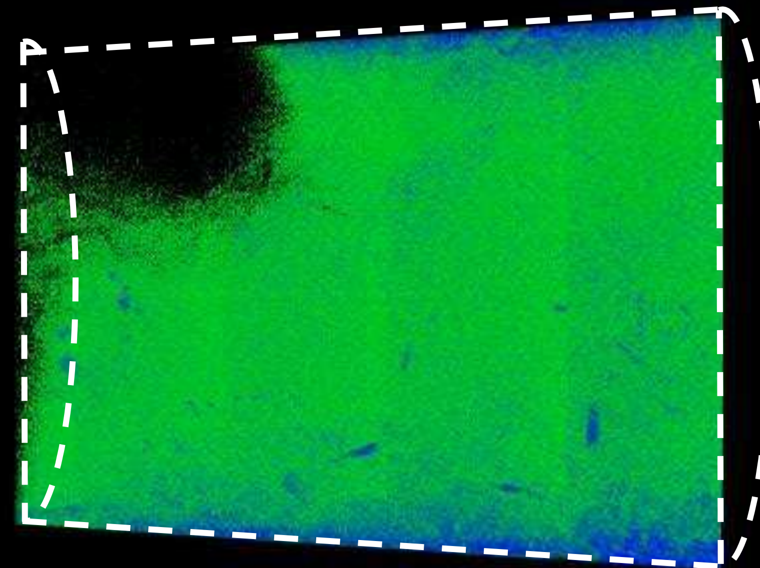


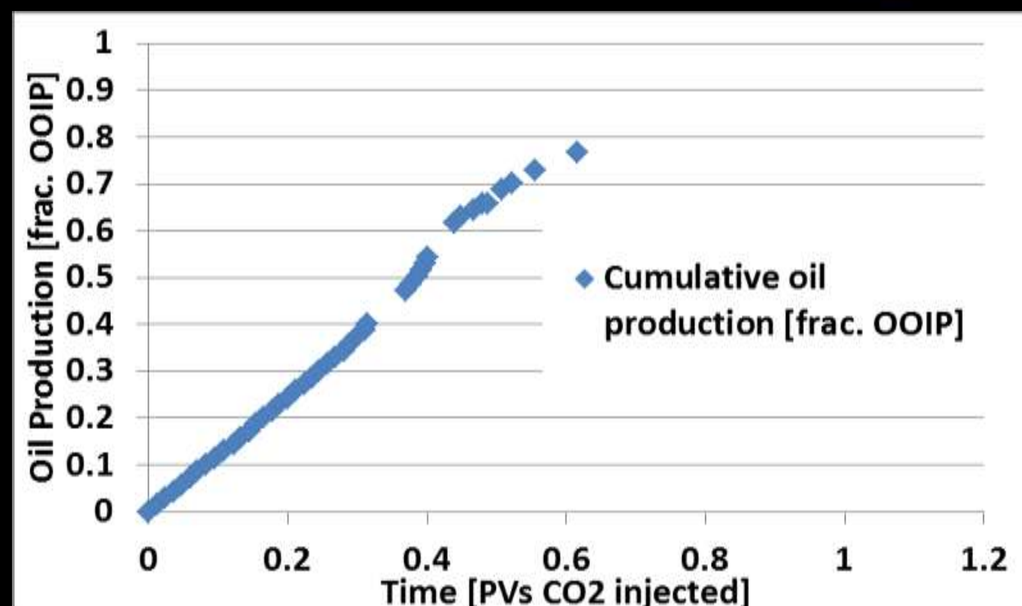



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

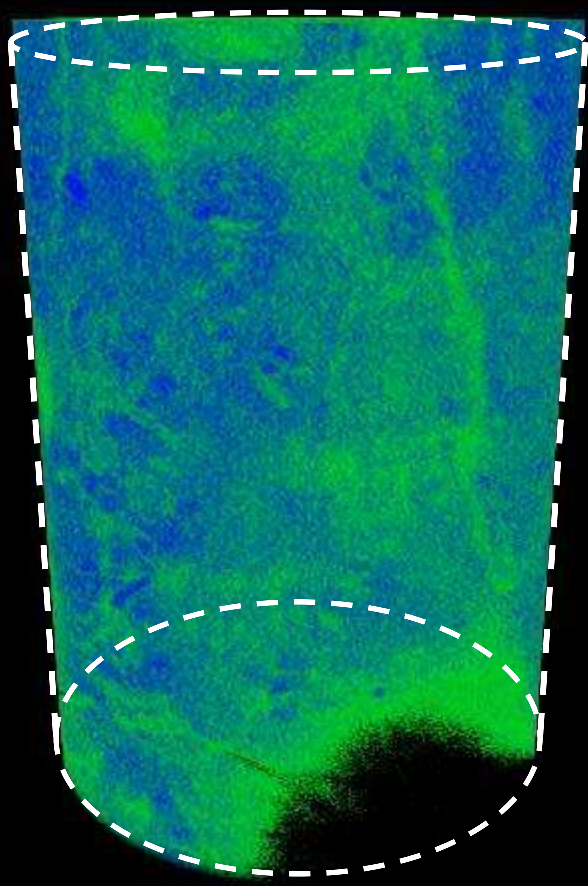
0.65 PV

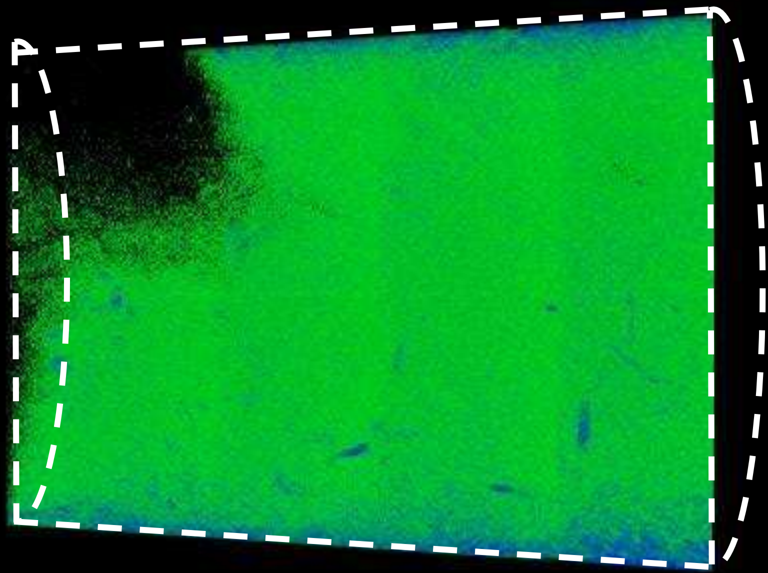


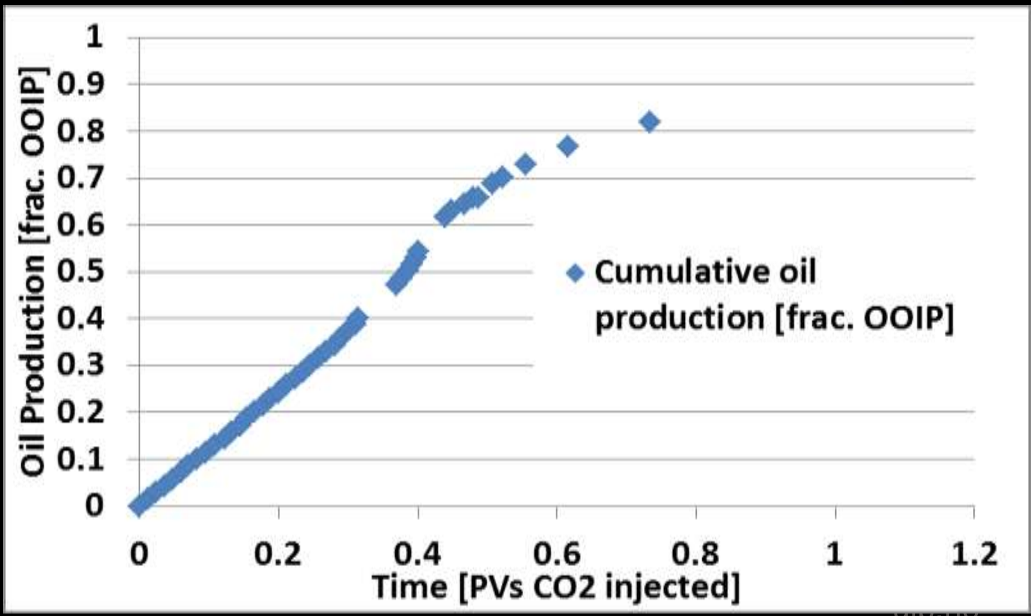



Oil Production [frac. OOIP]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

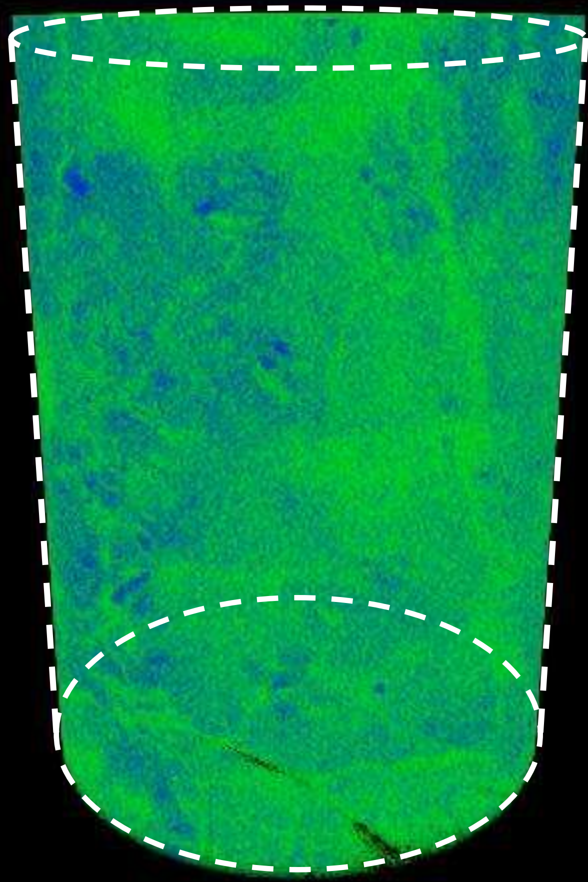
0.88 PV

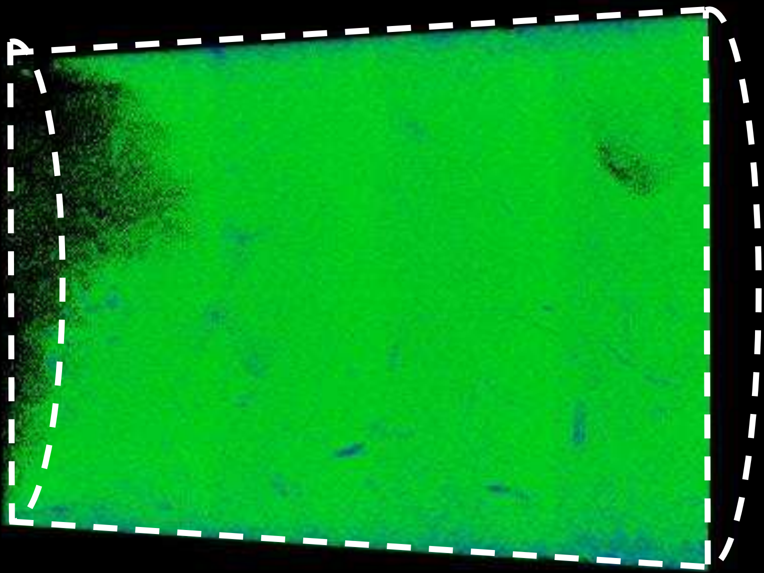


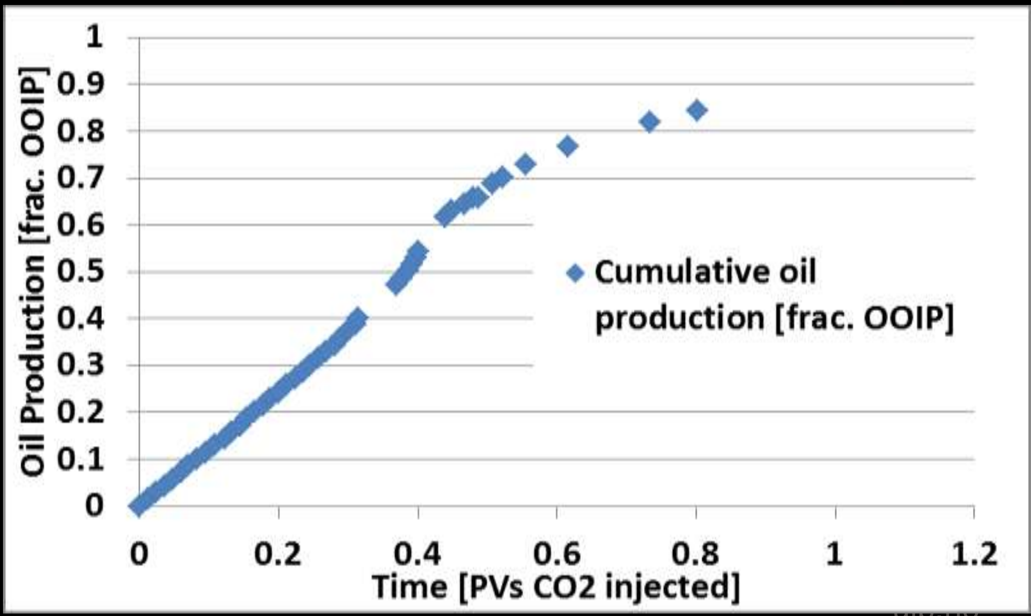



Oil Production [frac. OOIP]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative oil production [frac. OOIP]
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]

1.06 PV





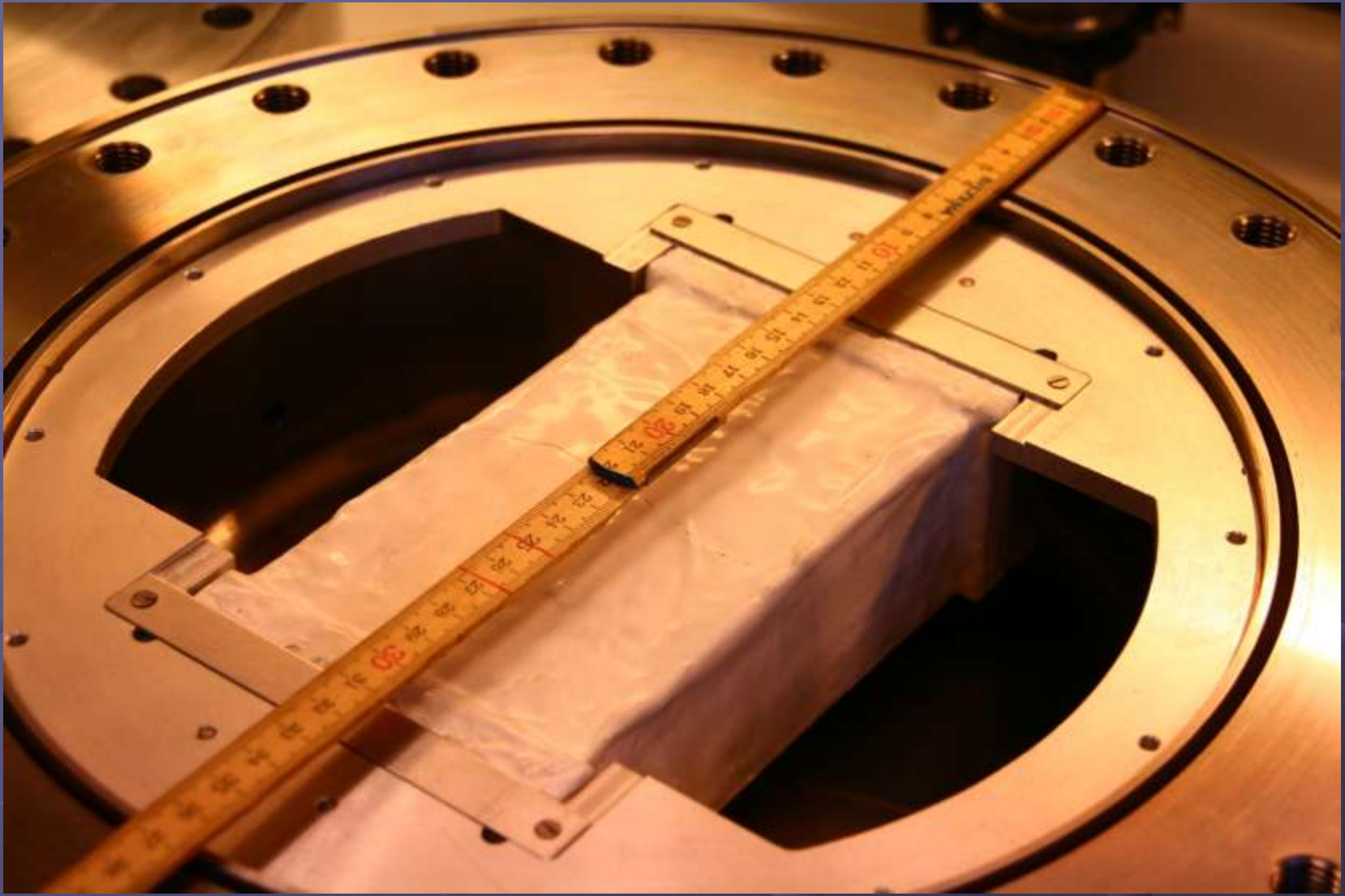


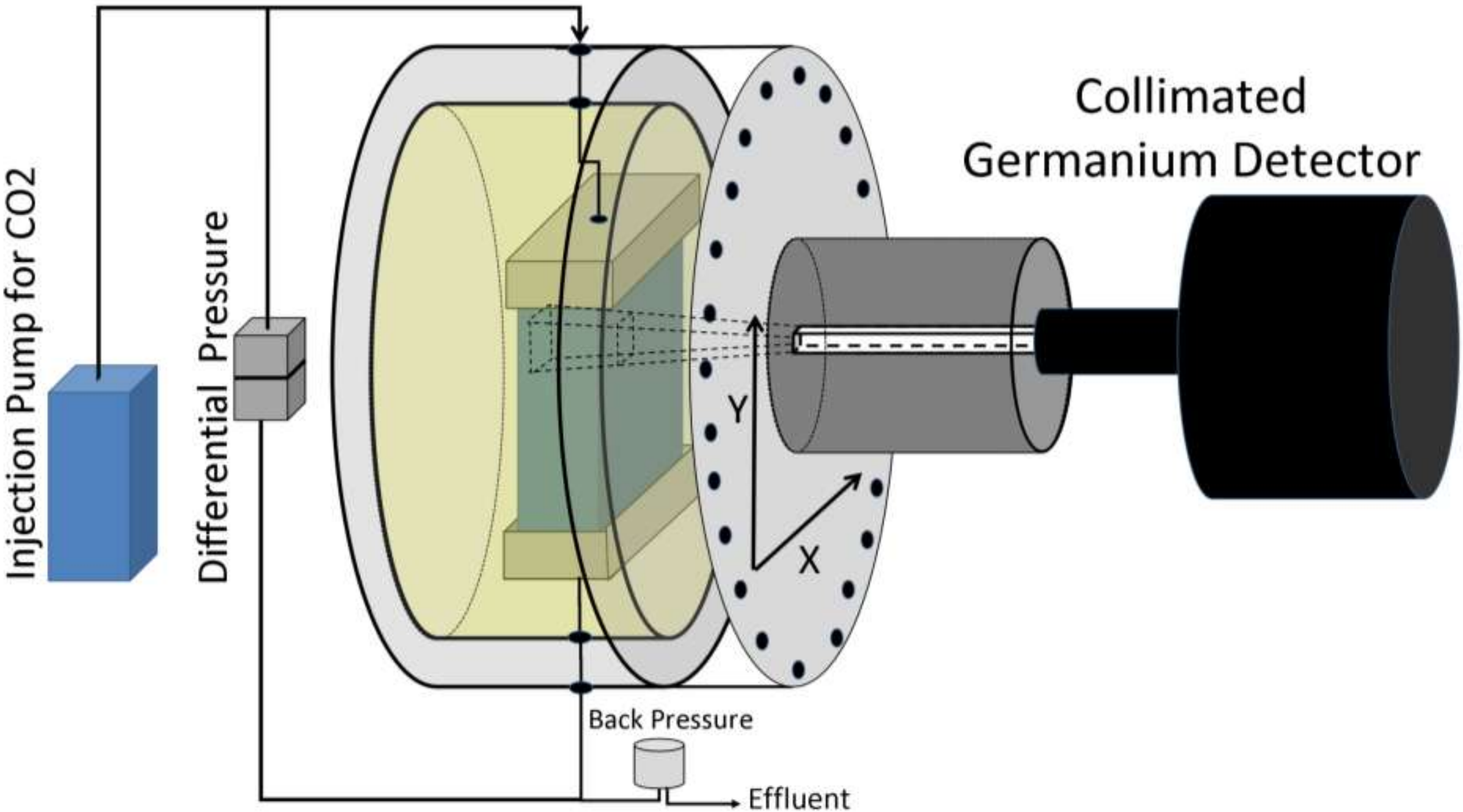
Oil Production [frac. OOIP]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
Time [PVs CO2 injected]
Cumulative oil production [frac. OOIP]

Large Volume Blocks

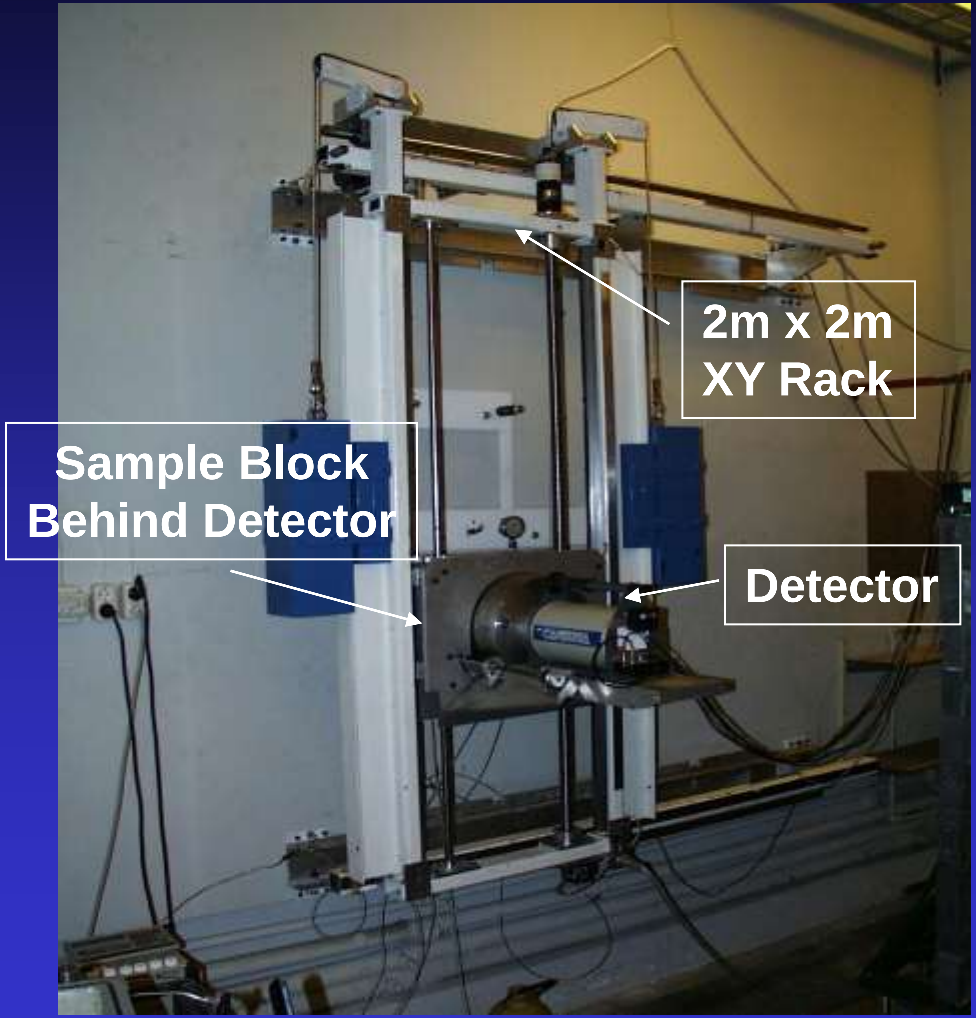
Block Preparation

High Pressure, Large Volume




Injection Pump for CO2
Differential Pressure
Collimated
Germanium Detector
Y
X
Back Pressure
Effluent

Nuclear Tracer Imaging



<u>EXPERIMENTAL PROCEDURES</u>

1. **Waterflood <u>whole</u> block**
2. **Oilflood to S_{wi}, fracture and reassemble block**
3. **Waterflood <u>fractured</u> block**

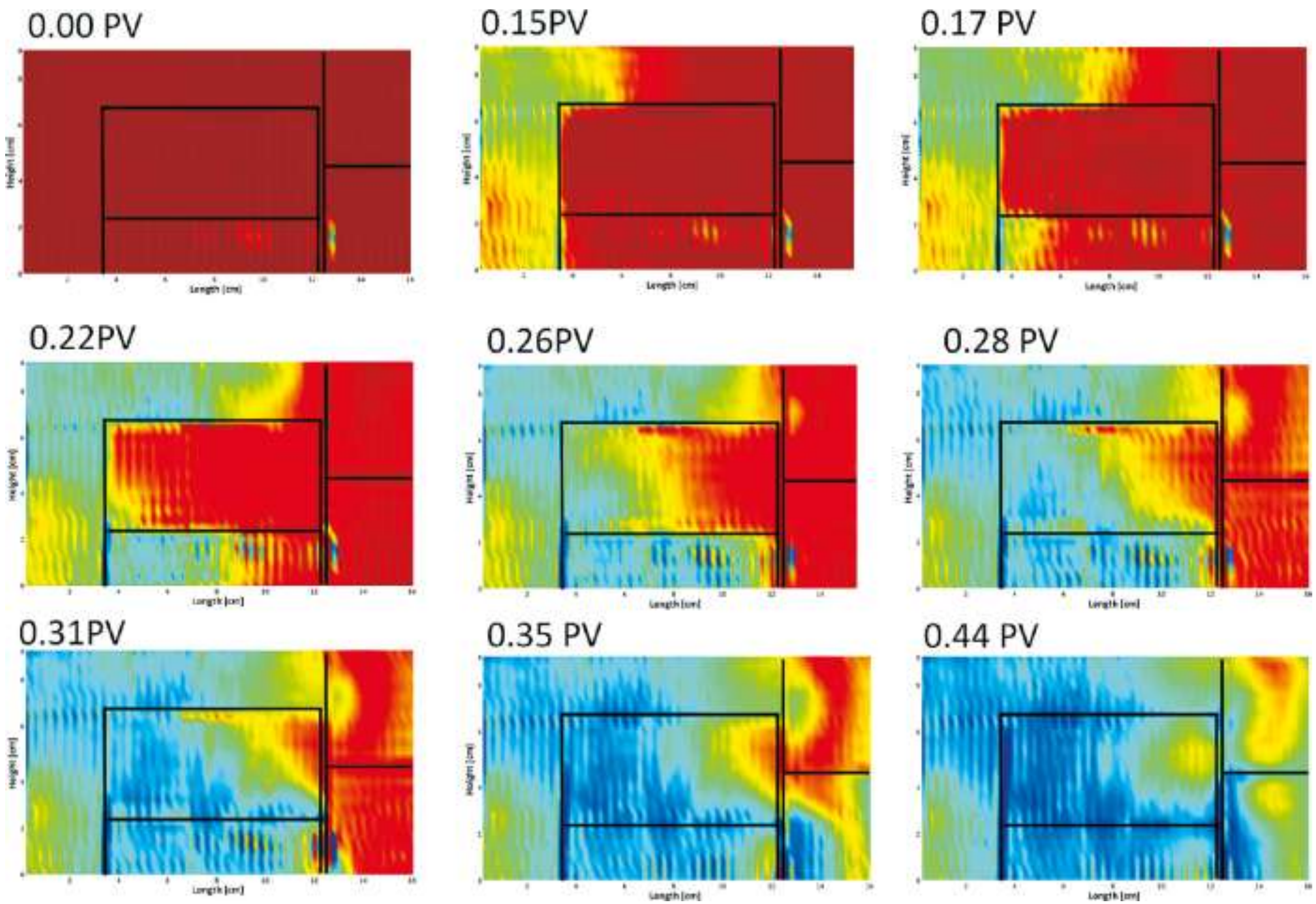
<u>Conditions:</u>

A) Strongly-water-wet

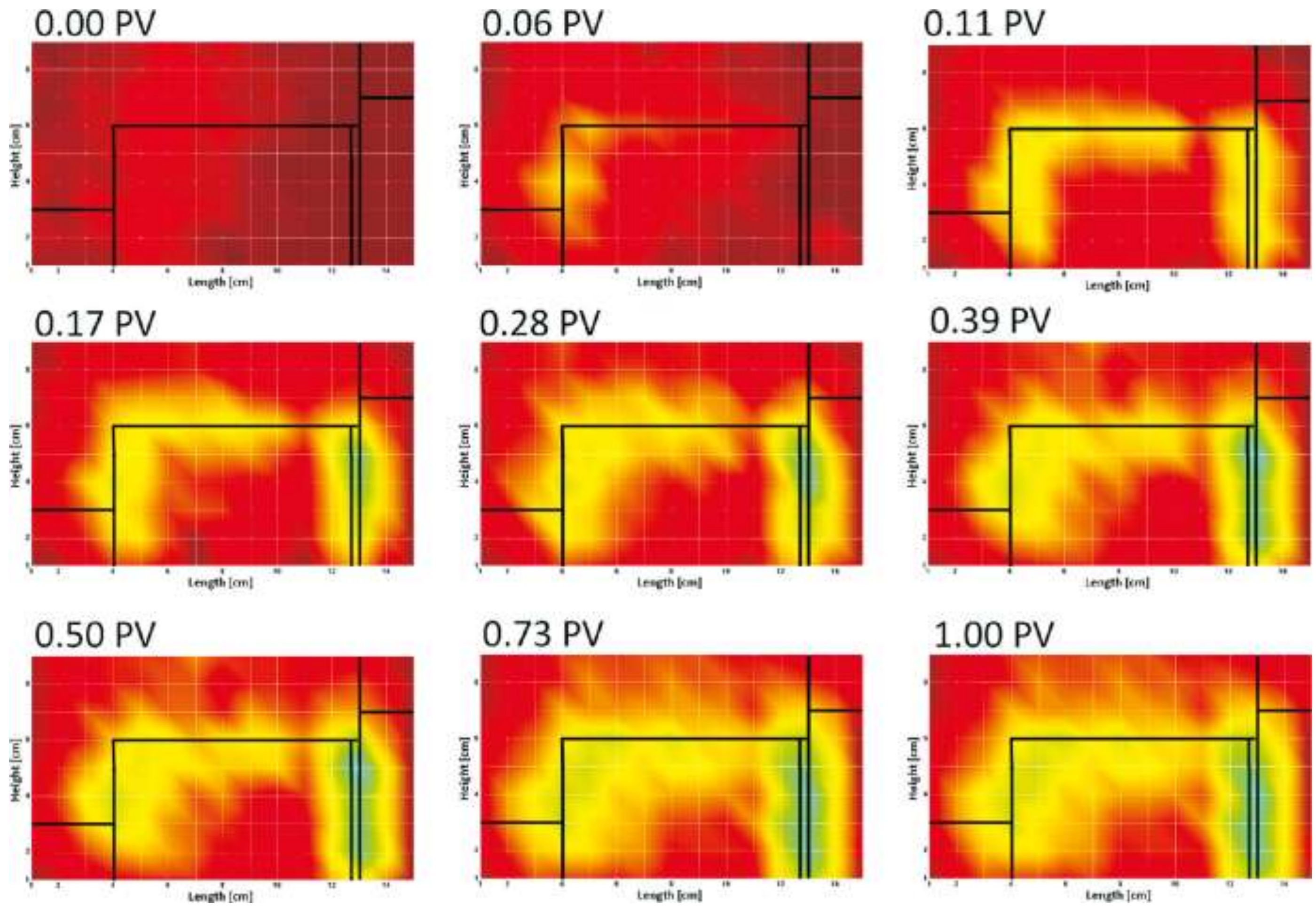
B) Moderately-water-wet

C) Nearly-neutral-wet

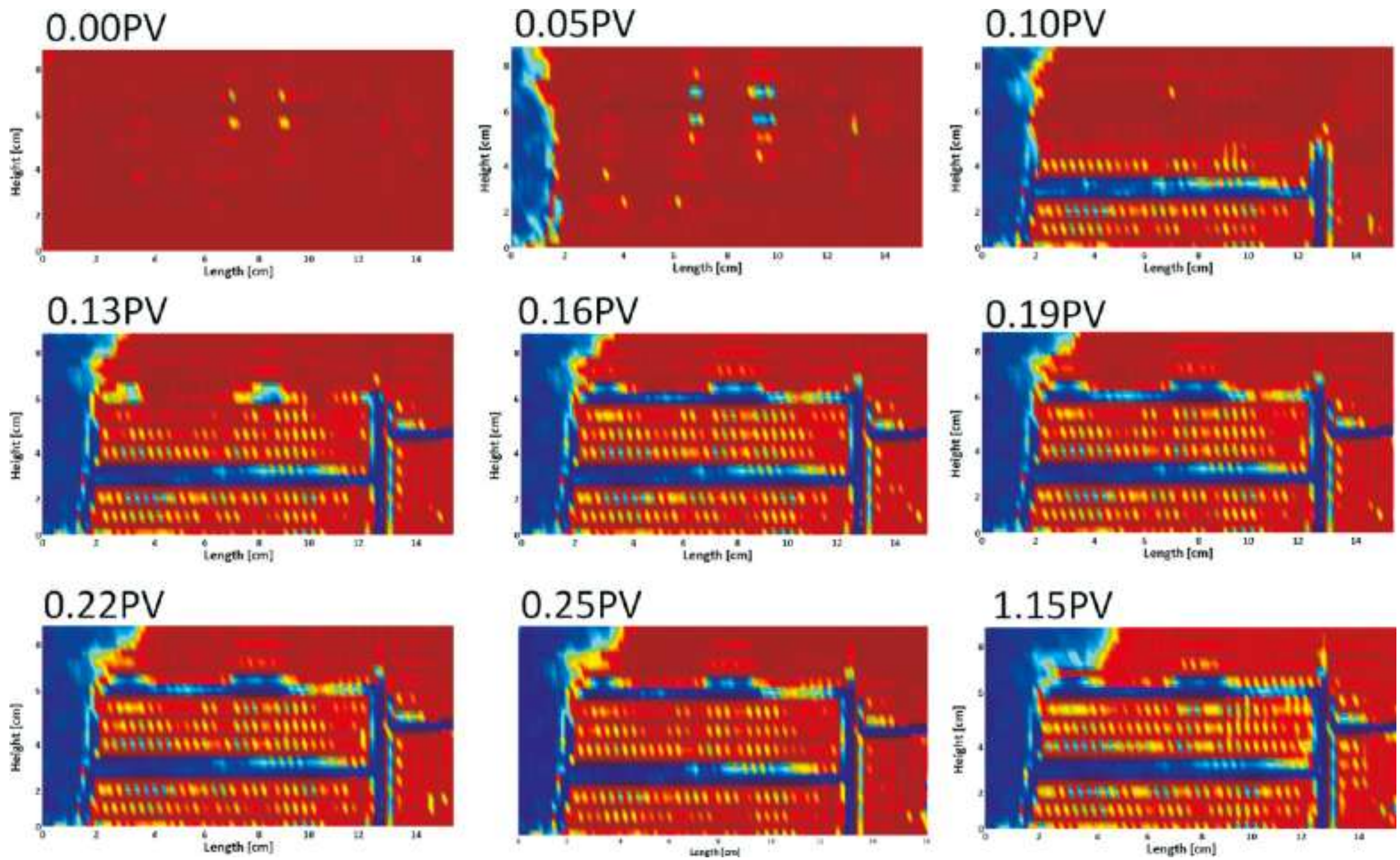
BLOCK SCALE Strongly water-wet



BLOCK SCALE Moderately water-wet



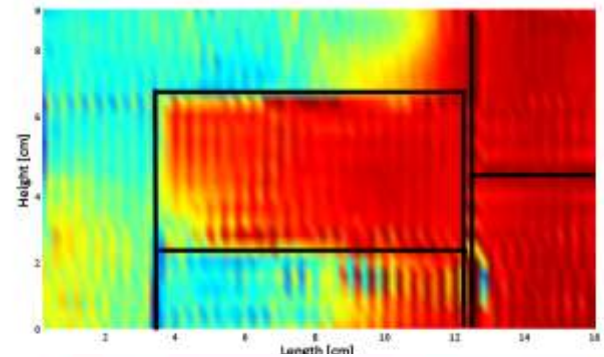
BLOCK SCALE Moderately oil-wet



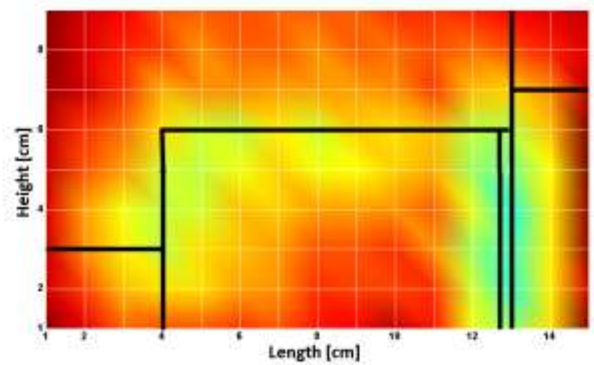
Wettability effects in fractured blocks

Waterflood in Fractured Blocks

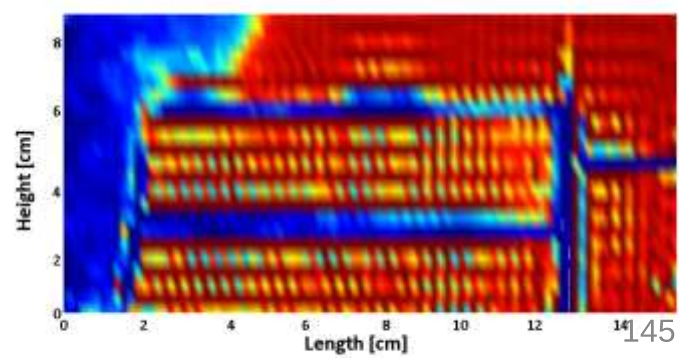
- **Strongly water-wet**
  - Block-by-block displacement
  - Recovery determined by potential for spontaneous imbibition



- **Weakly water-wet**
  - Spontaneous Imbibition
  - Low oil recovery



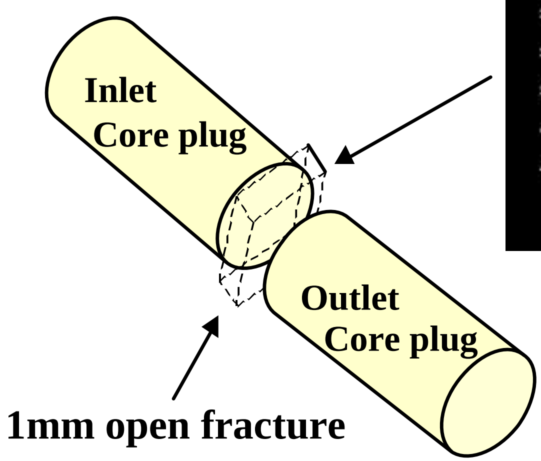
- **Weakly oil-wet**
  - Water fingers through fracture network
  - Low sweep efficiency
  - Low oil recovery by waterflood

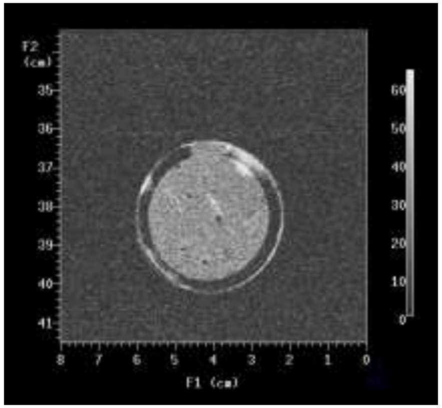


What happens inside the fractures during fluid flow?

- MRI (Magnetic Resonance Imaging)

  The high spatial resolution allow visualization of fluid flow patterns inside a 1mm fractures between stacked core plugs. The high resolution reveal wetting phase bridging phenomena inside the fracture.

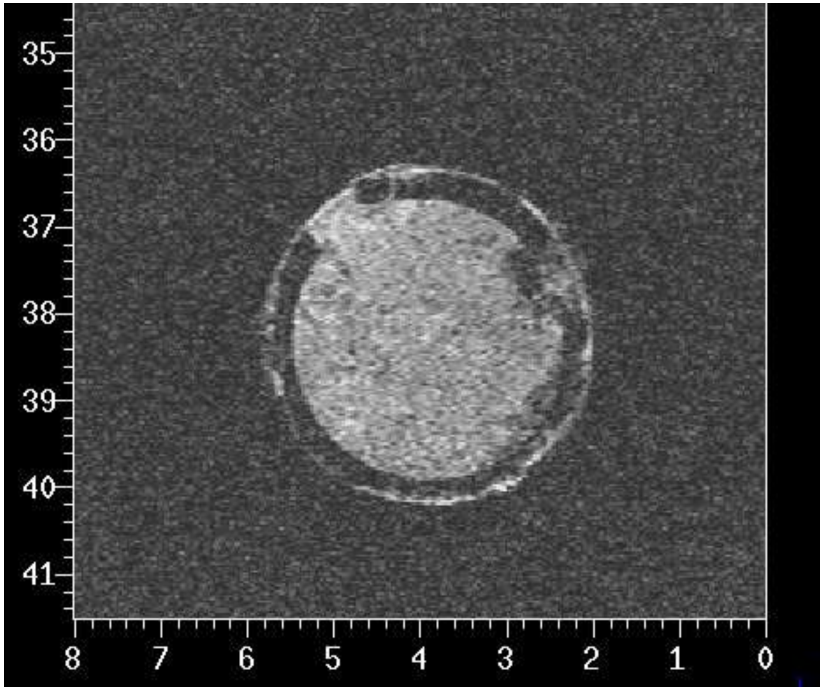




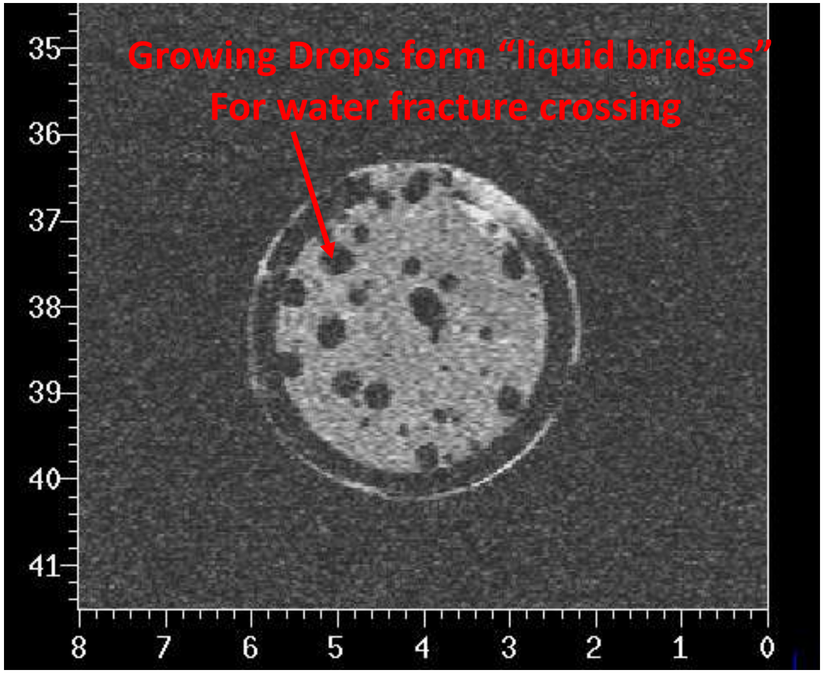
Cross sectional MRI image containing fracture

Recap: WF in water-wet fractured chalk

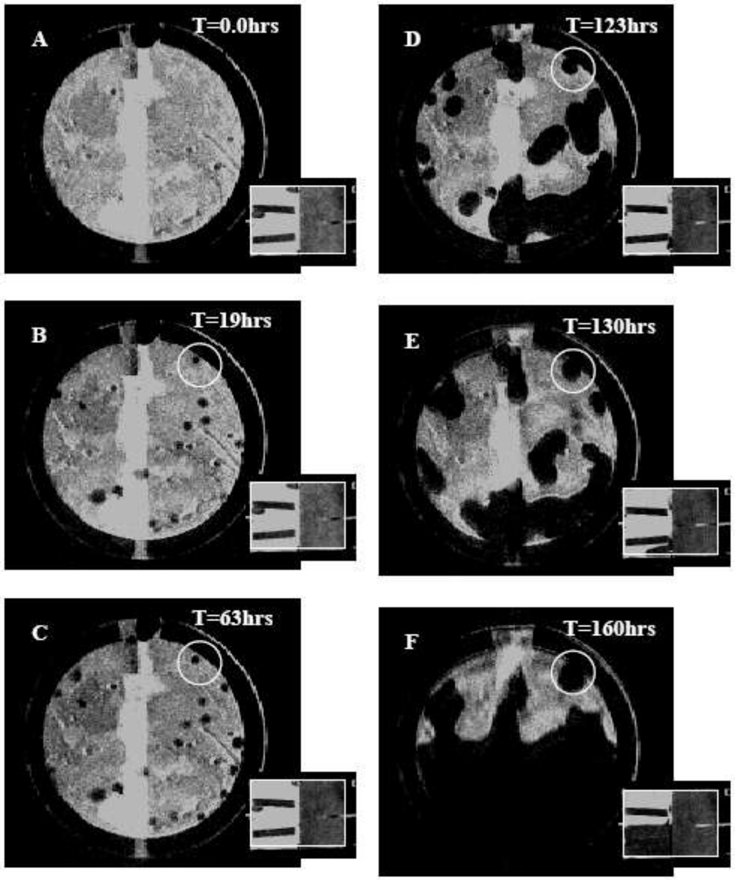
Wettability: I_w =1.0



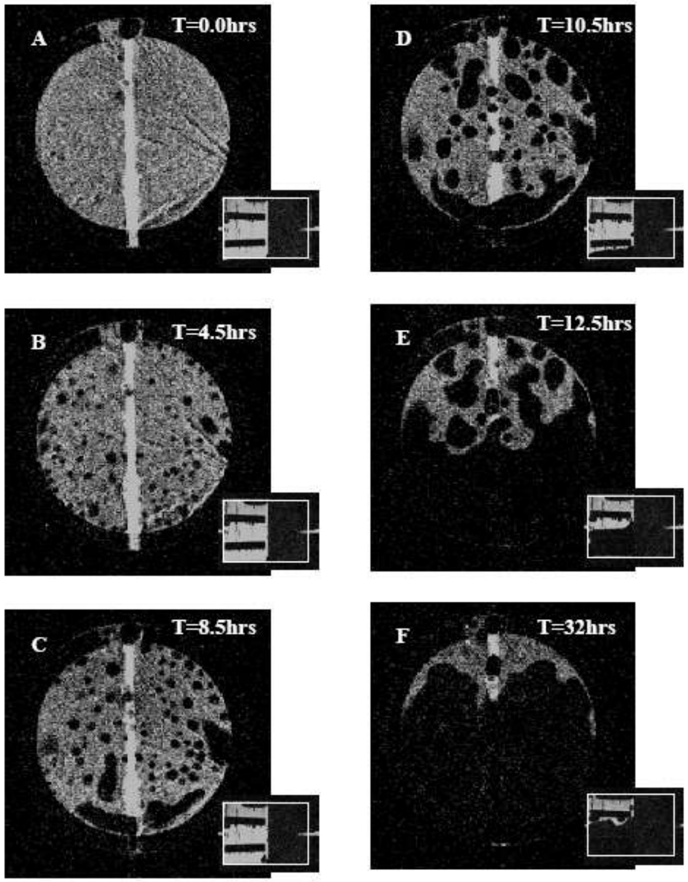
Wettability: I_w =0.7



Water Bridges with Escape Fracture



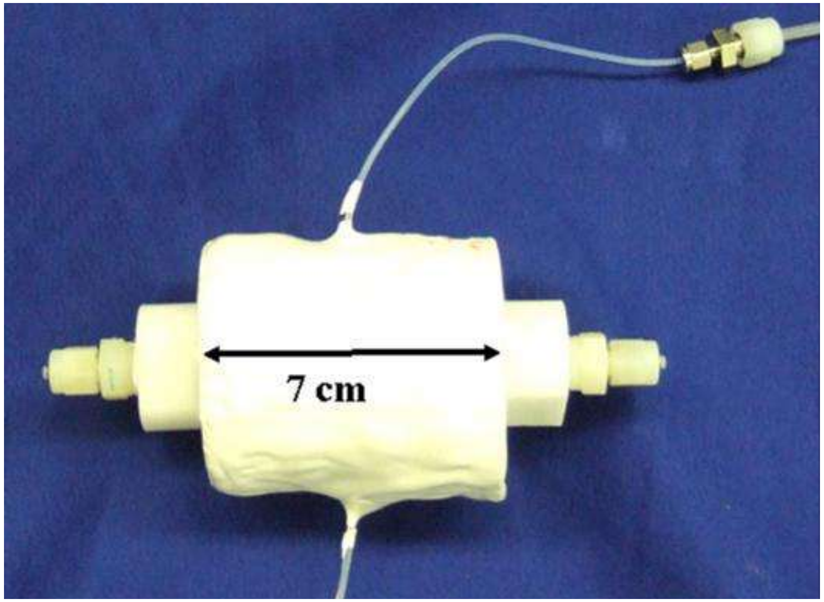
Constant differential pressure



Constant flow rate

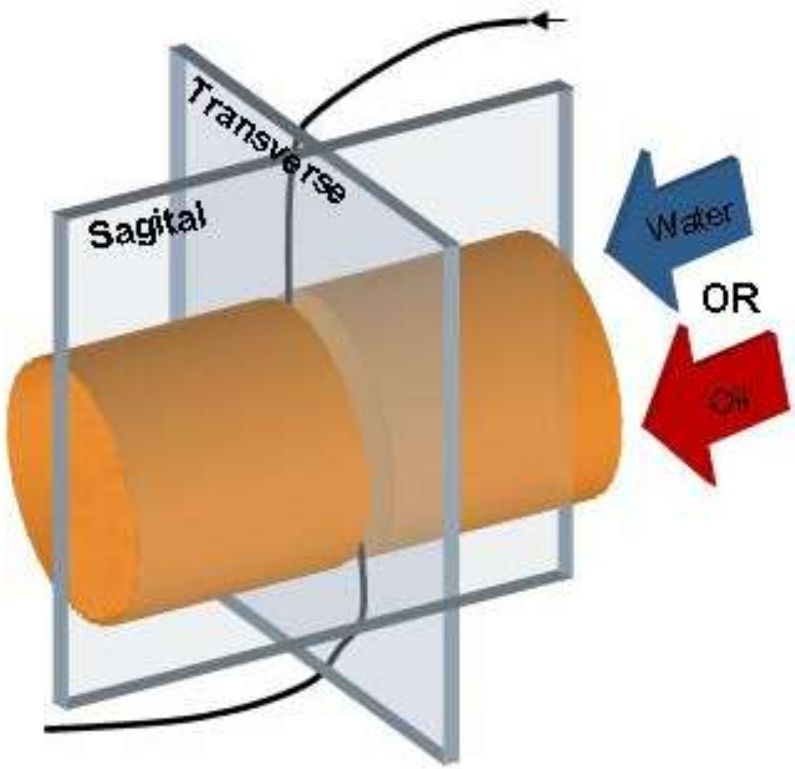
Experimental setup

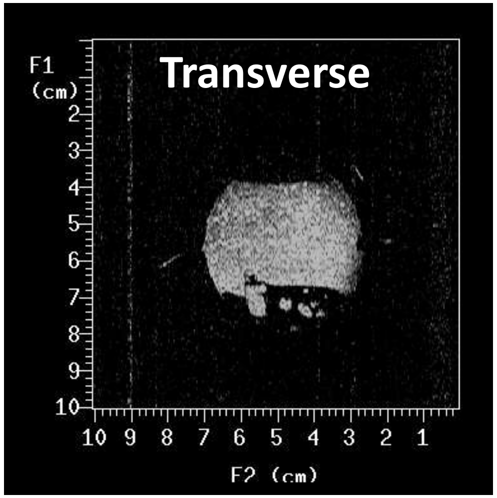
Whole view

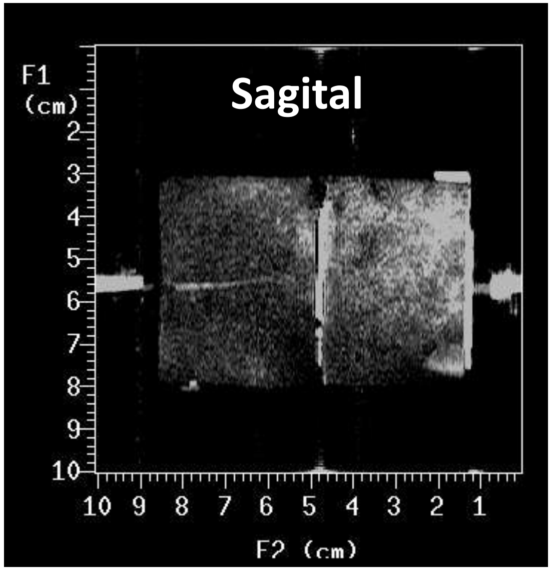


Cut in two

Fracture flow in oil-wet limestone



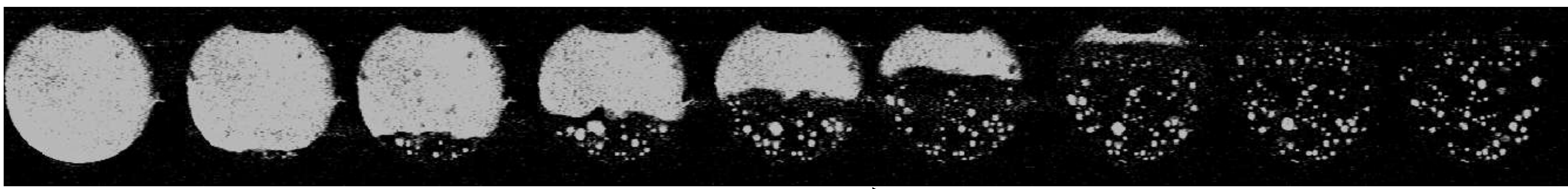




Waterflooding

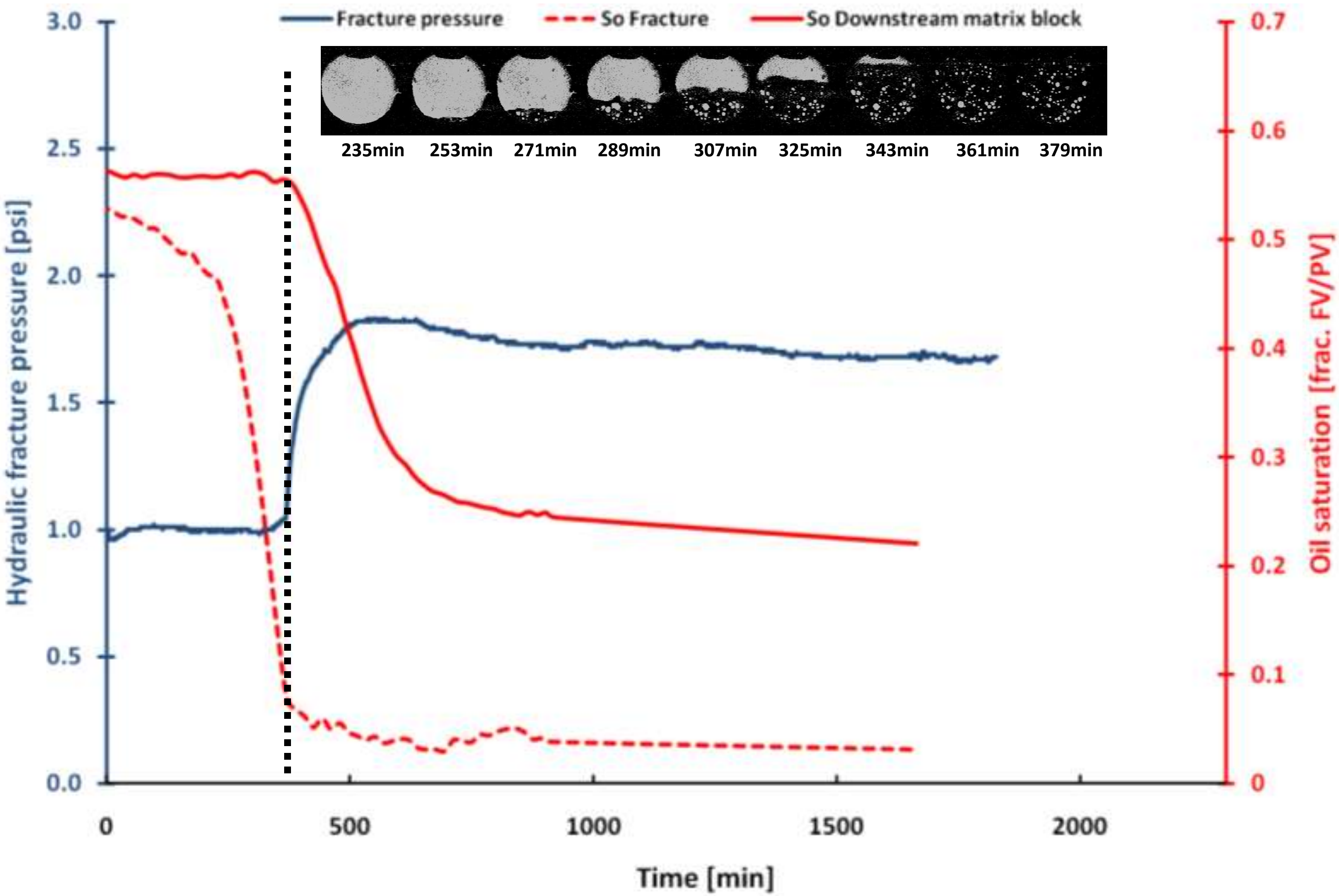
Fracture filling at strongly water-wet conditions

Fracture filling at moderately oil-wet conditions



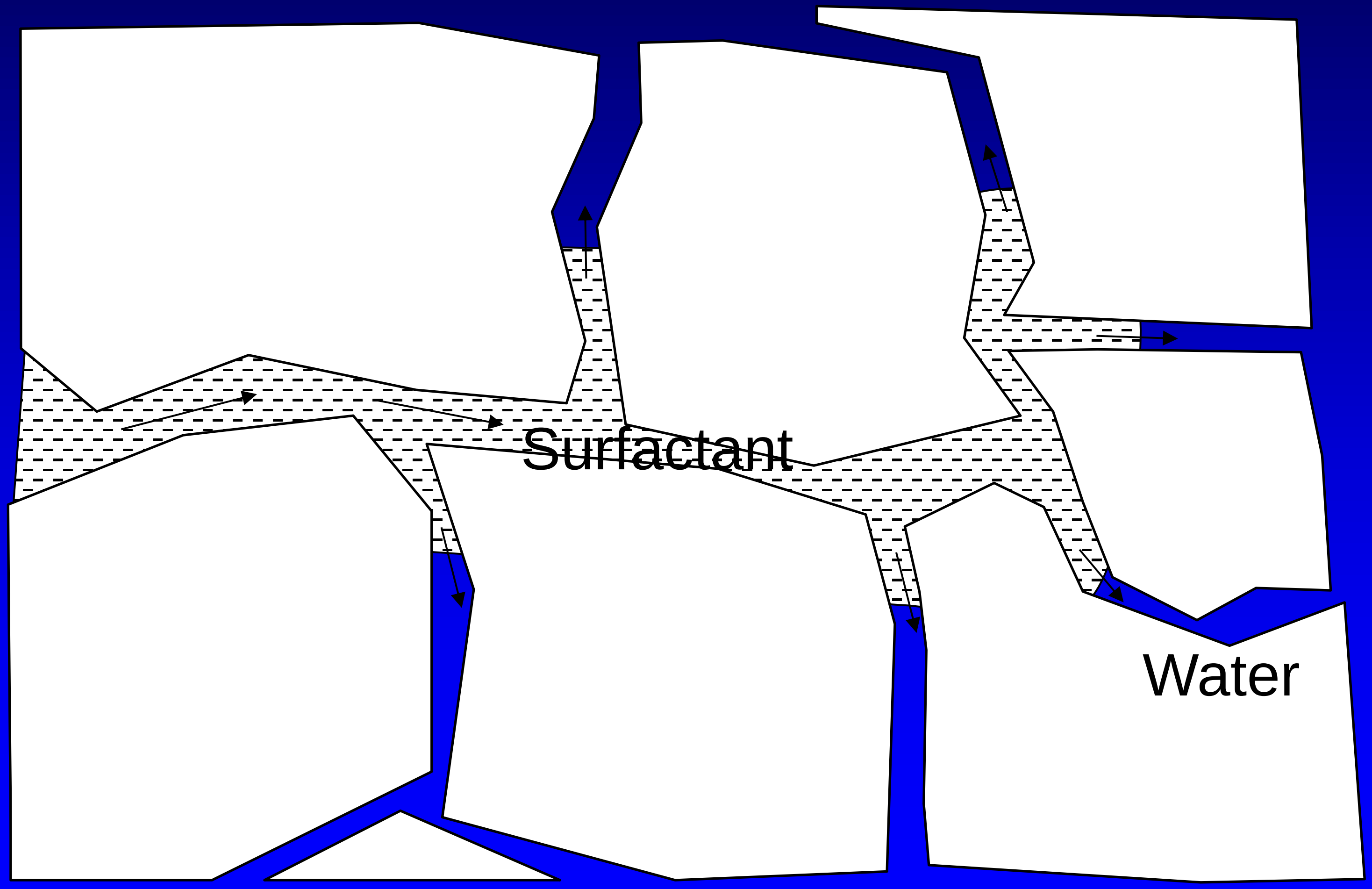
Start → **TIME** **end**

WF oil-wet conditions



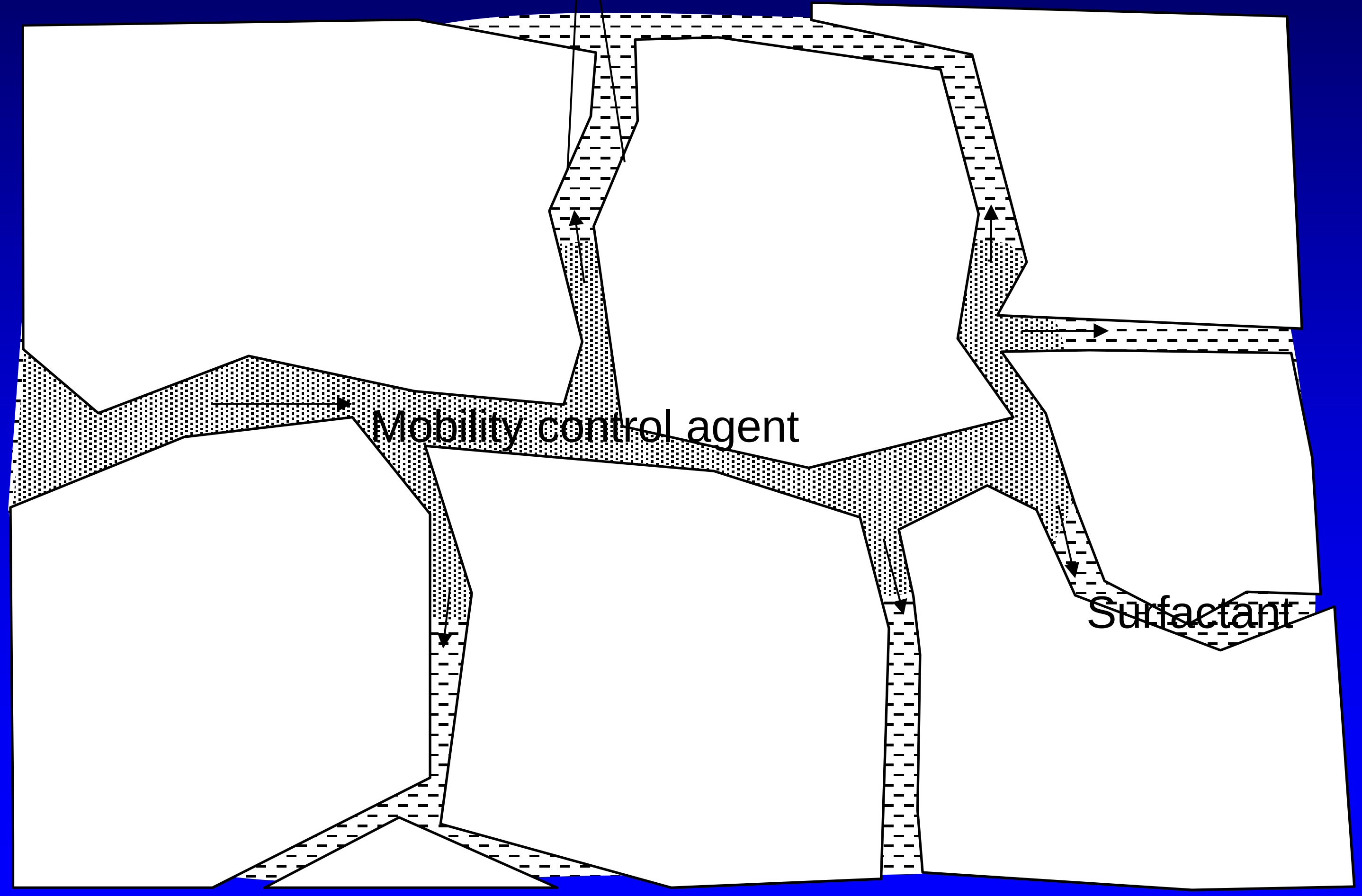
IEOR: Water + (Surf) + CO2 Foam

Pretreatment of fracture surfaces



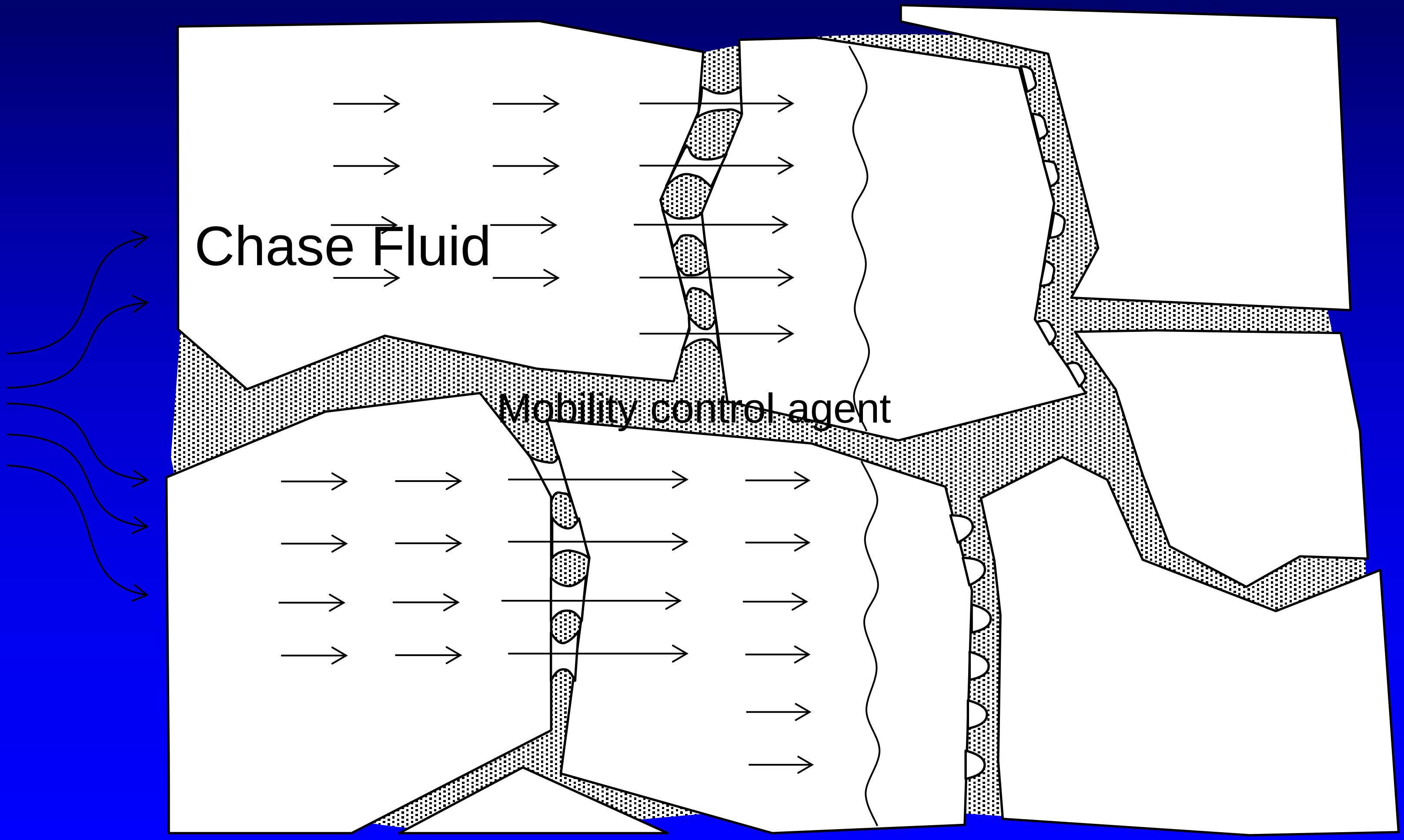
IEOR: Water + (Surf) + CO_2 Foam

Injection of mobility control agent



IEOR: Water + (Surf) + CO_2 Foam

Chase fluid injection



Large Scale Collaboration Emphasizing Mobility Control and CO_2 EOR in Field Pilots in Texas

<u>**Collaboration: 11 universities**</u>

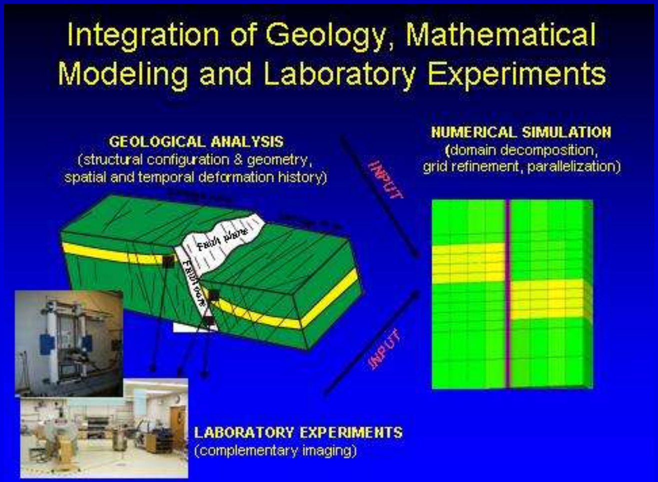
- Rice University
- University of Texas at Austin
- Texas A&M U.
- Stanford U.
- Imperial College, London
- TREFLE, Bordeaux, France
- U. of Kansas
- New Mexico Tech
- TU Delft, The Netherlands
- NTNU , Trondheim, Norway
- University of Bergen, Norway

CO_2 as CCUS for Integrated EOR

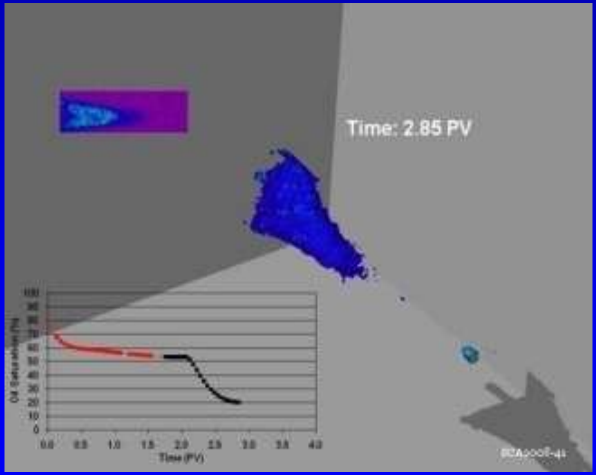
Arne Graue, Dept. of Physics, University of Bergen, NORWAY

Collaboration: 11 Universities in France, UK, Netherland, USA and Norway
Funding: The Research Council of Norway and 3-5 oil companies

Objective: ***Experimentally determine optimum conditions for CO_2 as CCUS for Integrated EOR, low S_{or} & prod. of ROZ***



Lab to pilot field test



MRI of CO2 injection

Complementary NTI & MRI facilities

END