Surfaces formed by Subcritical Crack Growth in Silicate Glasses

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Talk Outline

- *Search for cavities at crack tips in silicate glasses. (are cavities present, does nano plasticity occur?).*
- *Surface Roughness for slowly moving cracks. (how rough are the surfaces (are they fractal?)?).*

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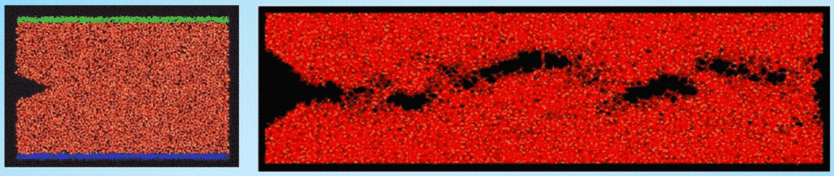
Molecular Dynamic Simulation of the Fracture Process in Silica Glass

Silica glass ⟷ **Open structure**: **pre-existing voids 4.5 A**

T. P. Swiler, J. H. Simmons, A.C. Wright, J. Non-cryst. Solids 182, (1995) 68-77

Multi million atoms simulation

L. van Brutzel et al. Mat. Res. Soc. Symp. Proc. 703, 117 (2002)



2-6 nm cavities
(size for a stressed material)

- Pure Silica glass
- Free of corrosive environment (H_2O)
- Rayleigh wave speed (3370 m/s)

Phys. Rev. Let. [71], 19, (1993), p 3162-3165

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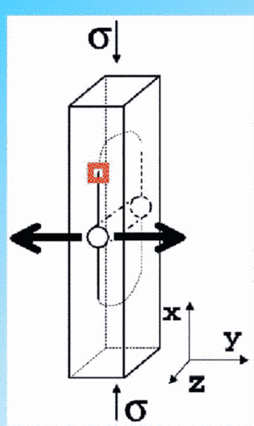
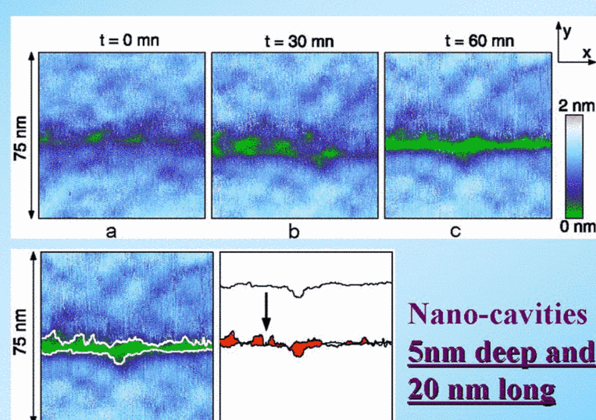
Glass breaks like metal,but at the nanometer scale

F. Celarie et al., Phys. Rev. Let., [90] 7 (2003) p 1-4





Nano-cavities up to
5nm deep and
20 nm long

- Alumino-silicate glass
- Environment: 42% Rh
- Crack velocity: 10^{-11} m/s

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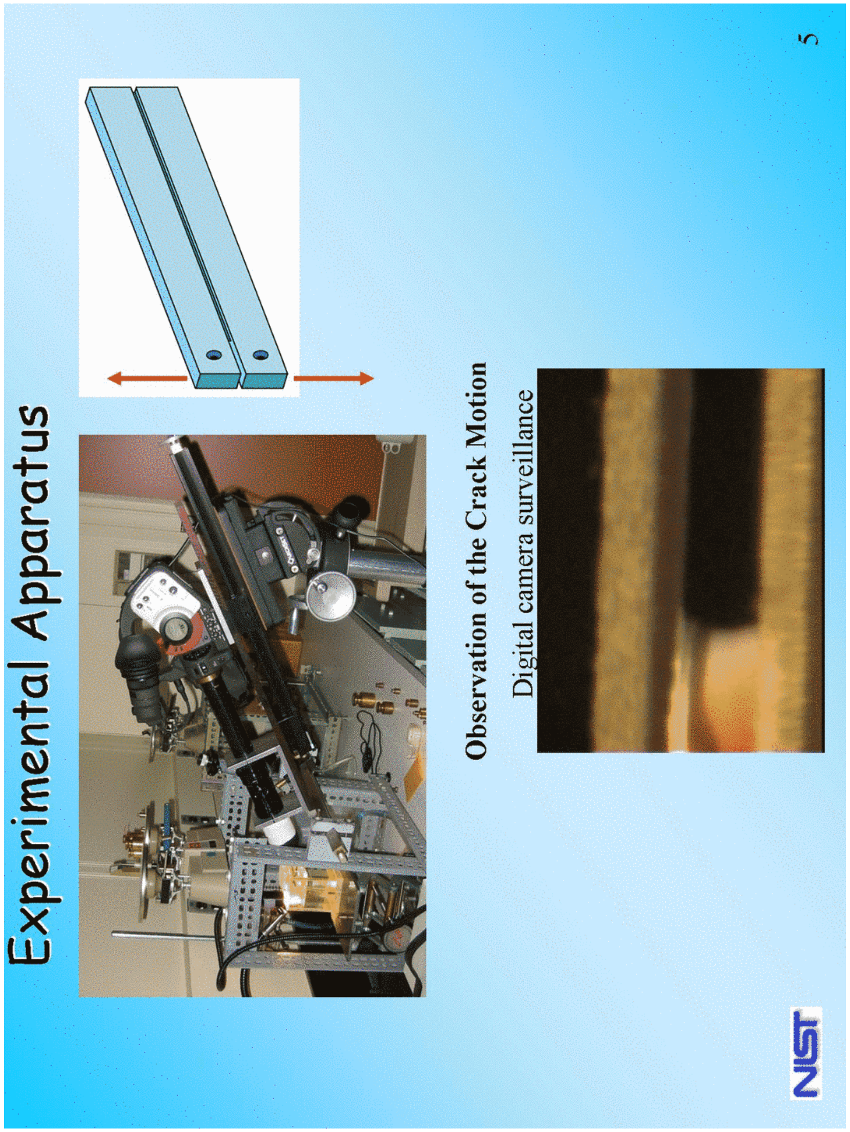
Experimental Apparatus
Observation of the Crack Motion
Digital camera surveillance
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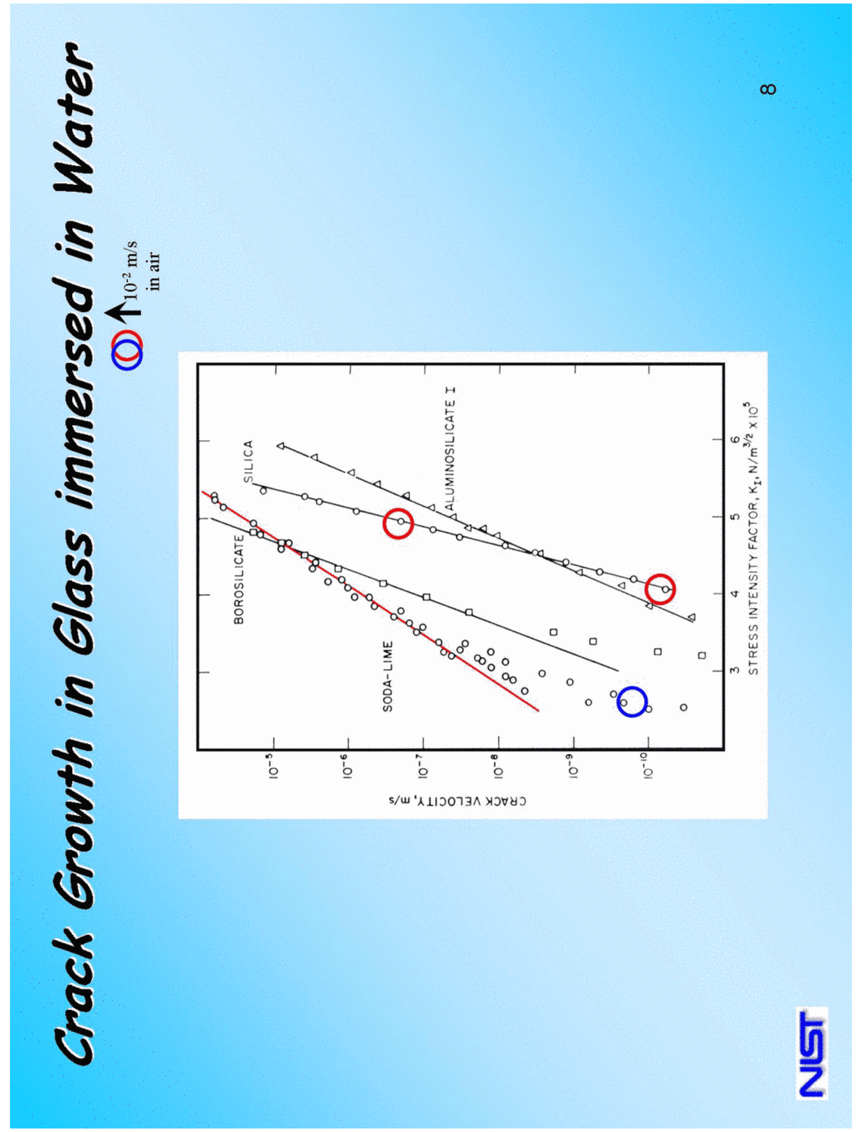
Crack Growth in Glass immersed in Water
10-2 m/s
in air
SILICA
ALUMINOSILICATE I
BOROSILICATE
SODA-LIME
STRESS INTENSITY FACTOR, K_I, N/m^3/2 x 10^5
CRACK VELOCITY, m/s
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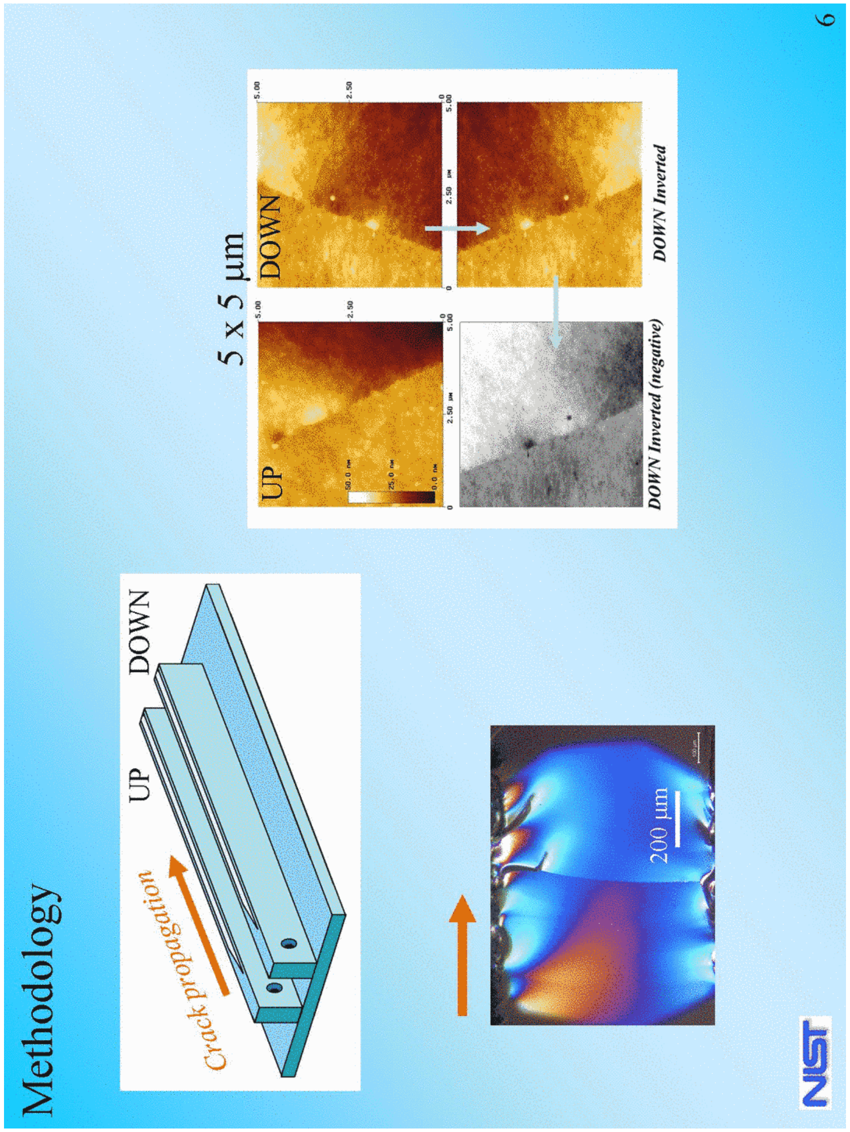
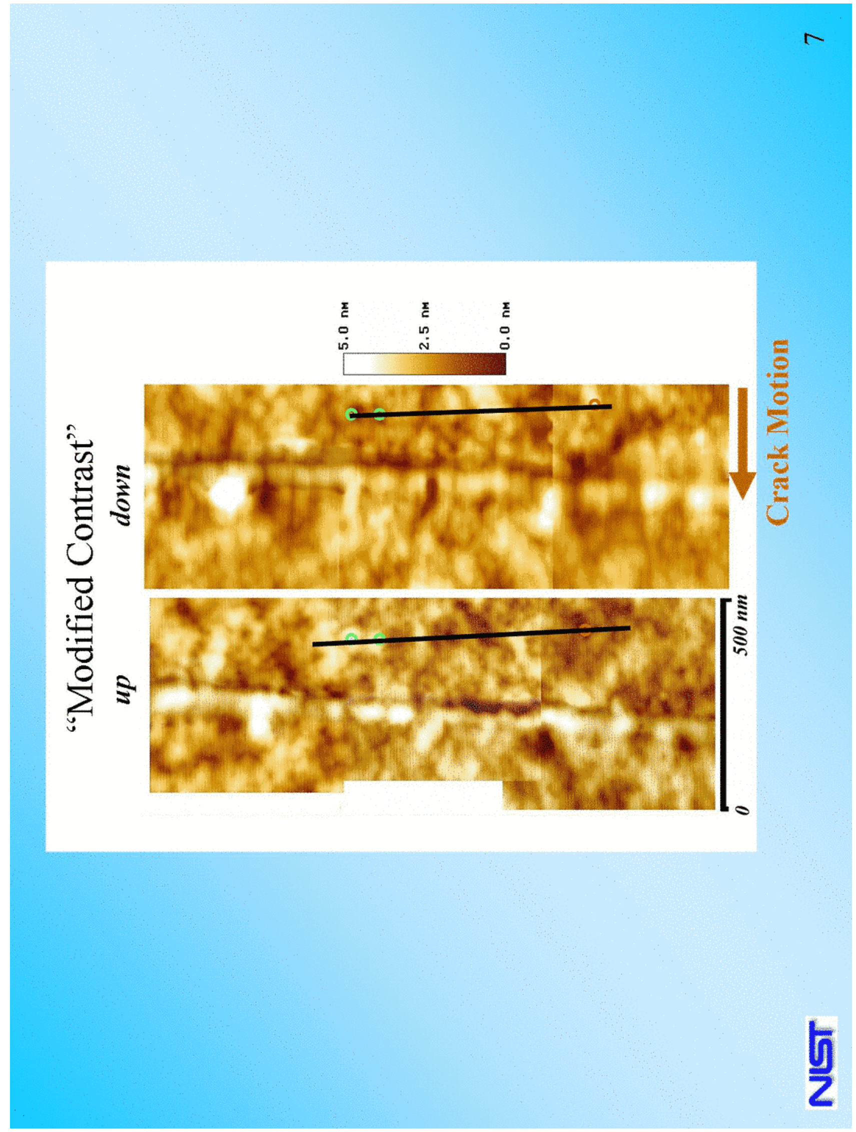

Methodology
UP
DOWN
Crack propagation
200 µm
5 x 5 µm
UP
DOWN
DOWN Inverted (negative)
DOWN Inverted
6


“Modified Contrast”
up
down
5.0 nm
2.5 nm
0.0 nm
500 nm
0
Crack Motion
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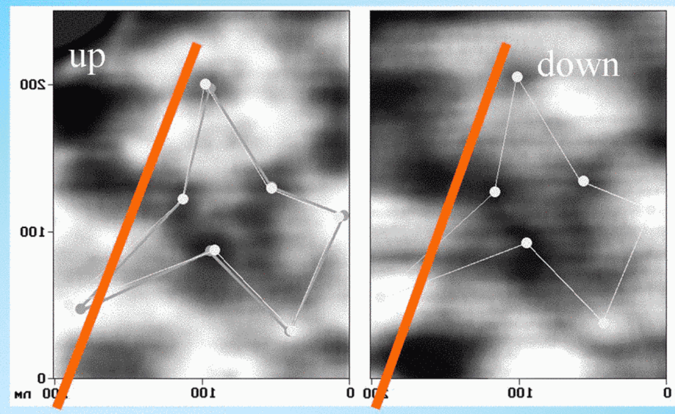
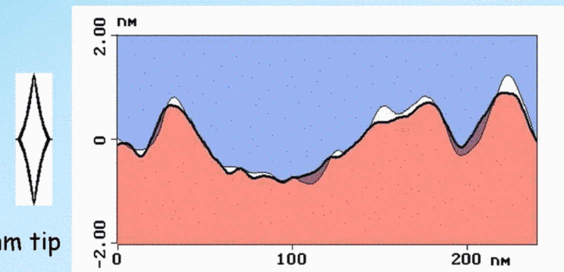
Commercial Soda-Lime-Silicate Glass

Tip radius 20-60 nm

lateral resolution >5nm

C. Bustamente, D. Keller
Physic Today 48 [12], (1995), 32-38





40 nm tip

- Soda-lime silica glass
- air
- 3.10^{-2} m/s

The two surfaces match to within 1/3 nm!!

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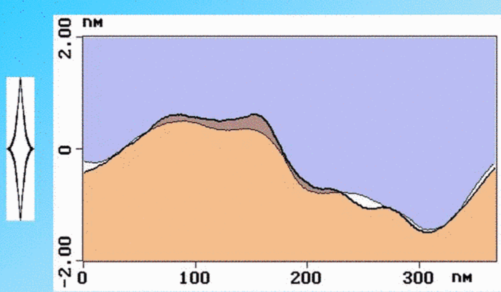
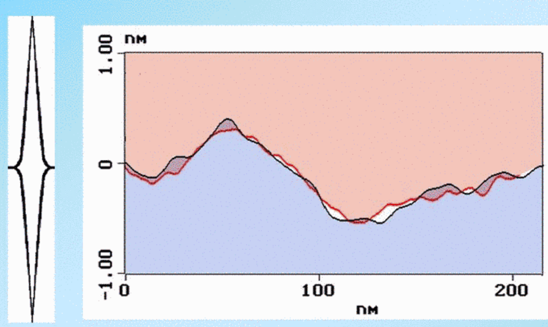
Silica Glass



- Silica glass
- Immersed in water
- 3.10^{-7} m/s



- Silica glass
- Air
- Fast fracture (manually broken)

We see no cavities <u>20 nm wide by 5 nm deep</u> in silica or soda-lime-silicate glass at crack velocities of 10^{-7} nm or greater.

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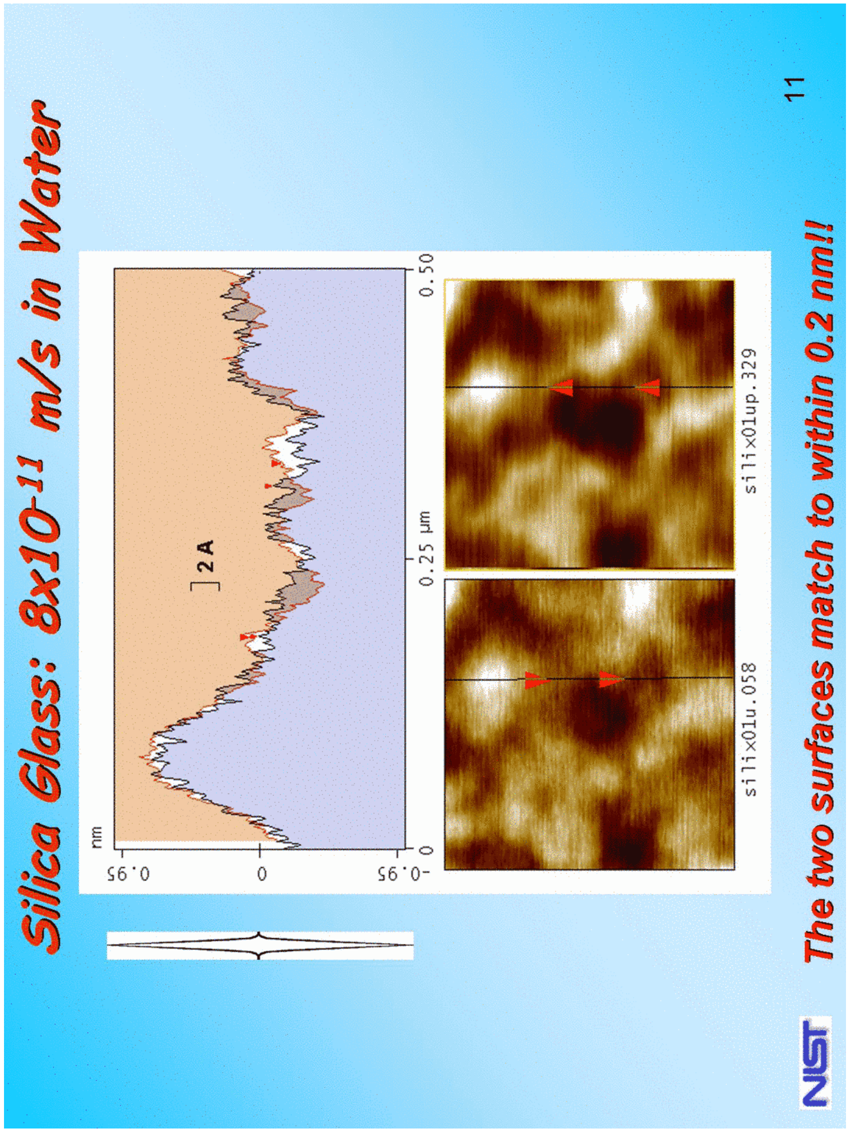
Silica Glass: 8x10-11 m/s in Water
2 A
nm
0.95
0
-0.95
0
0.25 µm
0.50
silix01u.058
silix01up.329
The two surfaces match to within 0.2 nm!!
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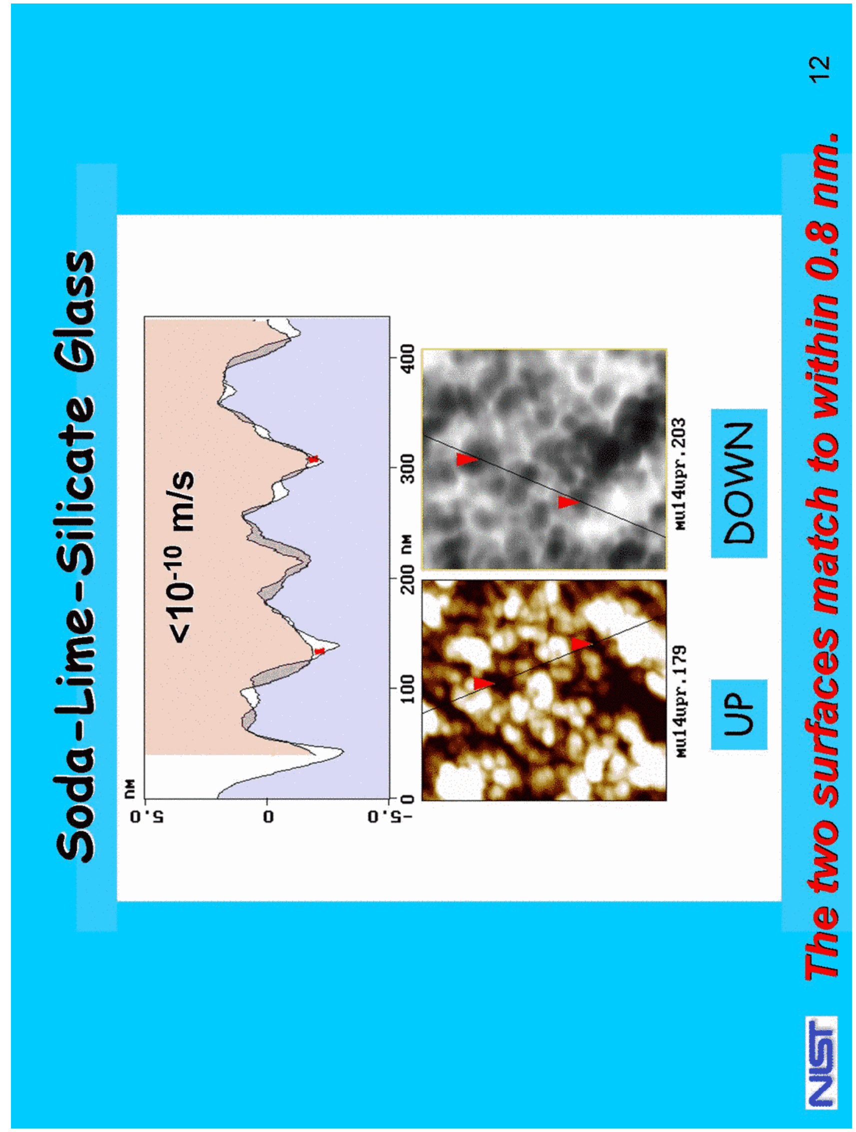
Soda-Lime-Silicate Glass
<10-10 m/s
nm
5.0
0
-5.0
0
100
200 nm
300
400
mu14upr.179
mu14upr.203
UP
DOWN
The two surfaces match to within 0.8 nm.
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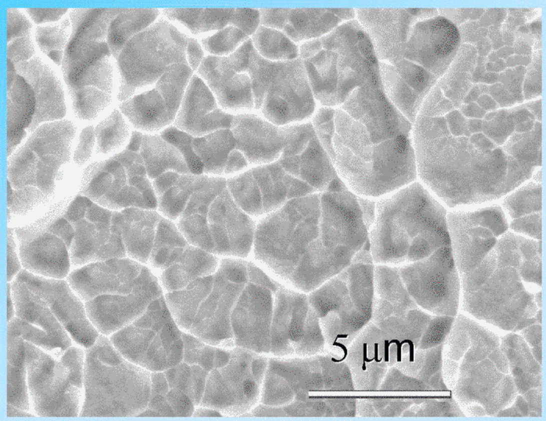
Fracture Surface in a Bulk Metal Glass



Bulk Metal Glass ($Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$)

Lewandowski, Wang and Greer, *Phil. Mag.* 2005

- Fracture surfaces form by cavitation and the coalescence of cavities.
- Shear lips bound each cavity
- Opposite fracture surfaces match edge to edge.

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Conclusion: We see no cavities.

- Neither the 20 nm x 5 nm cavities reported by Célarié *et al.* on alumino silicate glass, nor the 150 nm x 25 nm cavities reported by Prades *et al.* on silica glass are present in the fracture surface.

Rational for Experimental Observations

- The plastic zone at the crack tip is not large enough to form the size cavities predicted.

$$w = \frac{1}{6\pi}\left(\frac{K_{Ic}}{\sigma_y}\right)^2$$

For silica glass: K_{Ic}=0.8 MPa·m$^{1/2}$, σ_y=10 GPa and w=0.34 nm (Dugdale-Barenblatt eq.).

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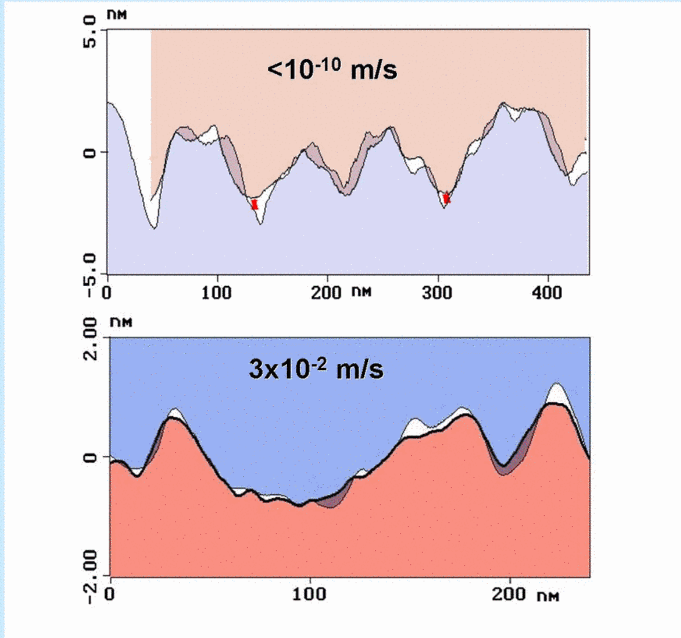
Does Roughness Depend on Crack Velocity?



Faster crack is smoother than the slower one

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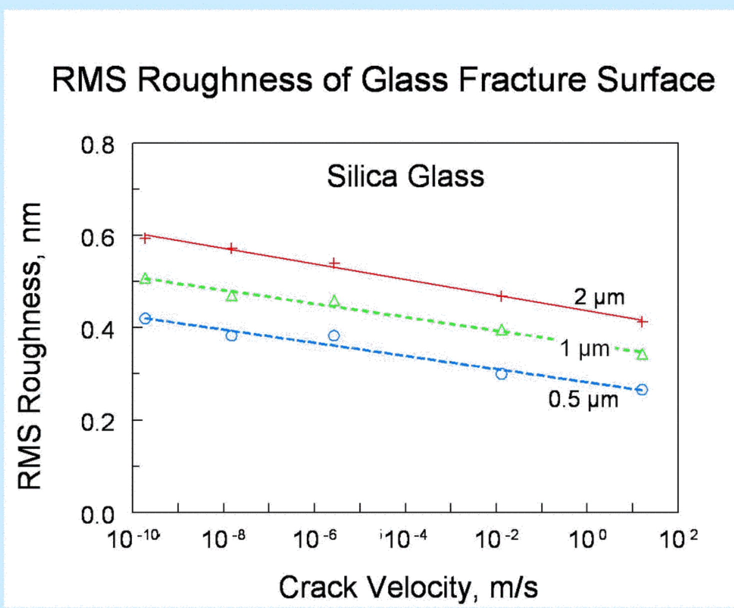

- ***Small but detectable decrease in roughness.***
- ***Contrary to findings at high velocities, >100 m/s***

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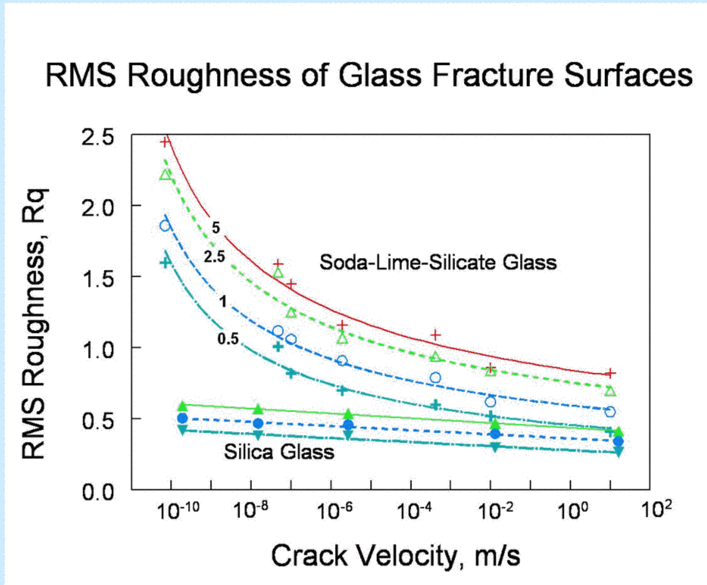

The roughness of soda lime silicate glass is much larger than that of silica glass.

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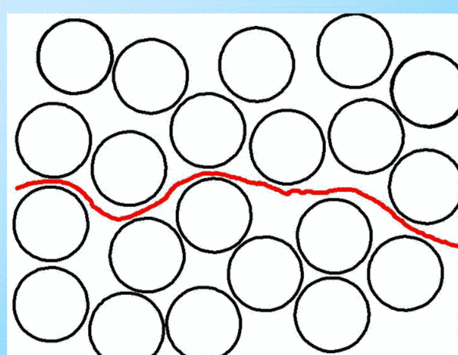
The Effect of Intrinsic Structural Inhomogenieties

- Frozen-in density and composition fluctuations.
- Clusters in Glass structures
- *Microscopic stresses which are postulated to exist in disordered structures*

Schematic of a fracture surface passing through weak regions in a glass structure [Gupta, Inniss, Kurkjian and Zhong, *J. Non-Cryst. Solids (2000)*]



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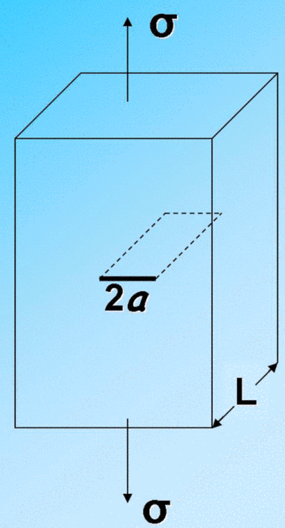
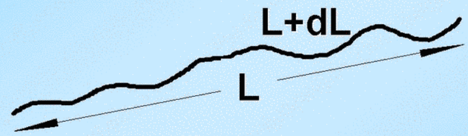
"Line Tension" as a Restoring Force



$$G = \frac{\sigma^2 \pi a}{E}$$



Elastic energy difference between a crack of length L and length L+dL is

$$G = G_o\left[1 + \frac{dL}{L}\right]$$

A driving force to propagate the crack onto a single plane

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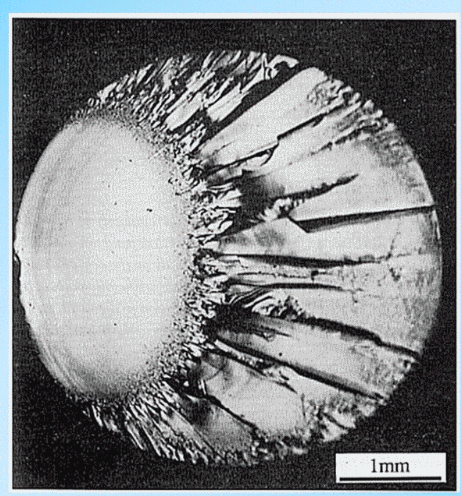
Mirror, Mist and Hackle Regions on a Fracture Surface



Johnson and Holloway, *Phil. Mag. (1966)*

- Prediction of Breaking Stress: $\sigma_f \sqrt{r} = M$
- Prediction of Lifetime: Original Crack Size

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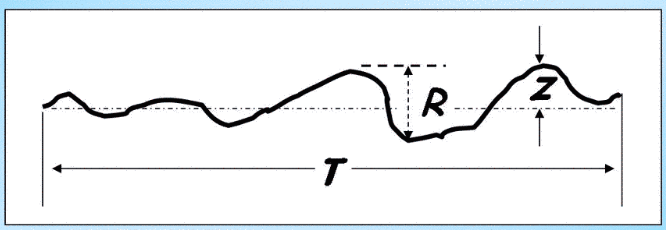
Hurst Analysis

$$R(\tau) \sim \tau^H$$

- R is the range of the variable over the interval τ.
- H is a constant called the Hurst exponent.



H varies between 0 and 1. Its value gives an idea of the quality of the curve. H=0.5 indicates a curve formed by random motion of the crack front in and out of the plane. H>0.5 suggests persistent behavior; H<0.5 anti persistent behavior.

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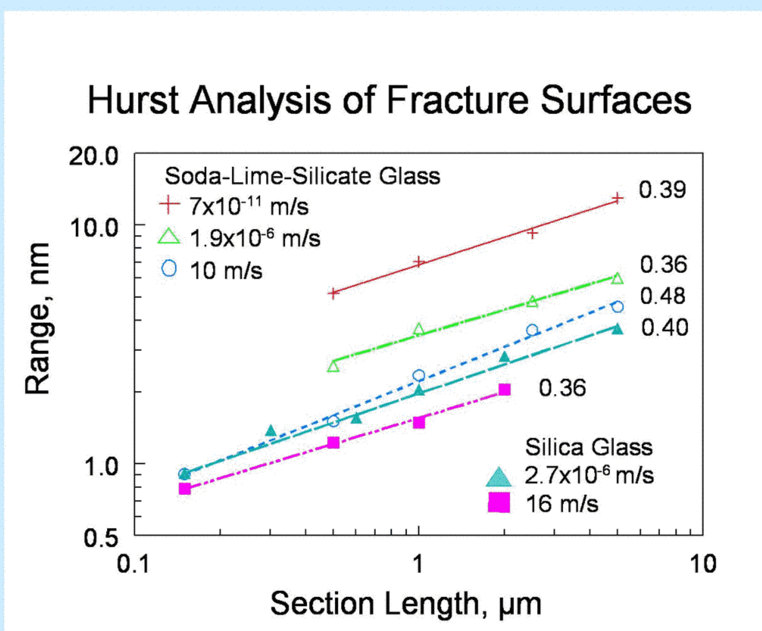

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Estimations of the Fractal Dimensions

Glass	Velocity m/s	Island Method	Hurst Analysis
		D	D=3-H
Soda-Lime-Silicate	$7x10^{-11}$	2.54	2.61
	$1.9x10^{-6}$	2.56	2.64
	10	2.65	2.52
Silica	$2.7x10^{-6}$	2.72	2.6
	$2.7x10^{-6}$	2.82	2.6
	16	2.78	2.64

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Summary

- Crack propagation in silicate glasses occurs by elastic rupture of bonds – no cavities detected during the fracture process.
- Fracture surface RMS roughness depends on crack velocity and glass composition.
- The dependence of roughness on crack velocity and composition is a consequence of the combined action of a stress-dependent line tension and nano inhomogenieties in the glass.
- Fractal Dimension, D, does not depend on K_I.

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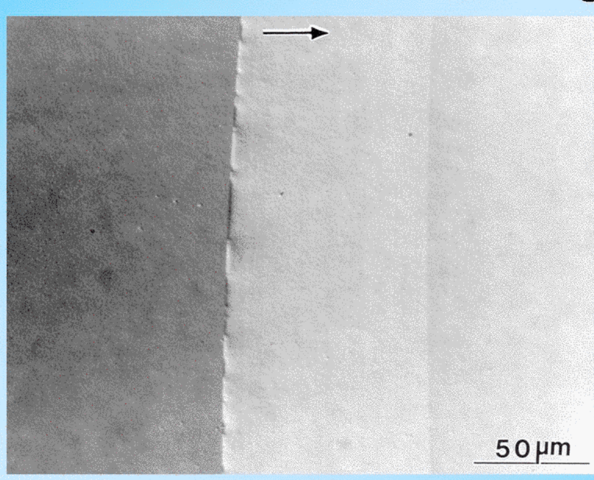
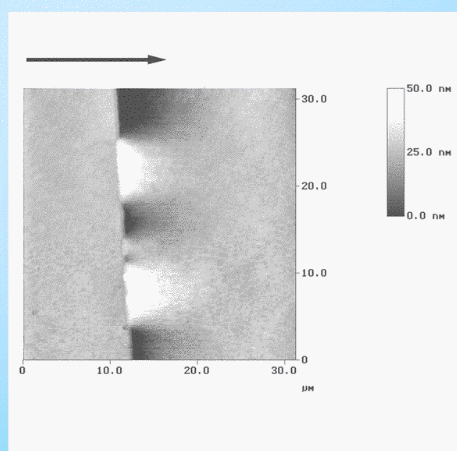
Repropagation of a "Wavy" Crack Front

Holding a crack at the static fatigue limit produces a wavy crack front. On repropagation, the crack returns to a single plane.





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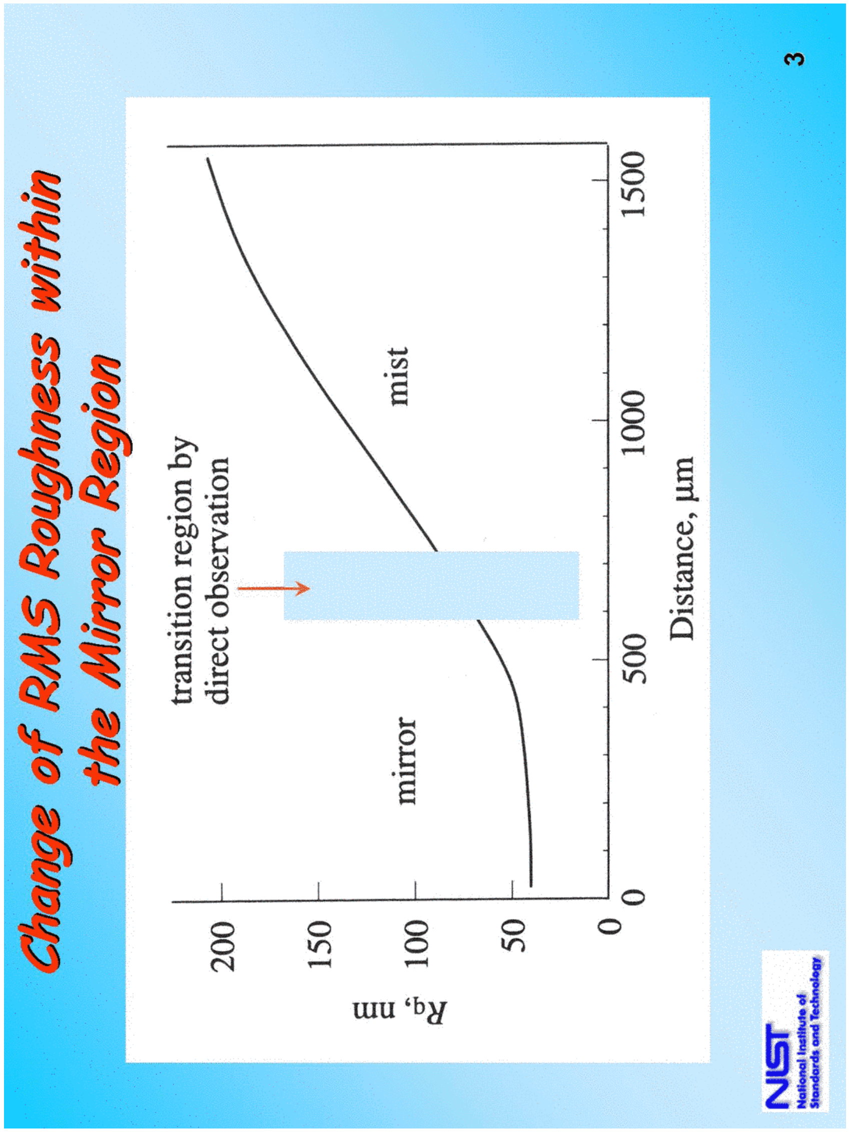
Change of RMS Roughness within the Mirror Region
transition region by direct observation
mirror
mist
R_q, nm
200
150
100
50
0
0
500
1000
1500
Distance, µm
3
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