Forming

Fundamentals of inorganic glasses, A.K. Varshneya, The society of glass technology, 2006 – Ch. 13-20

glass: liquid → viscous liquid → solid

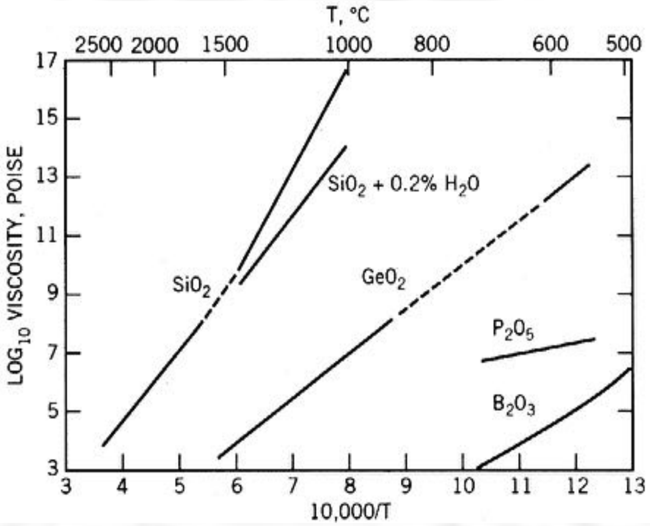
T

1 / viscosity

working range
10^4 - $10^{7.6}$ P

undercooled liquid

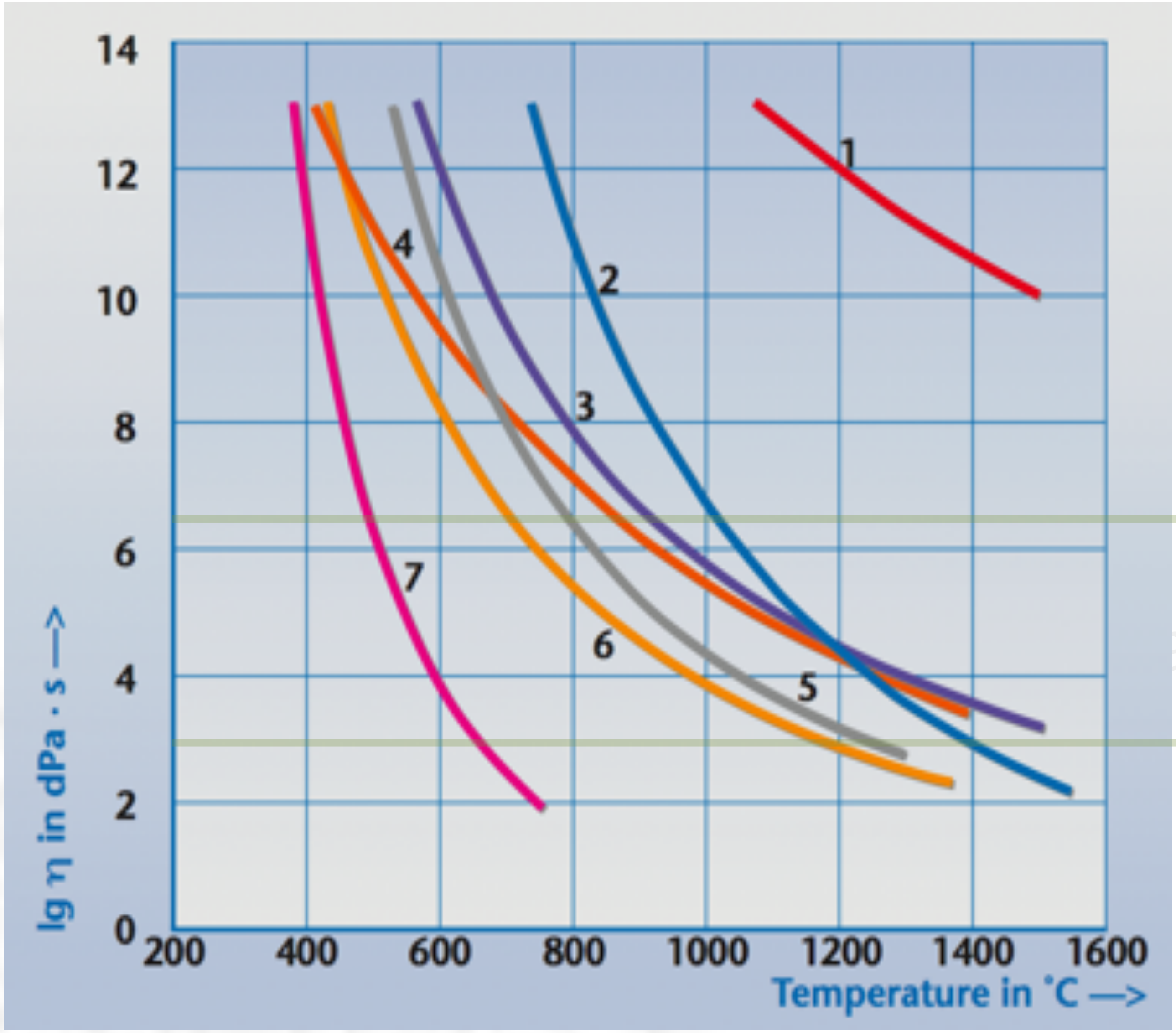
1 Pa s = 10 P
η_{H2O} @ 25°C = 10^{-2} P = 1 cP



in pure oxide glasses

$$\eta = \eta_0 \exp\left(\frac{Q}{RT}\right)$$

in commercial glasses



1 – silica
2 – aluminosilicate
3 – borosilicate
4 – soda borosilicate
5 – soda-lime silicate
6 – soda-lead silicate
7 – lead silicate

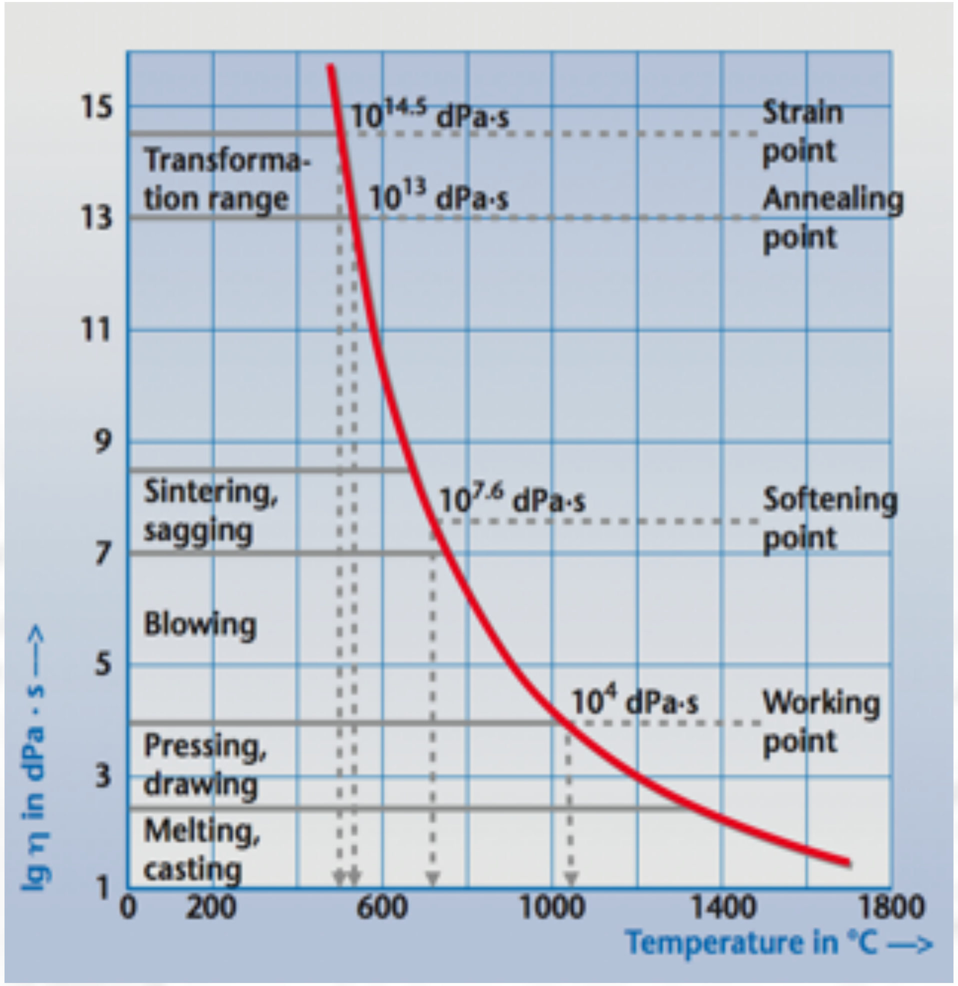
"solid"

working range
10^4 - $10^{7.6}$ P

"liquid"

SCHOTT Technical Glasses, 2007

soda-lime silicate glass



Name of reference temperature	Viscosity (Pa s)
Practical melting temperature	≈1–10
Working point	10^3
Littleton softening point	$10^{6.6}$
Dilatometric softening temperature	10^8–10^9
Glass transformation temperature	≈$10^{11.3}$
Annealing point	10^{12} or $10^{12.4}$
Strain point	$10^{13.5}$

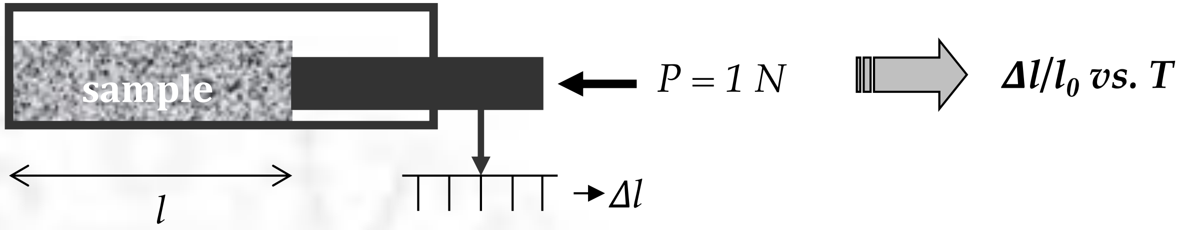
- *working point* $\eta = 10^3$ *Pa s;* *forming, moulding*
- *softening point* $\eta = 10^{6.6}$ *Pa s* *flow under its own load*
- *annealing point* $\eta = 10^{12}$ *Pa s* *stresses removed in few minutes*
- *strain point* $\eta = 10^{13.5}$ *Pa s* *stresses removed in few hours; cooling without stresses*

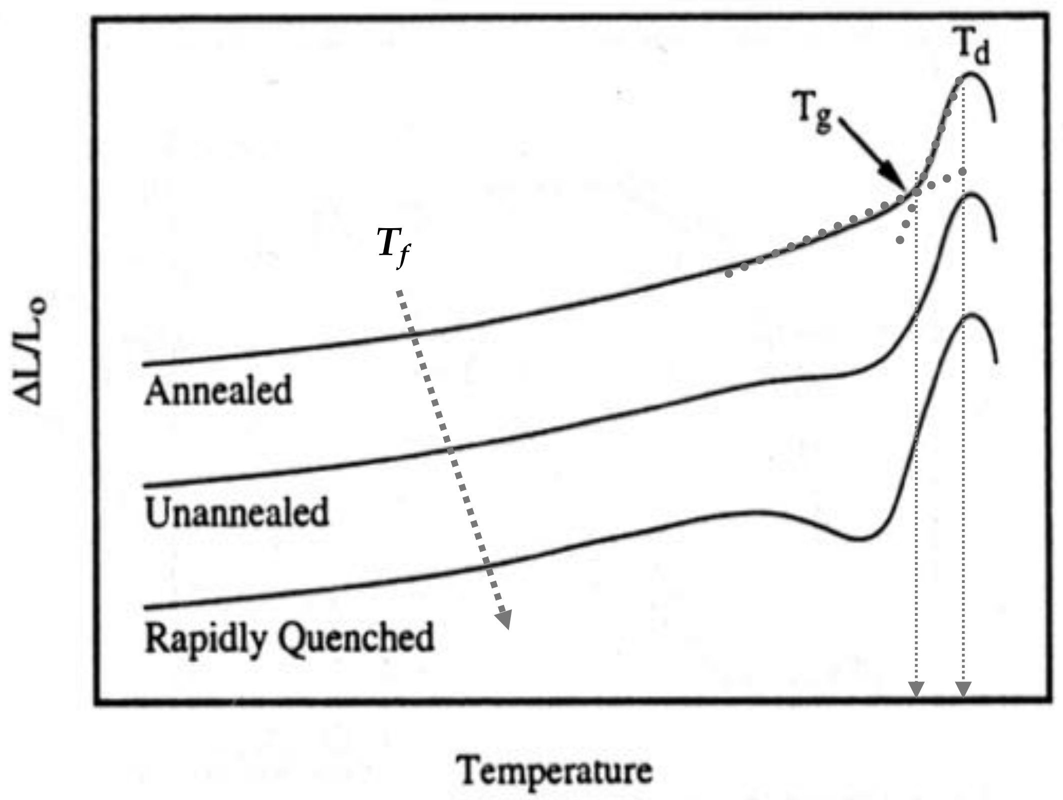
SCHOTT Technical Glasses, 2007

Introduction to glass science and technology, J. E. Shelby, The Royal Society of Chemistry, 1997

Dilatometric analysis

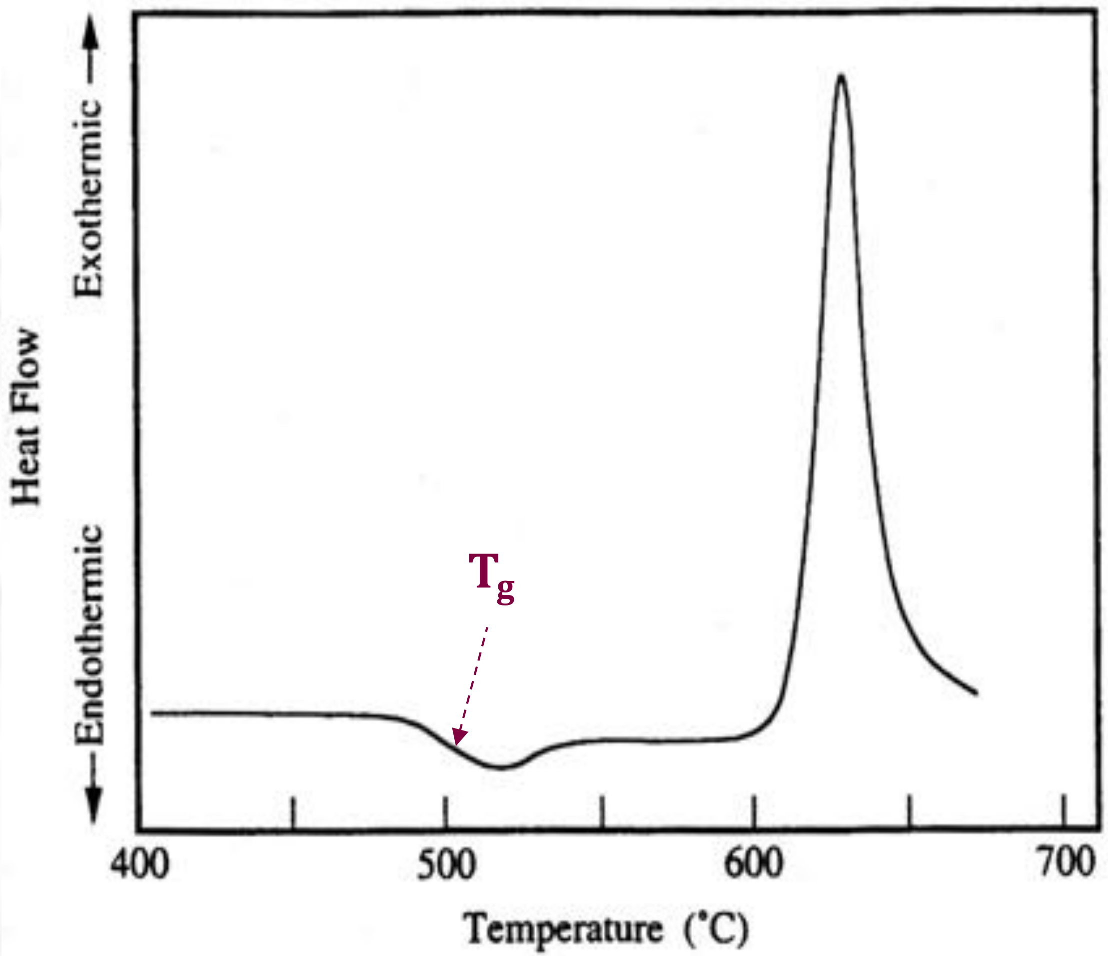
Monothonic heating (dT/dt = constant)





Introduction to glass science and technology, J. E. Shelby, The Royal Society of Chemistry, 1997

DSC analysis



Viscosity - composition

Silicate glasses

- *silica:* $T_g = 1060\text{-}1200°C$

- *alkaline oxides* → *η reduction (non-bridging oxygens)*

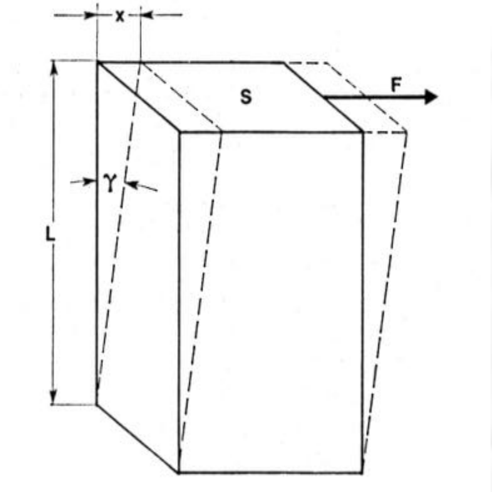
- *alkaline-earth oxides ÷ alkaline oxides* → *η increase*

- *PbO* → *η reduction*

- B_2O_3 → *η reduction*

Visco-elastic behaviour

elastic strain



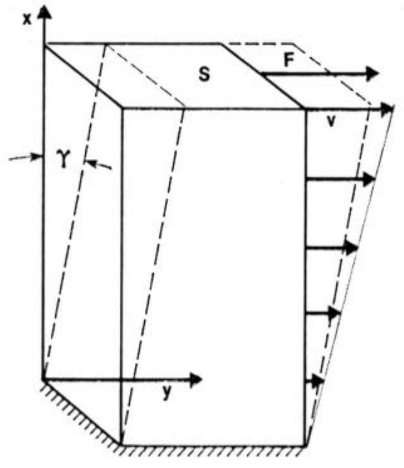
$$\frac{x}{L} = \tan\gamma \approx \gamma$$

$$\boxed{\tau = G\gamma}$$

elastic modulus

glass at low temperature

viscous strain



$$\tau = \eta \frac{dv}{dx} \qquad \frac{dv}{dx} = \frac{d}{dx}\left(\frac{dy}{dt}\right) = \frac{d}{dt}\left(\frac{dy}{dx}\right) = \frac{d}{dt}\gamma$$

$$\boxed{\tau = \eta \frac{d\gamma}{dt}}$$

"Newton's law"

viscosity

glass at high temperature

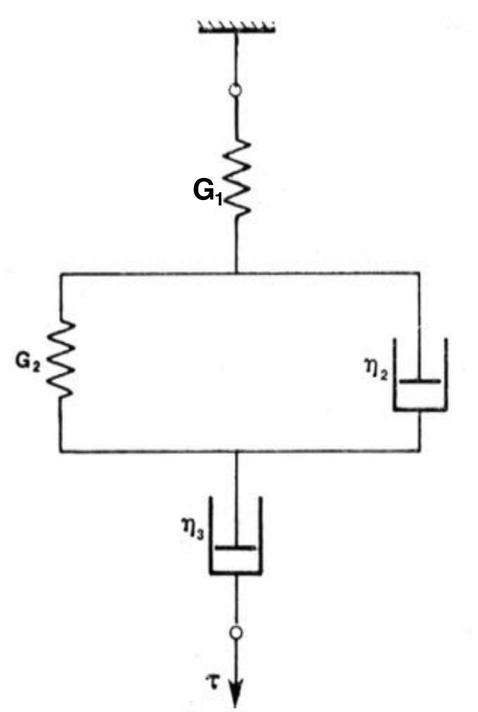
Vetri, G. Scarinci, T. Toninato e B. Locardi, Casa Editrice Ambrosiana, 1977

glass at intermediate temperature...

viscous friction among molecules

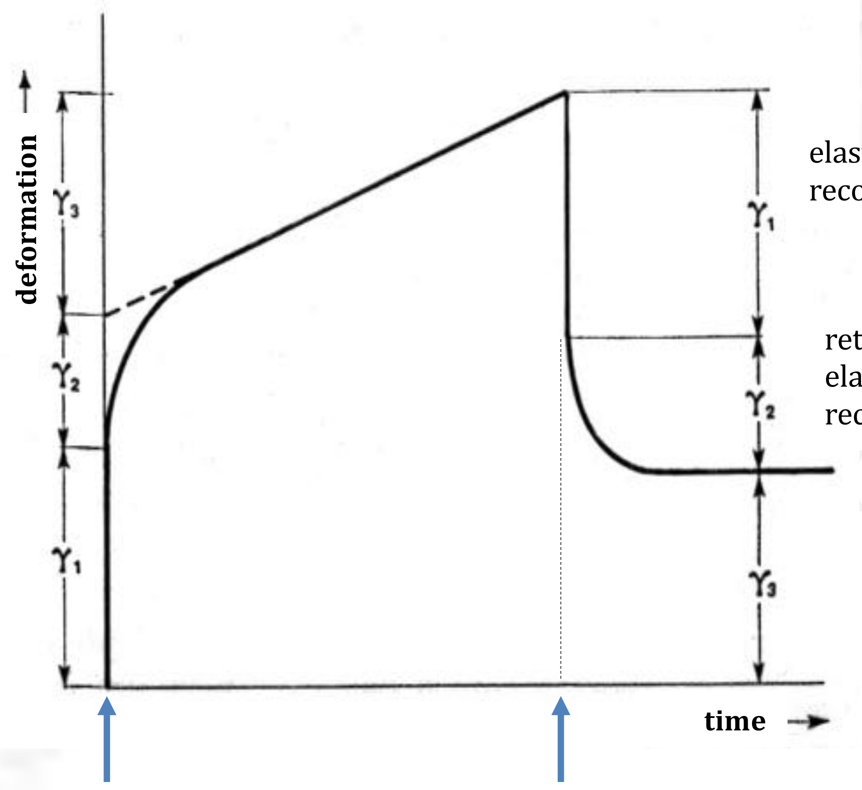
observed deformations:
- *elastic (reversible)*
- *elastic "retarded" (reversible)*
- *viscous (irreversible)*

Mix model (Burger)



$$\gamma = \frac{\tau_0}{G_1} + \frac{\tau_0}{G_2}\left(1 - e^{-\frac{G_2}{\eta_2}t}\right) + \frac{\tau_0}{\eta_3}t$$

γ_1 γ_2 γ_3



$\mathcal{T} = \eta/G$ = **delay time**

Vetri, G. Scarinci, T. Toninato e B. Locardi, Casa Editrice Ambrosiana, 1977

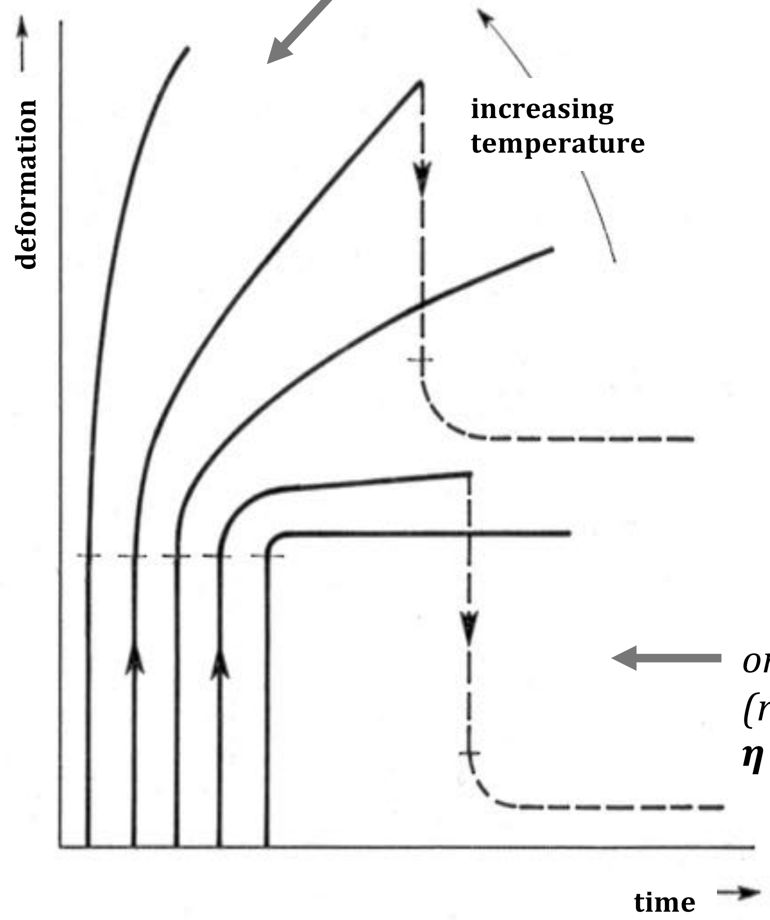
$\mathcal{T} = \eta / G$

forming time

only viscous term

($T \geq T_g$)

$\eta \approx 10^8$ P, G ≈ 30 GPa → $\mathcal{T} \approx 3 \times 10^{-4}$ s



soda-lime silicate glass

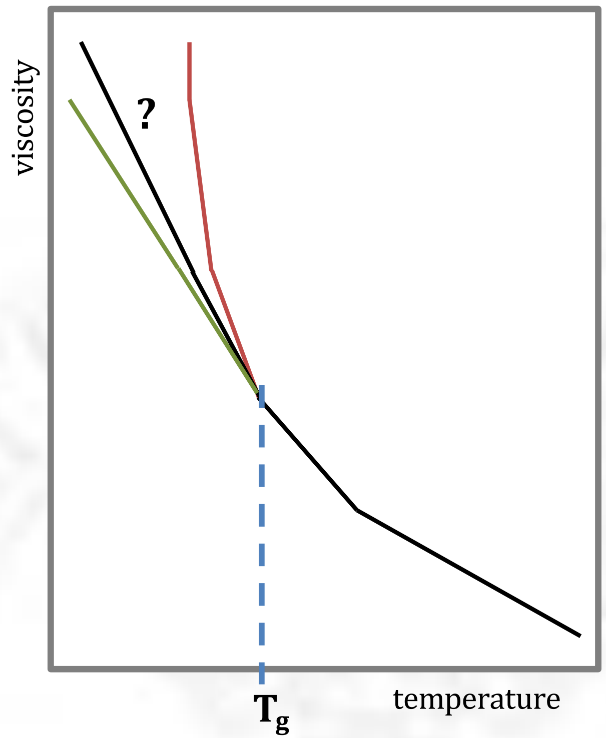
only elastic term

(room temperature)

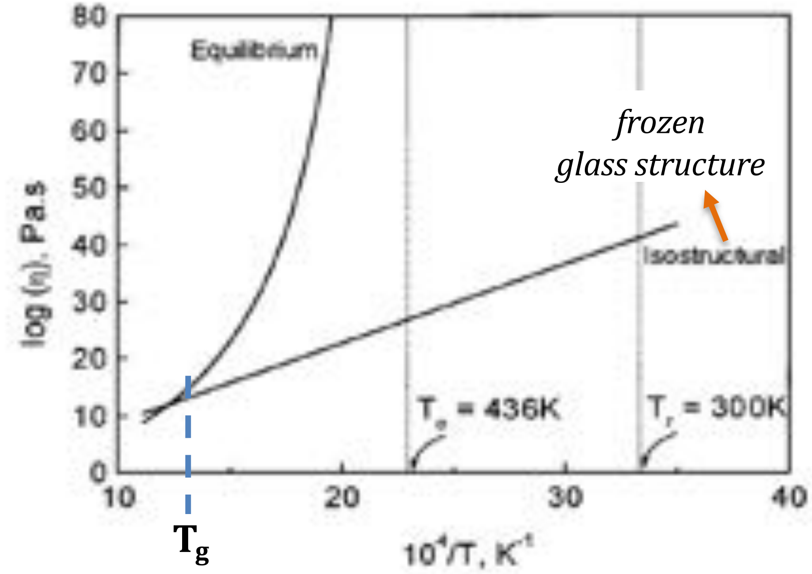
$\eta \approx 10^{14}$ P, G ≈ 30 GPa → $\mathcal{T} \approx 330$ s

Vetri, G. Scarinci, T. Toninato e B. Locardi, Casa Editrice Ambrosiana, 1977

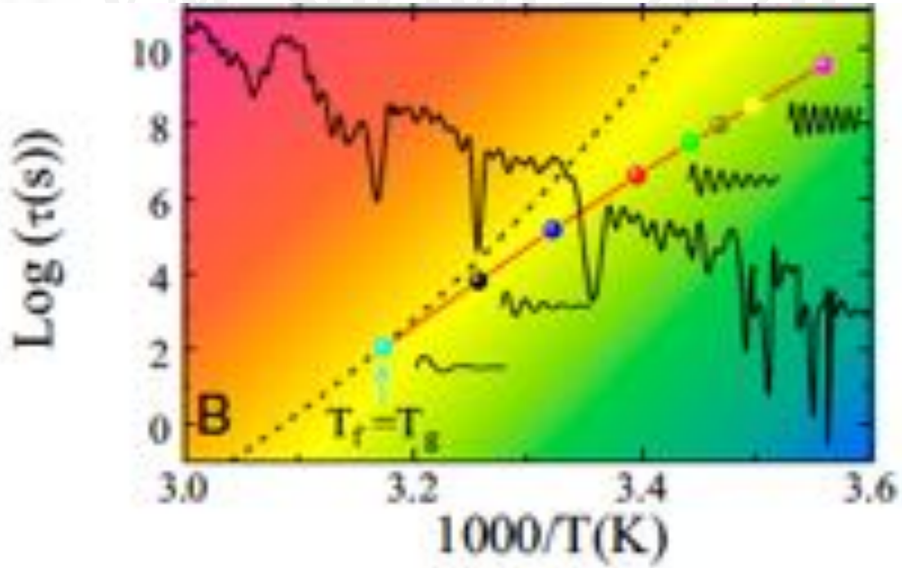
Viscosity at low temperature (< T_g)?



extrapolation



measurement on IMC (indomethacin - *antipyretic*) PVD glasses



in any case, at RT $\mathcal{T}$ >10^{20} years!

Suggested readings:

Probing equilibrium glass flow up to exapoise viscosities, Proc. Nat. Ac. Sciences, 2015

Do cathedral glasses flow?—Additional remarks, Am.J.Phys, 1999