Composition-Structure-Mechanical properties relationships in glass : metallic, oxide, and non-oxide

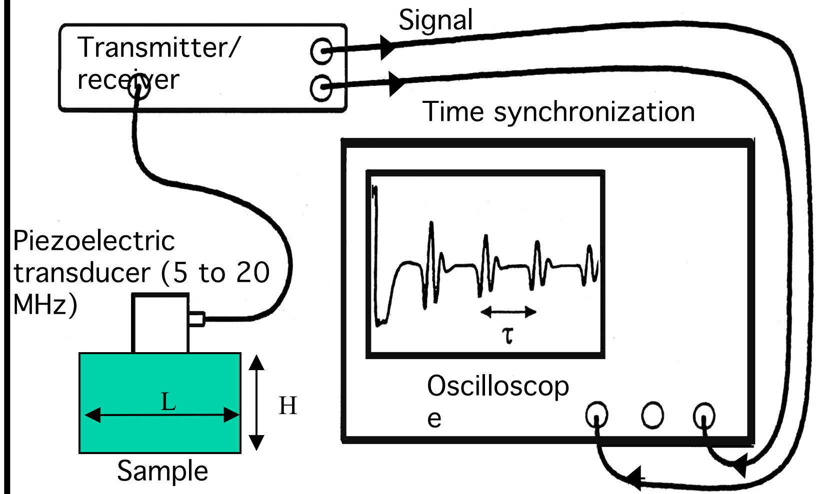
- **Interatomic bonding and atomic packing density: How it governs the elastic properties of glasses**
- **Shear viscosity**
- **What we know about indentation cracking, and fracture toughness**

Glass Engineering-MV-IPR-UMR 6251 - Université de Rennes 1, France. E-mail: Tanguy.Rouxel@univ-rennes1.fr

- **Interatomic bonding and atomic packing density: How it governs the elastic properties of glasses**

Measurement of elastic moduli by ultrasonic echography

Measurements at ambient temperature

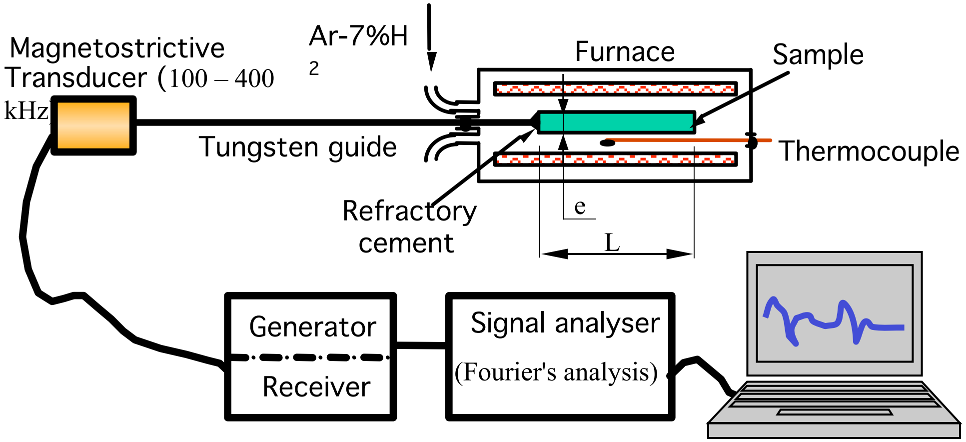


Elastic wave in semi-infinite medium : λ<<L and λ << H

$E = \rho\, (3V_l^2-4V_t^2)/((V_l/V_t)^2-1)$
$G= \rho\, V_t^2$
$\nu=E/(2G)-1$

Where: ρ: specific mass
V_l: longitudinal wave velocity
V_t: transverse wave velocity

High temperature measurements



Long beam bar mode : e<<L and e << λ (10 to 100 mm)

$E = \rho\, V_l^2$

Small size specimens: Acoustic microscopy

When (L,H)<λ, regular piezoelectric transducers are unable to efficiently promote the propagation of shear waves through the specimen. Focused piezoelectric transducers can be used to propagate surface-type waves, also called Rayleigh waves, which velocity is given by: $V_R=\zeta V_t$, where ζ is a function of Poisson´s ratio, or of the V_l/V_t ratio. V_R and V_l are measured and V_t is optimised to satisfy the following equation:

$$V_R = \frac{V_t\,(0.715-(V_t/V_l)^2)}{0.750-(V_t/V_l)^2}$$

High Temperature Mechanical Resonance technique

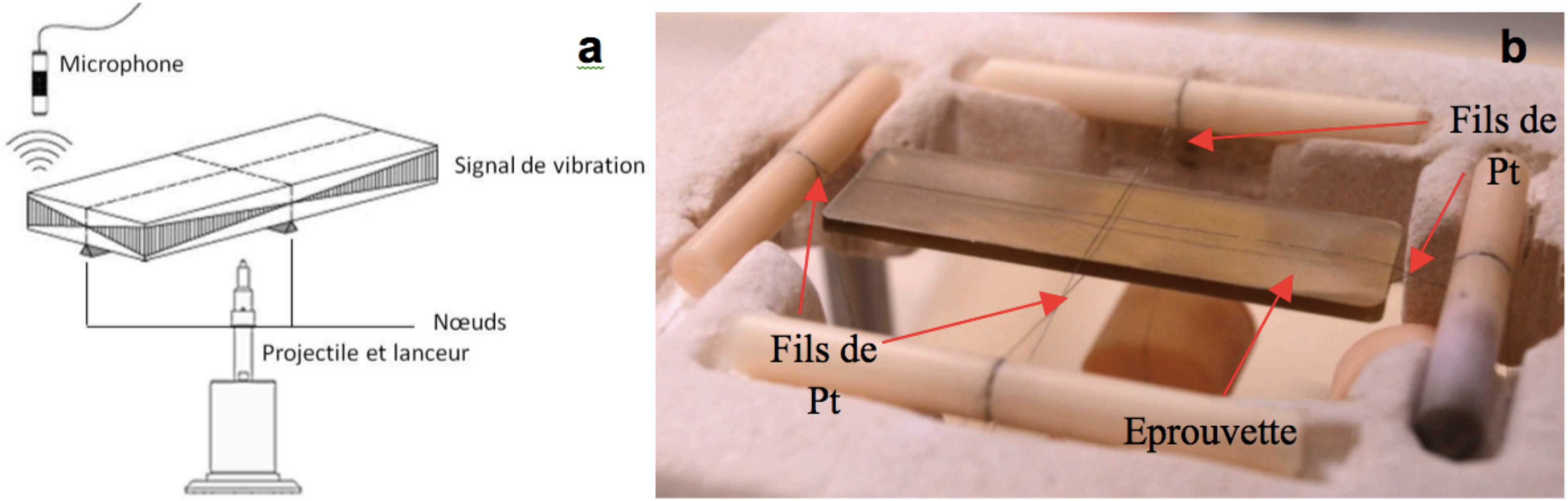
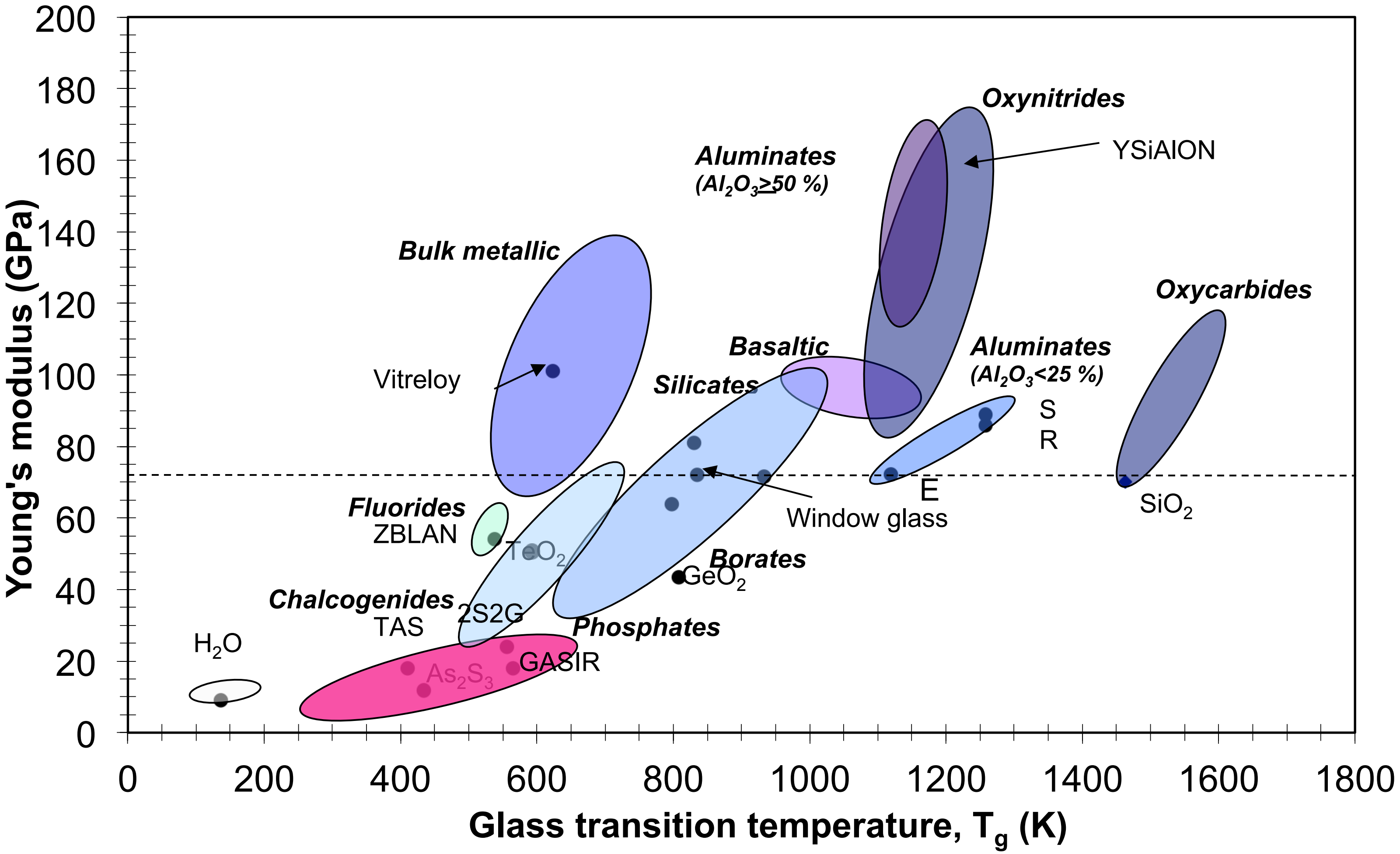


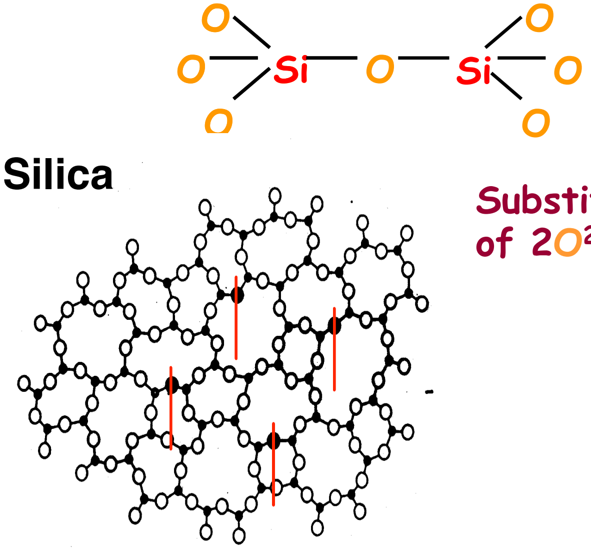
Schéma (a) et photographie (b) du dispositif RFDA en température.



- **There is no direct correlation between E and T_g**
- **Elastic moduli are expressed in Pascals, i.e. in J/m^3 , and are thus governed by the volume density of energy**

J. Am. Ceram. Soc, 90 [10] 3019 (2007)

3D units and crosslinking

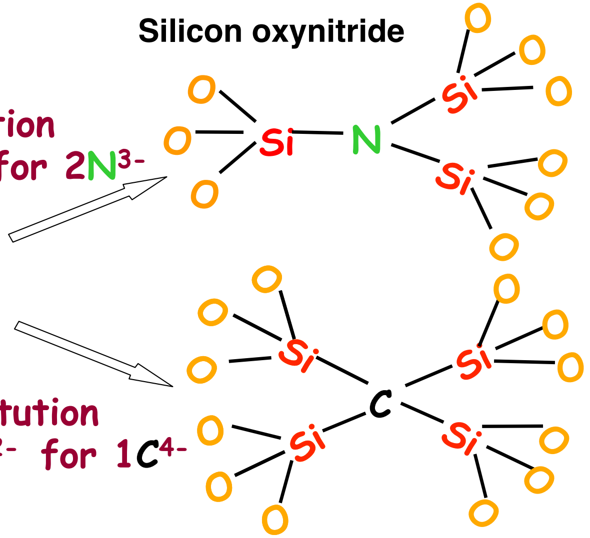


Silica

Substitution of $3O^{2-}$ for $2N^{3-}$

Substitution of $2O^{2-}$ for $1C^{4-}$

Silicon oxynitride



Silicon oxycarbide

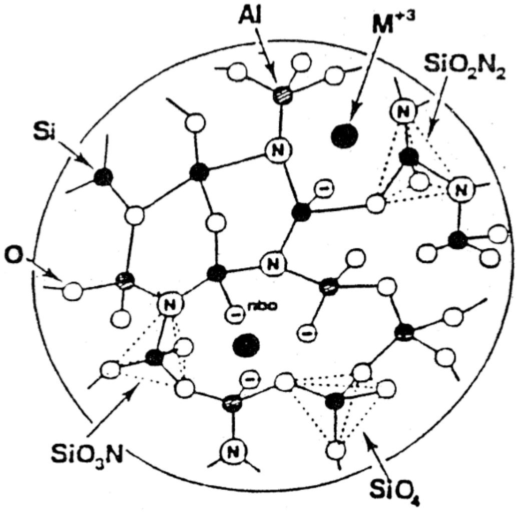


Fig. 7. Schematic representation of oxynitride glass structure (after [42]).

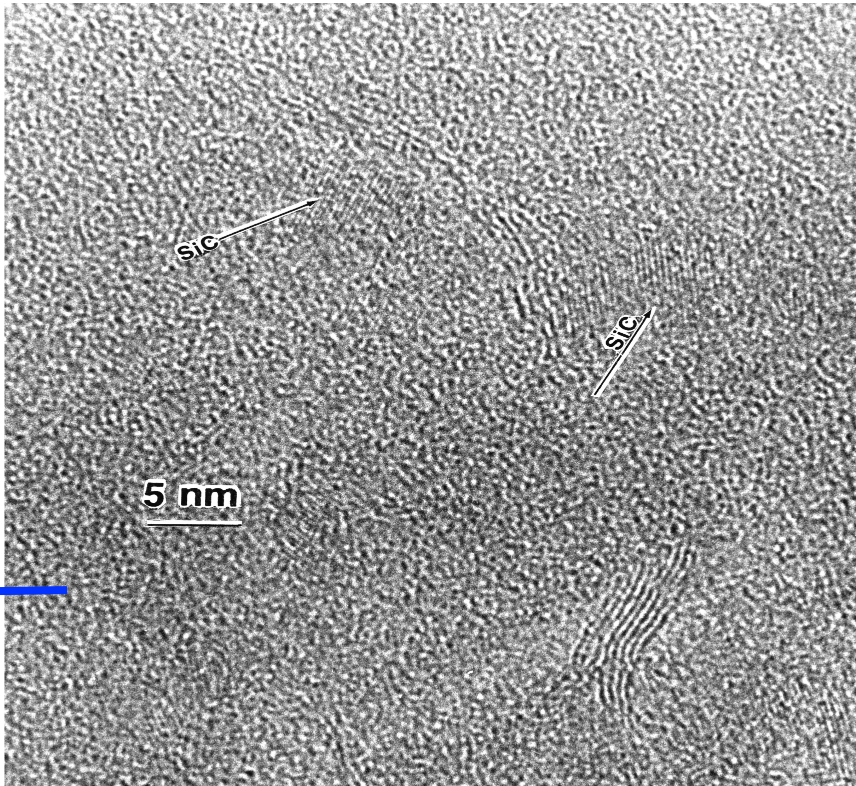
$SiC_xO_{2(1-x)}$
x=0.33 or 0.375

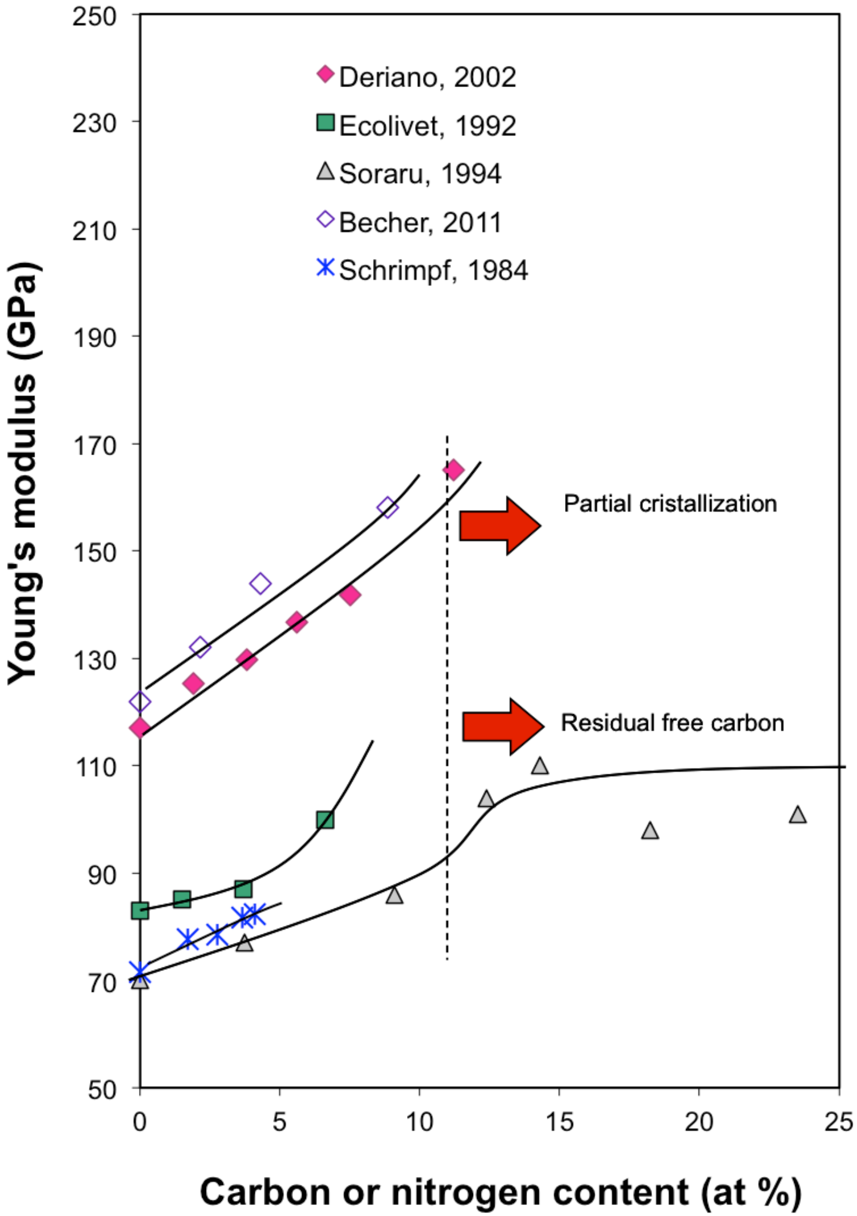
- **Playing on anions to increase the cross-linking degree of the glass network:**

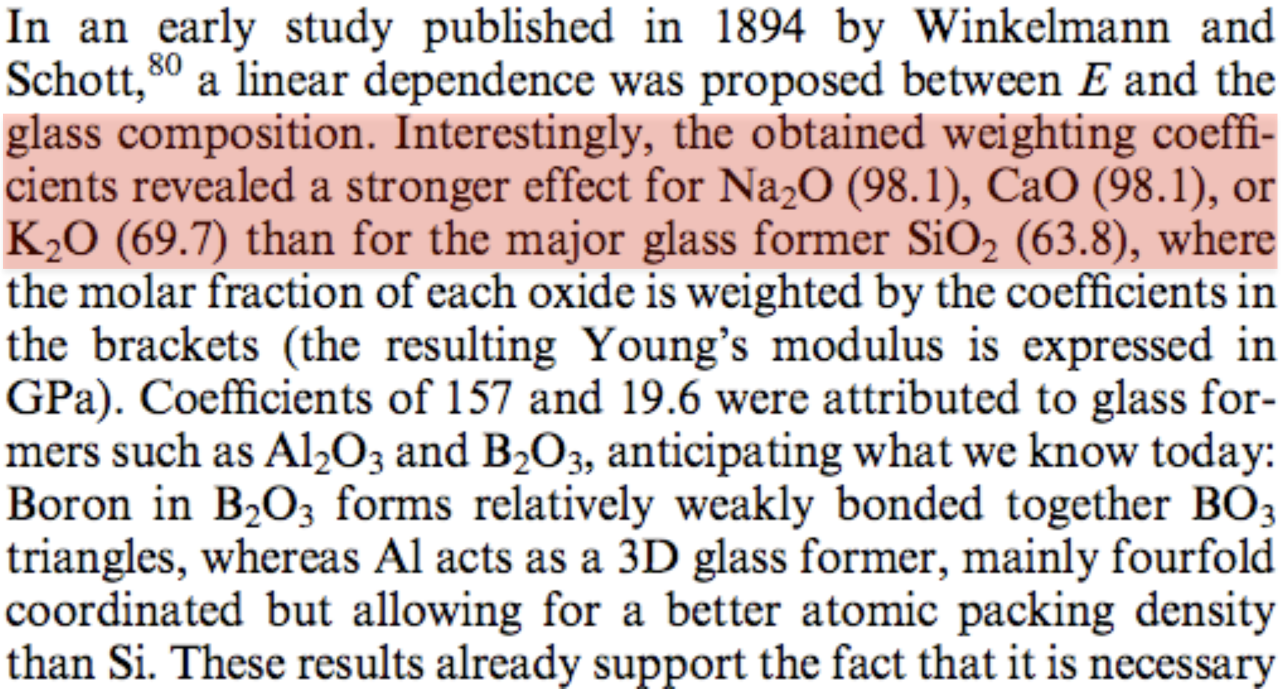
Increases the refractoriness (T_g > 750°C for oxynitride and >1300°C for oxycarbide glasses)
Increases the hardness
Favours a normal indentation cracking behavior
Stiffens the glass

Crystallization

At T>1200°C, 2.4 to 2.6 nm large b-SiC crystals, which grow little during annealing
Crystallization proceeds through the increase of the number of nanocrystals




Deriano, 2002
Ecolivet, 1992
Soraru, 1994
Becher, 2011
Schrimpf, 1984
Partial cristallization
Residual free carbon
Young's modulus (GPa)
250
230
210
190
170
150
130
110
90
70
50
0
5
10
15
20
25
Carbon or nitrogen content (at %)



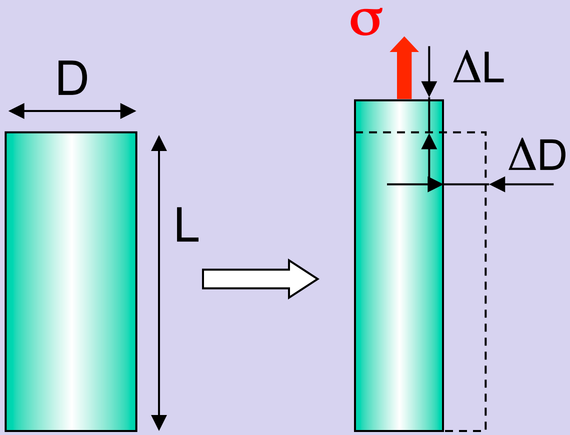
In an early study published in 1894 by Winkelmann and Schott,[80] a linear dependence was proposed between E and the glass composition. Interestingly, the obtained weighting coefficients revealed a stronger effect for Na_2O (98.1), CaO (98.1), or K_2O (69.7) than for the major glass former SiO_2 (63.8), where the molar fraction of each oxide is weighted by the coefficients in the brackets (the resulting Young's modulus is expressed in GPa). Coefficients of 157 and 19.6 were attributed to glass formers such as Al_2O_3 and B_2O_3, anticipating what we know today: Boron in B_2O_3 forms relatively weakly bonded together BO_3 triangles, whereas Al acts as a 3D glass former, mainly fourfold coordinated but allowing for a better atomic packing density than Si. These results already support the fact that it is necessary

$E = \Sigma a_i f_i$ with f_i: fraction of the i^{th} constituent

[1] A. Winkelmann and O. Schott, "Ueber die elasticität und über die Zug- und Druckfestigkeit ver-schiedener neuer gläser in ihrer abhängigkeit von der chemischen zusammensetzung," *Ann. der Phys. (Leipzig)*, **51** 697-729 (1894).

"Elastic properties and short-to-medium range order in glasses", J. Am. Ceram. Soc., 90 [10] 3019-3039 (2007).

Poisson's ratio (ν)

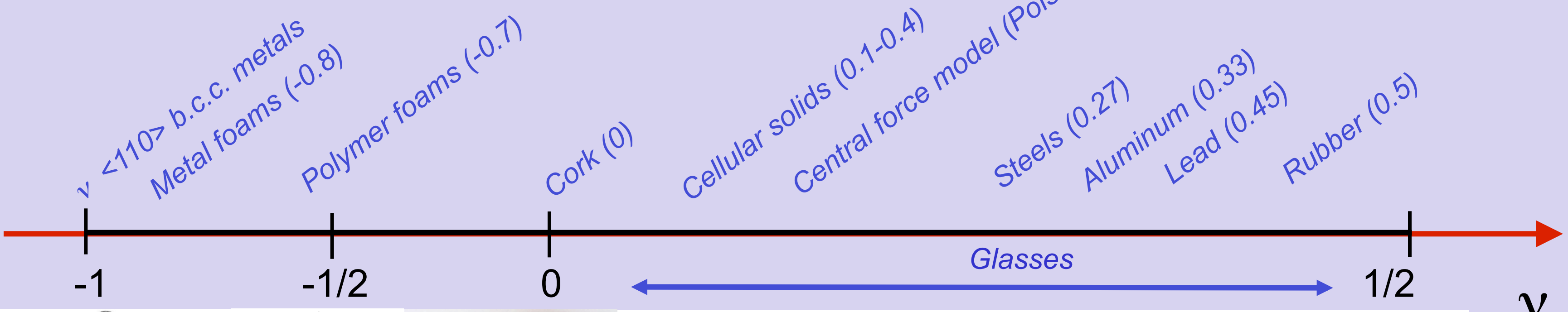


Siméon Denis POISSON

(1781-1840)

$\Delta V/V = \text{Trace } \varepsilon = (1-2\nu)\sigma/E$

$\nu = -\varepsilon_t/\varepsilon_l = -L/D \times \Delta D/\Delta L$



ν <110> b.c.c. metals

Metal foams (-0.8)

Polymer foams (-0.7)

Cork (0)

Cellular solids (0.1-0.4)

Central force model (Poisson) (0.25)

Steels (0.27)

Aluminum (0.33)

Lead (0.45)

Rubber (0.5)

-1

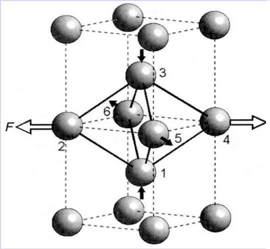
-1/2

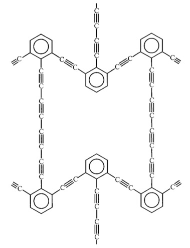
0

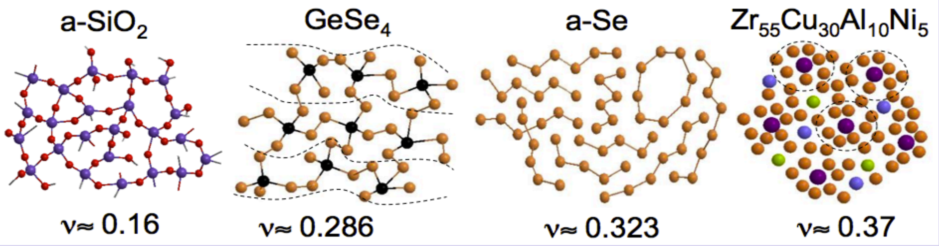
Glasses

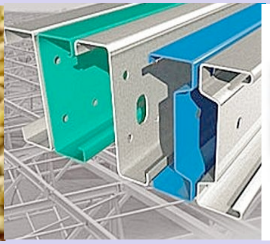
1/2

ν

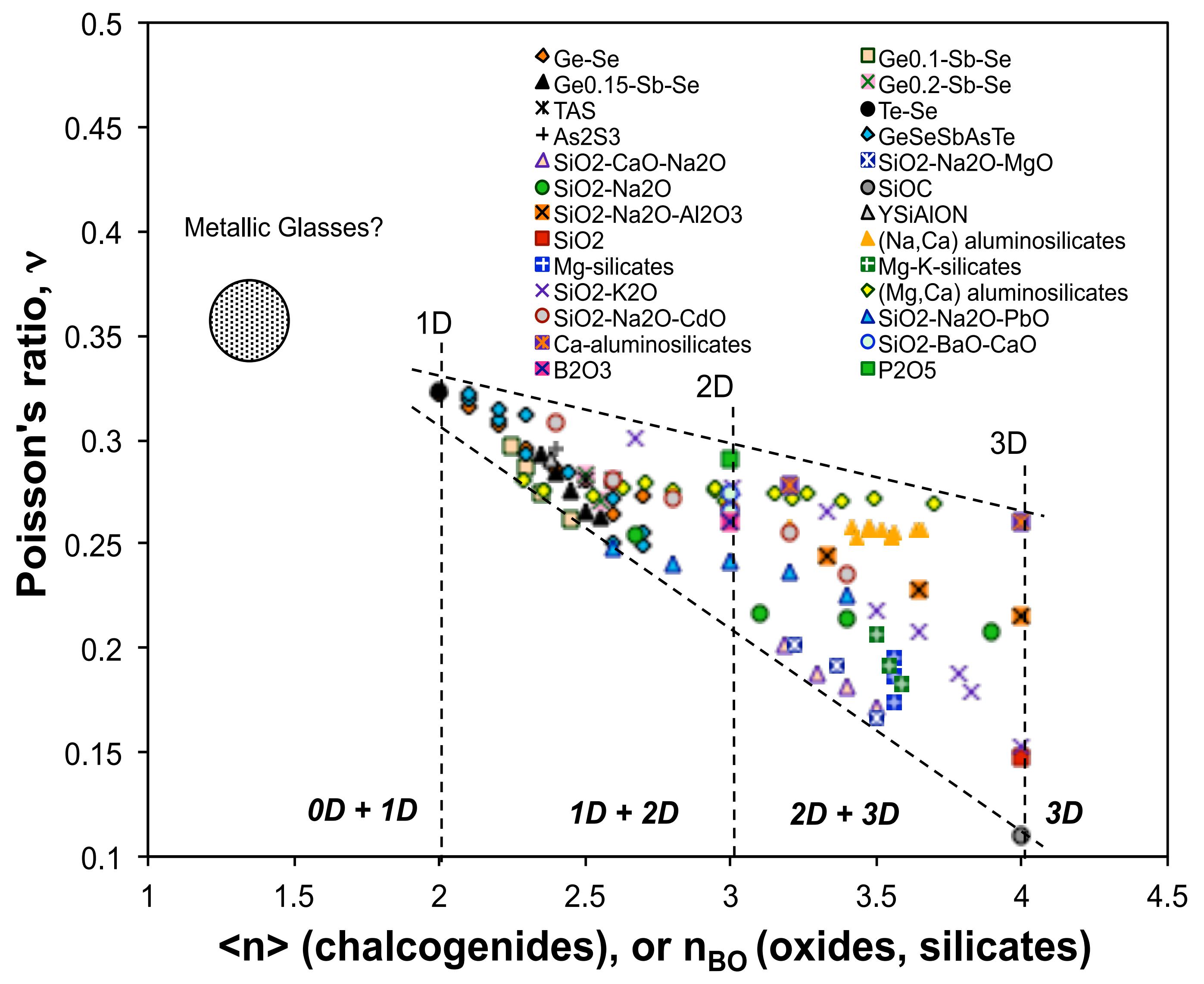








Poisson's ratio and dimensionality



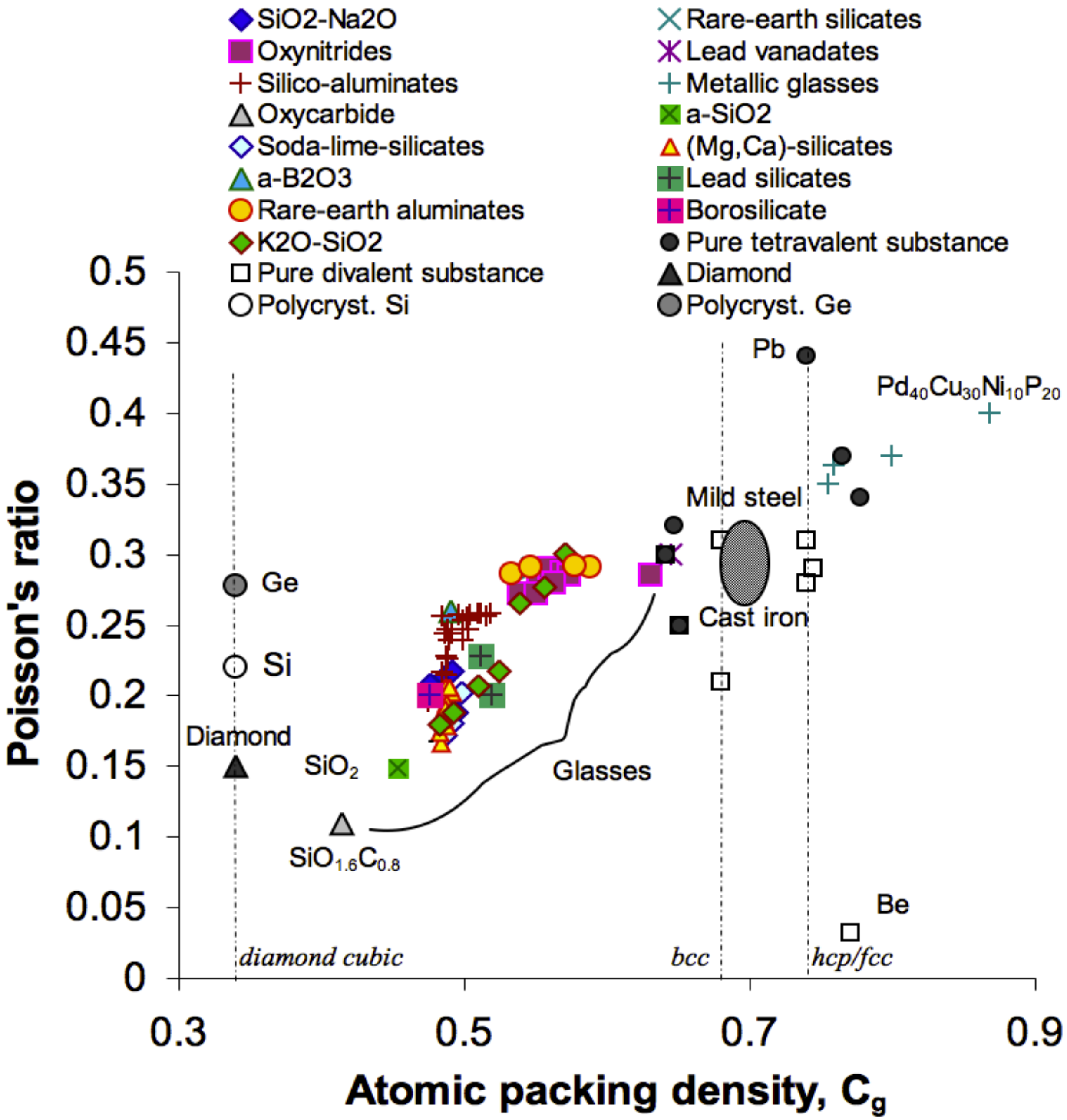
General tendencies:

$\nu_{cd}<\nu_{bcc}<\nu_{fcc,hcp}$

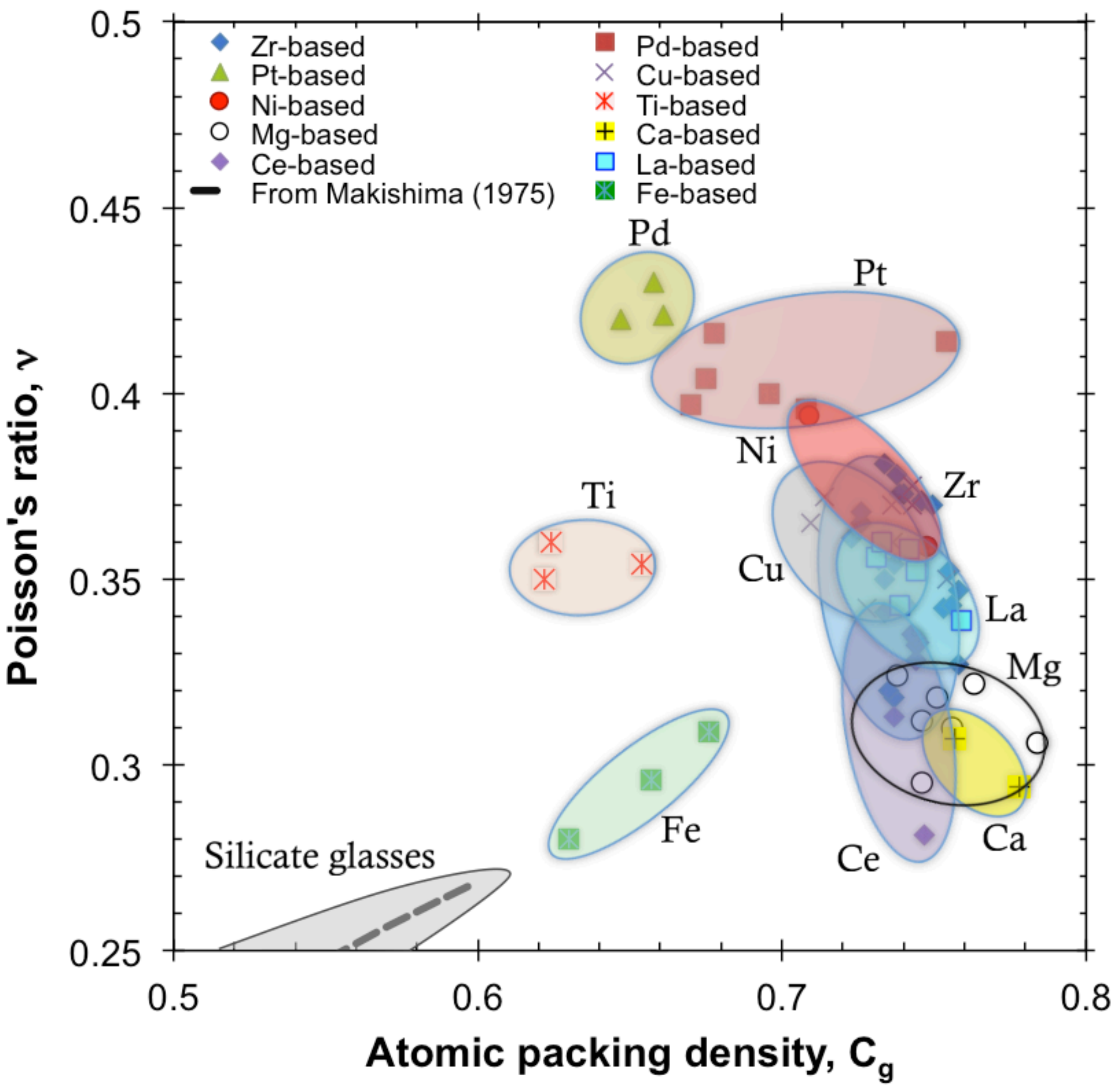
For a given crystalline structure and valency, Poisson’s ratio mostly increases with atomic number (Z) (Lead (ν_{Pb}=0.44) and thallium (ν_{Tl}=0.45) with high Z have remarkably high Poisson’s ratios)

High melting points favor low Poisson's ratio (beryllium, combining a small *Z* and a melting point (T_m=1560 K) much higher than those of the other elements in the same column, exhibits a remarkably small Poisson’s ratio of 0.032)

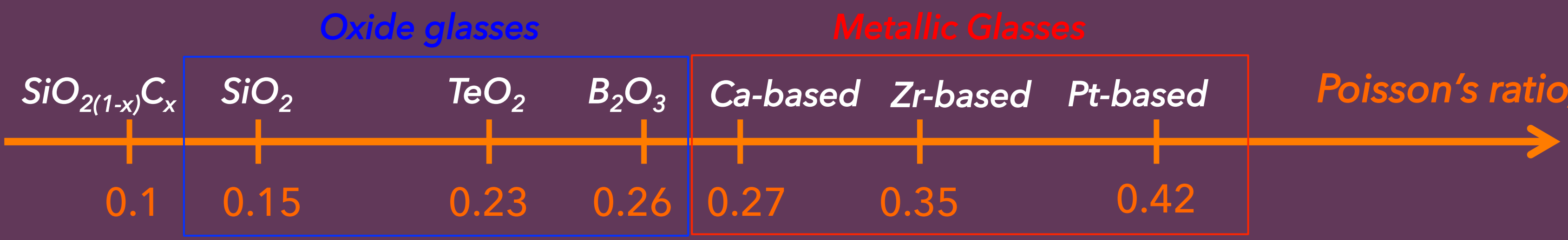
$$C_g = \rho\ \Sigma\ f_i V_i\ /(\Sigma\ f_i M_i)$$



Nat. Mat., 10, 823-837 (2011)



J. APP. PHYS. 118, 044901 (2015)



Oxide glasses

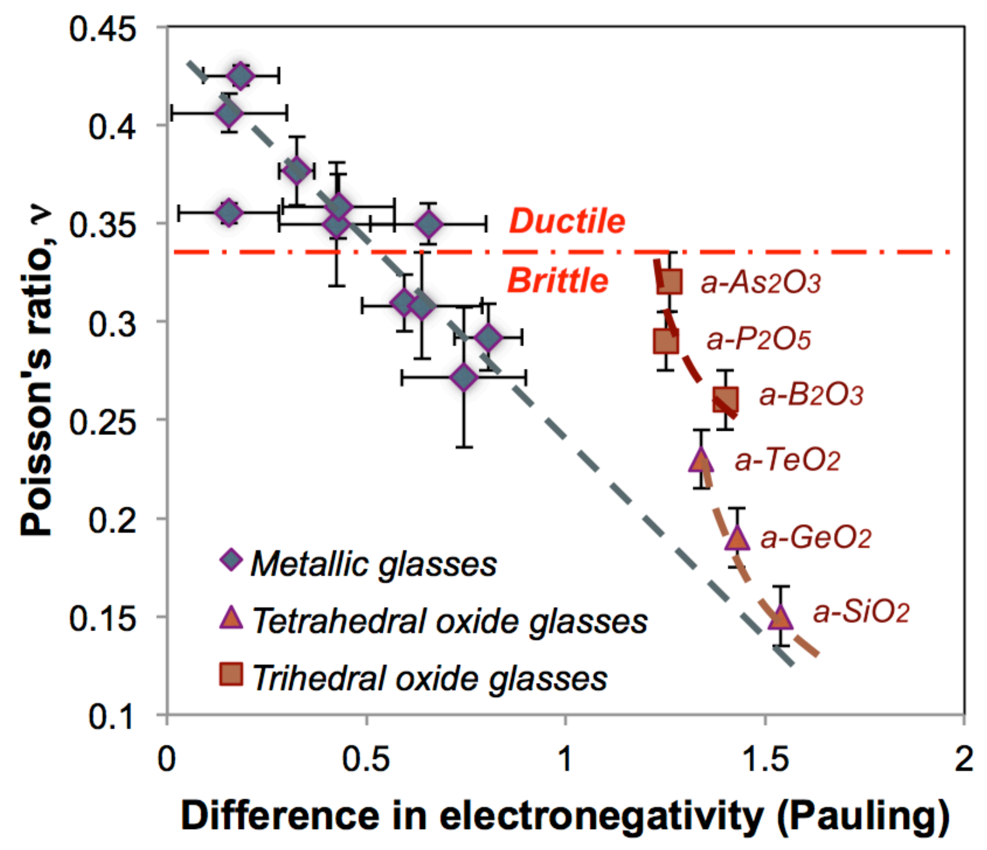
Metallic Glasses

Poisson's ratio, ν

$SiO_{2(1-x)}C_x$	SiO_2	TeO_2	B_2O_3	Ca-based	Zr-based	Pt-based
0.1	0.15	0.23	0.26	0.27	0.35	0.42

More directional bonding in the case of metal host elements such as Ce, Ca, or Mg due to localized f (for Ce) and sp (Ca, Mg) electrons

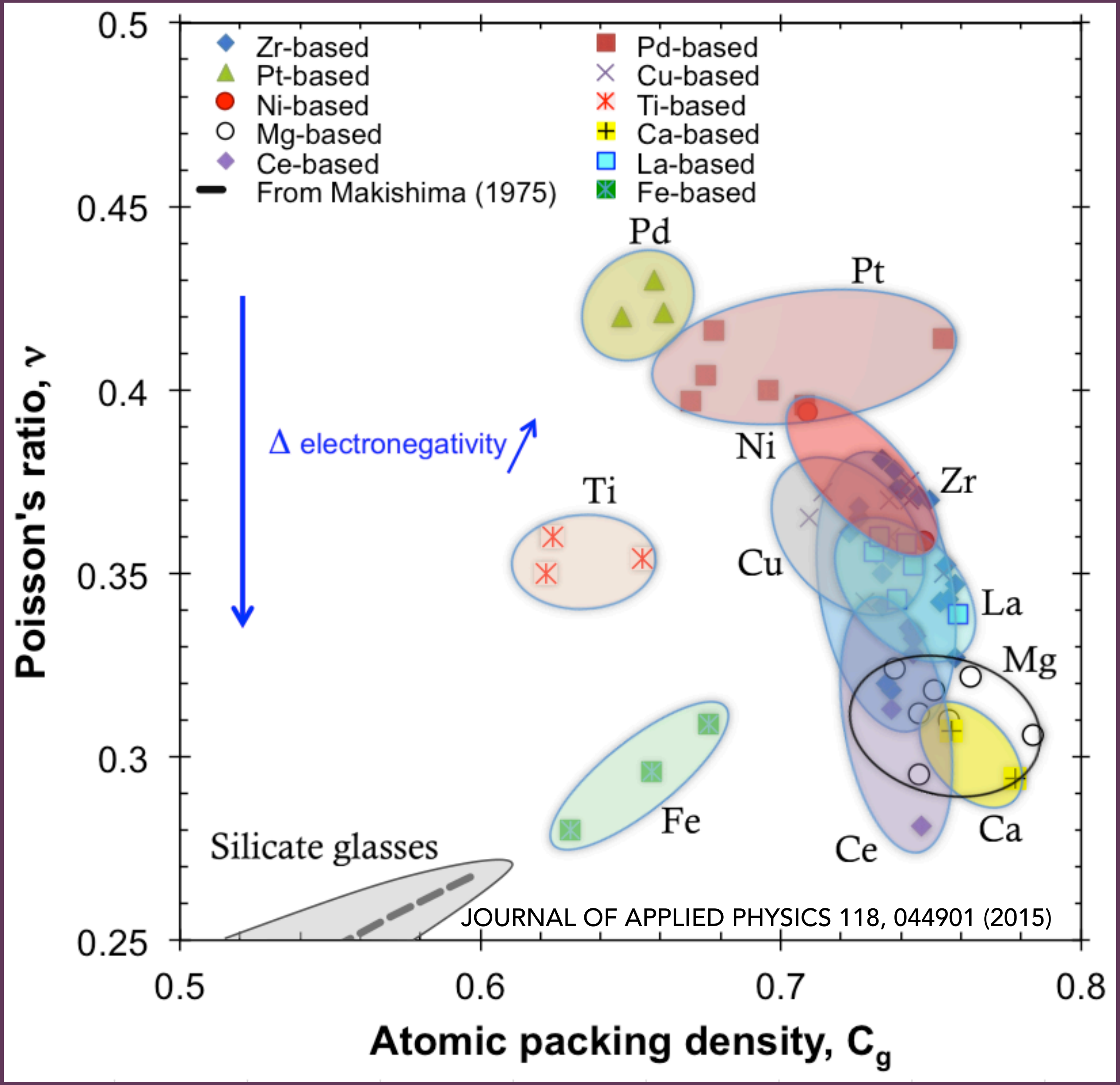
Δe^- is taken as the electronegativity mismatch between the host and the two major secondary solute elements



ν is correlated to Δe^-

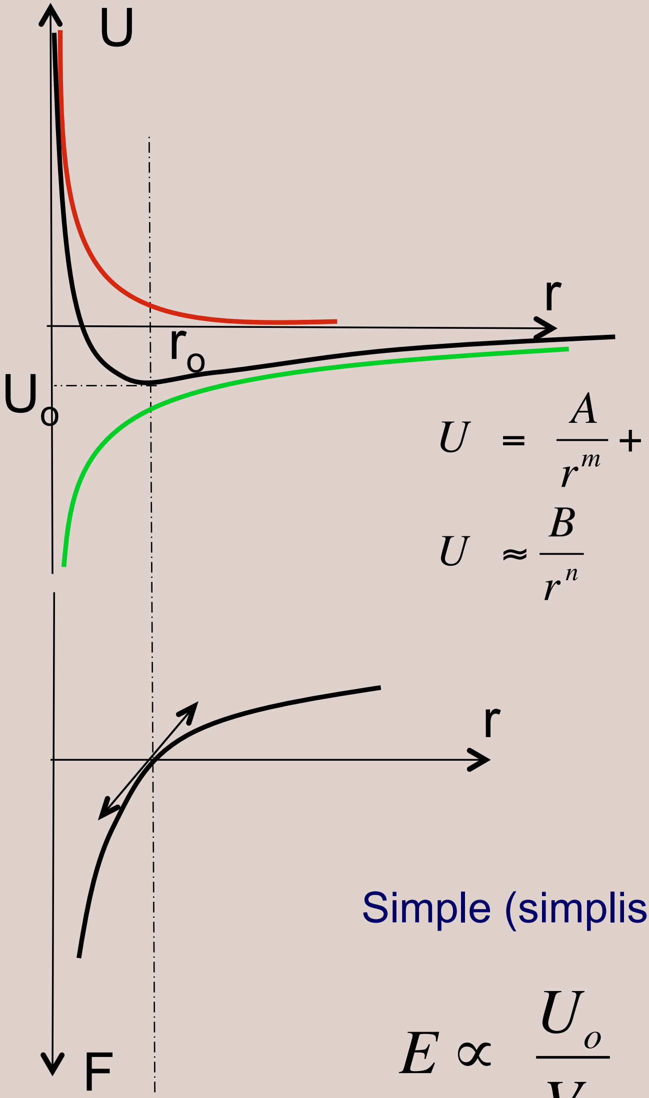
Ductility in MG
for $\nu > 0.32$ or
for $\Delta e^- < 0.5$

JAP 118, 044901 (2015)



JOURNAL OF APPLIED PHYSICS 118, 044901 (2015)

Elasticity and atomic packing density:



$$E = \left.\frac{d\sigma}{d\varepsilon}\right|_{r_o} \qquad \sigma = \frac{F}{r_o^2} \qquad F = -\left.\frac{dU}{dr}\right|_{r_o}$$

$$\left.\begin{aligned} U &= \frac{A}{r^m} + \frac{B}{r^n} \\ U &\approx \frac{B}{r^n} \end{aligned}\right\}$$

$$\left\{\begin{aligned} d\sigma &= -\frac{1}{r_o^2}\left.\frac{d^2U}{dr_o^2}\right|_{r_o} dr \\ d\varepsilon &= \frac{dr}{r_o} \end{aligned}\right.$$

$$\Rightarrow E = -\frac{1}{r_o}\left.\frac{d^2U}{dr_o^2}\right|_{r_o}$$

$$\left.\frac{d^2U}{dr^2}\right|_{r_o} \approx n(n+1)\frac{B}{r_o^{n+2}} \qquad \left.\frac{d^2U}{dr^2}\right|_{r_o} \approx n(n+1)\frac{U_o}{r_o^2}$$

Simple (simplistic) case of a Mie / Grüneisen potential (1st Grüneisen rule):

$$E \propto \frac{U_o}{V_o}$$

Bulk modulus:

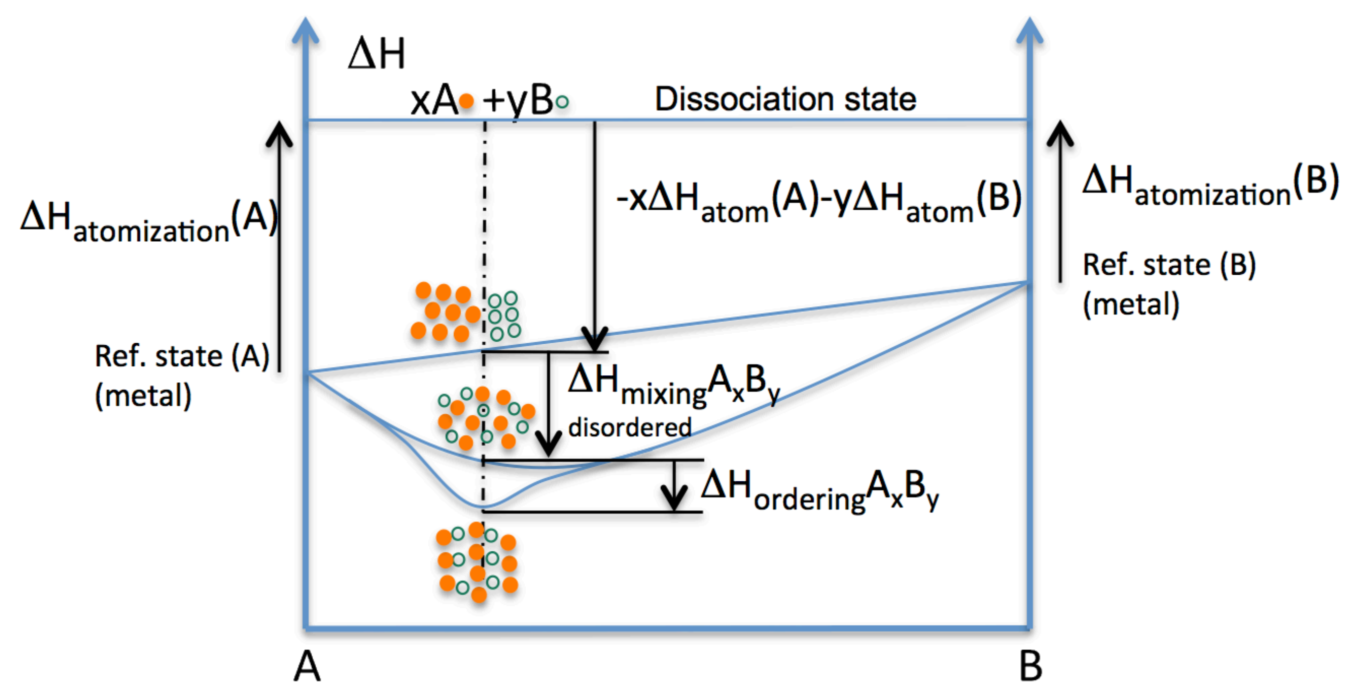
$$\boxed{K = V_o \left.\frac{\partial^2 U}{\partial V^2}\right|_{V_o} = \frac{mn}{9V_o} U_o}$$

$$U(r) = \frac{nU_o}{m-n}\left[\left(\frac{r_o}{r}\right)^m - \frac{m}{n}\left(\frac{r_o}{r}\right)^n\right]$$

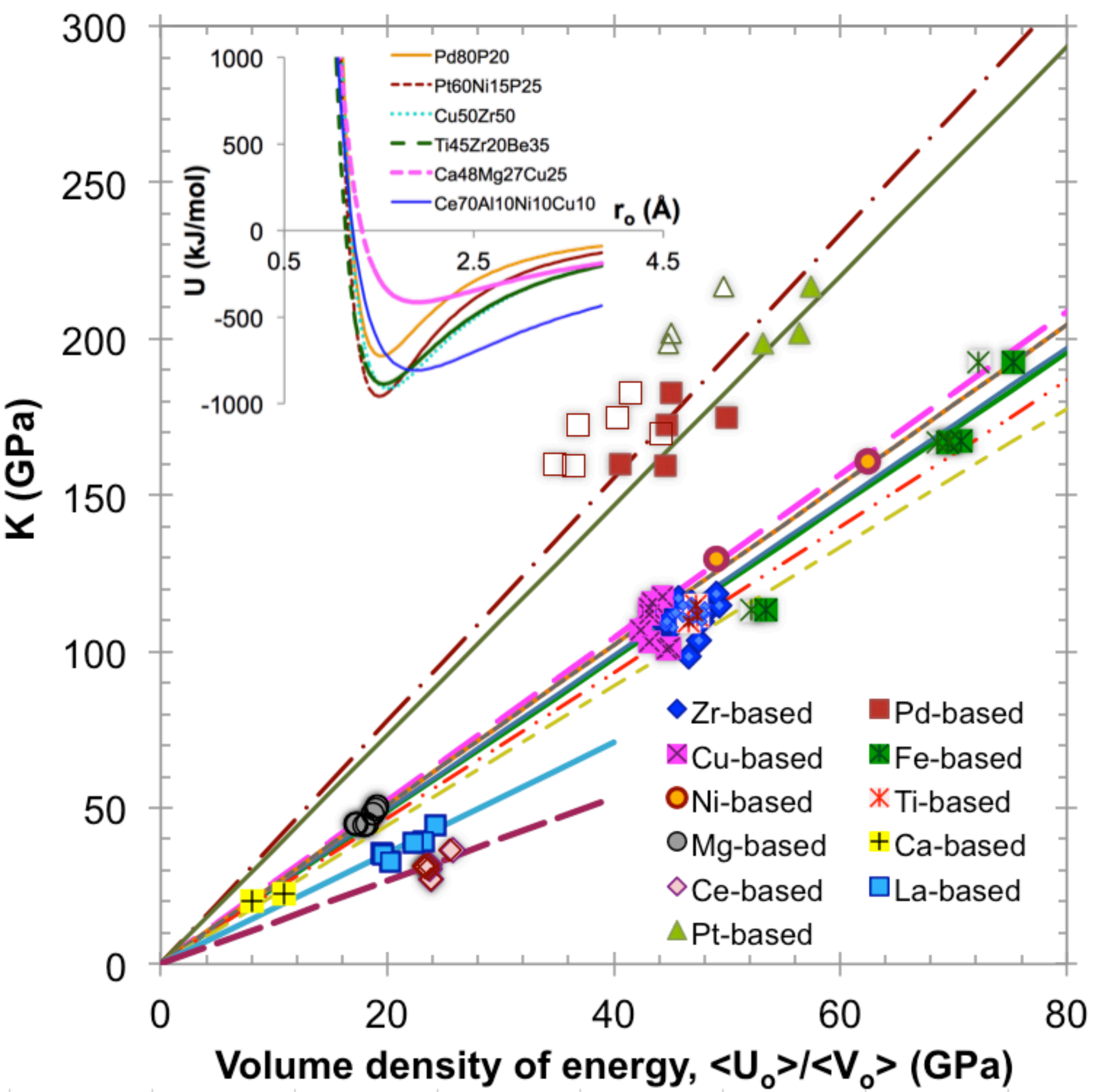
$$K = \frac{mnU_o}{9V_o}$$

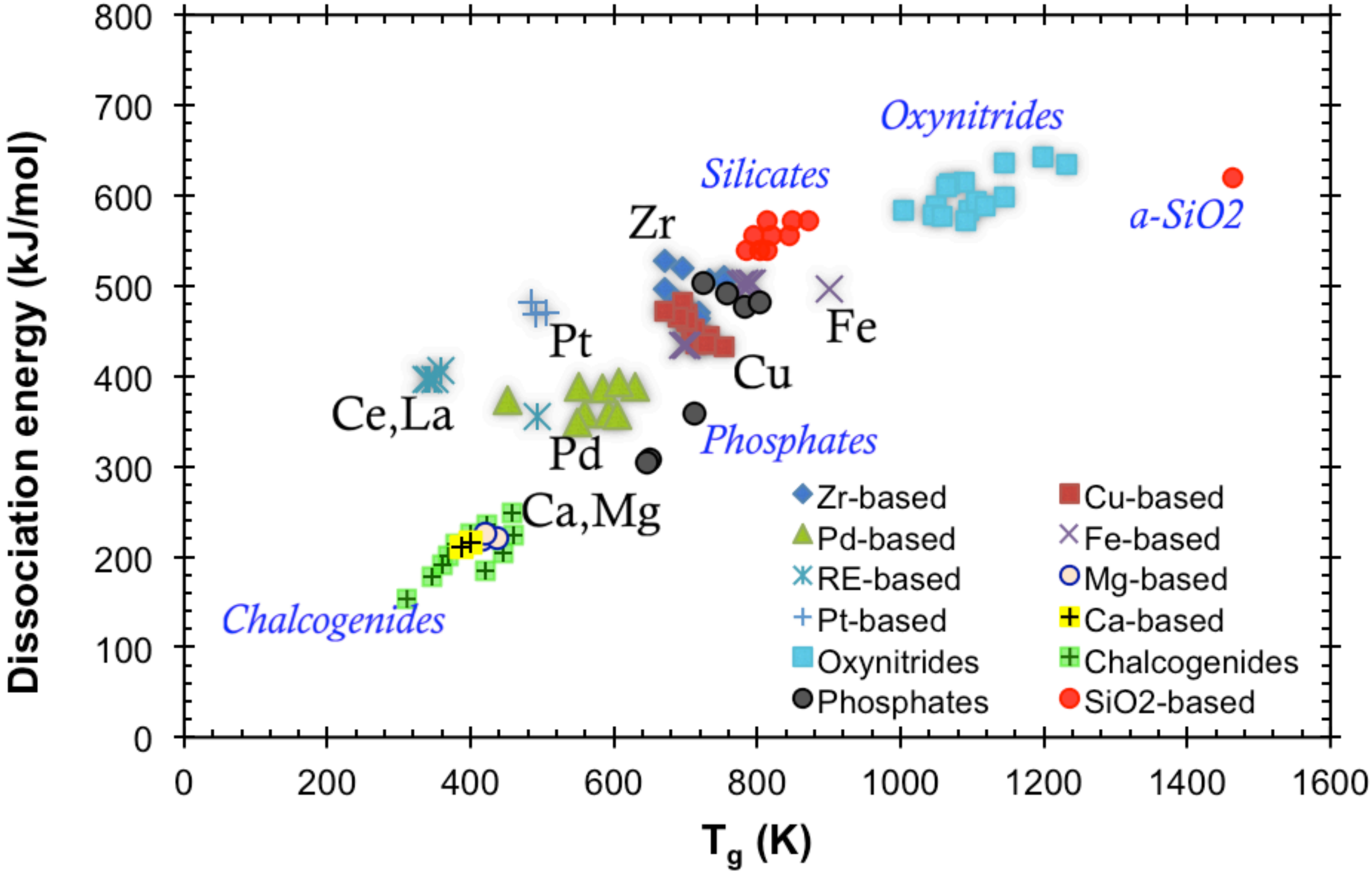
$$<V_o> = \sum\nolimits_i f_i\, M_I\,/\rho$$

$$<U_o> = x\Delta H_{at}(A,g) + y\Delta H_{at}(B,g) - \Delta H_{mixing}(A_xB_y)$$

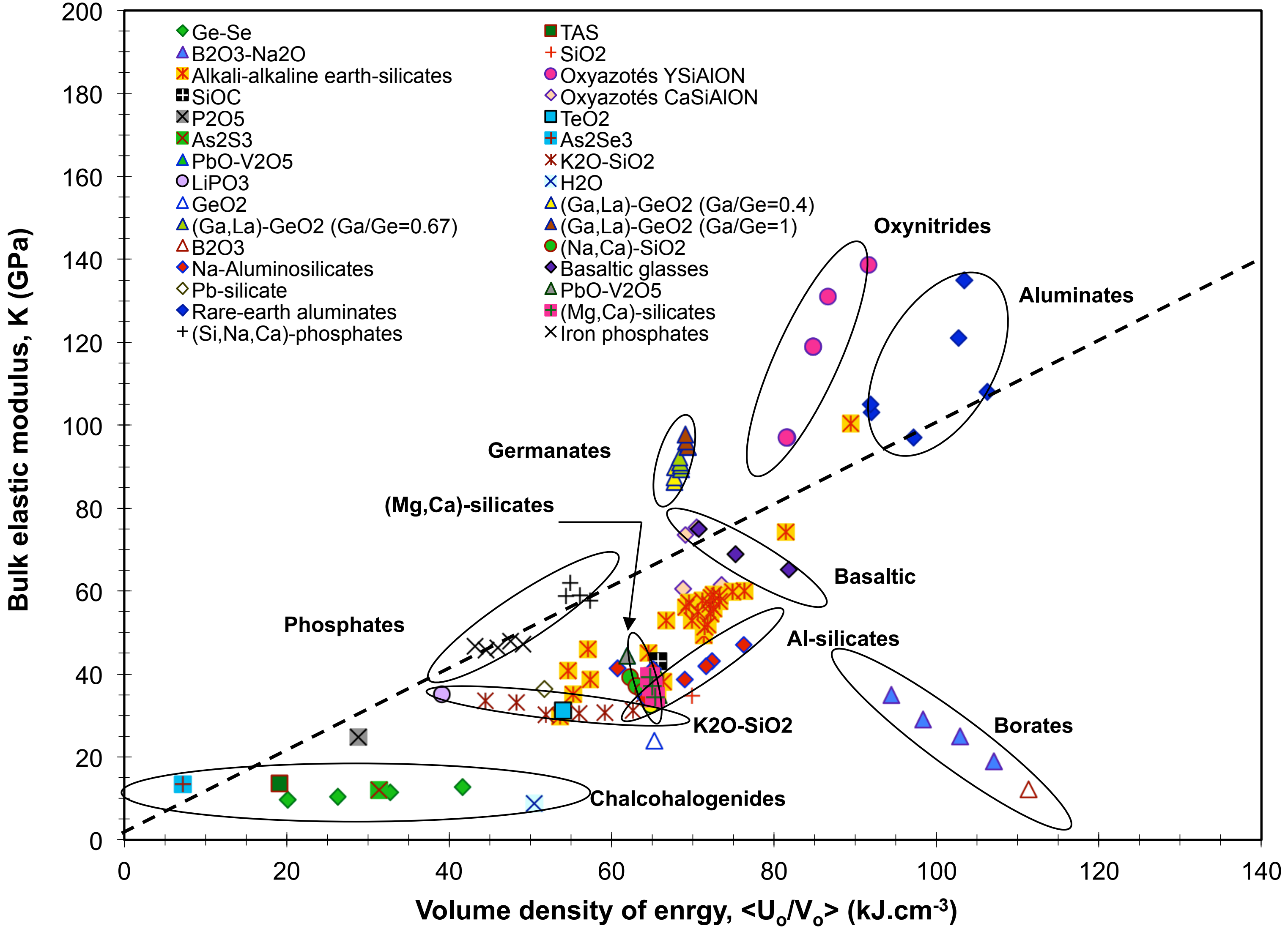


JAP118, 044901 (2015)


K (GPa)
300
250
200
150
100
50
0
0
20
40
60
80
Volume density of energy, $\langle U_o \rangle / \langle V_o \rangle$ (GPa)
U (kJ/mol)
1000
500
0
-500
-1000
0.5
2.5
4.5
r_o (Å)
Pd80P20
Pt60Ni15P25
Cu50Zr50
Ti45Zr20Be35
Ca48Mg27Cu25
Ce70Al10Ni10Cu10
Zr-based
Pd-based
Cu-based
Fe-based
Ni-based
Ti-based
Mg-based
Ca-based
Ce-based
La-based
Pt-based



JAP 118, 044901 (2015)

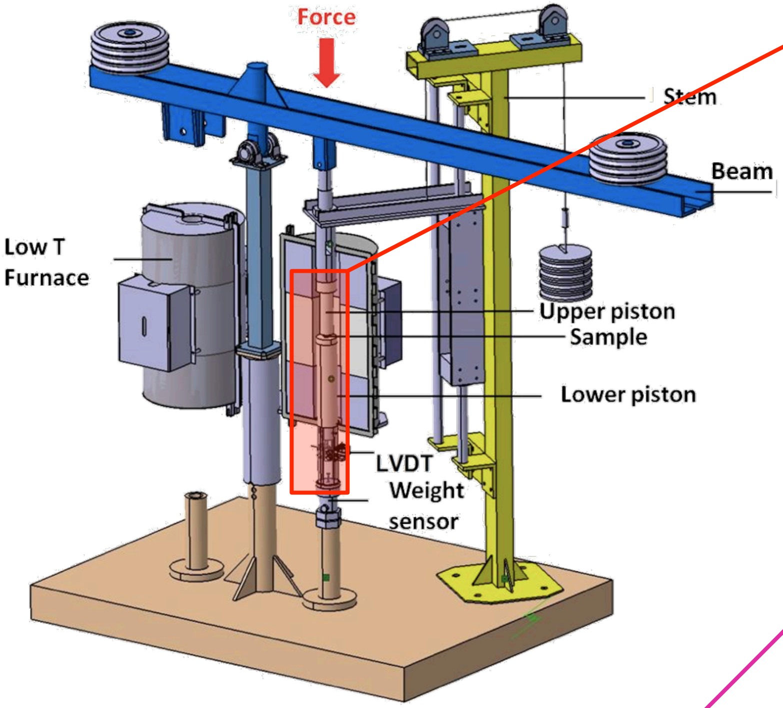

Ge-Se
B2O3-Na2O
Alkali-alkaline earth-silicates
SiOC
P2O5
As2S3
PbO-V2O5
LiPO3
GeO2
(Ga,La)-GeO2 (Ga/Ge=0.67)
B2O3
Na-Aluminosilicates
Pb-silicate
Rare-earth aluminates
(Si,Na,Ca)-phosphates
TAS
SiO2
Oxyazotés YSiAlON
Oxyazotés CaSiAlON
TeO2
As2Se3
K2O-SiO2
H2O
(Ga,La)-GeO2 (Ga/Ge=0.4)
(Ga,La)-GeO2 (Ga/Ge=1)
(Na,Ca)-SiO2
Basaltic glasses
PbO-V2O5
(Mg,Ca)-silicates
Iron phosphates
Oxynitrides
Aluminates
Germanates
(Mg,Ca)-silicates
Basaltic
Phosphates
Al-silicates
K2O-SiO2
Borates
Chalcohalogenides
Bulk elastic modulus, K (GPa)
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Volume density of enrgy, <U$_o$/V$_o$> (kJ.cm^{-3})

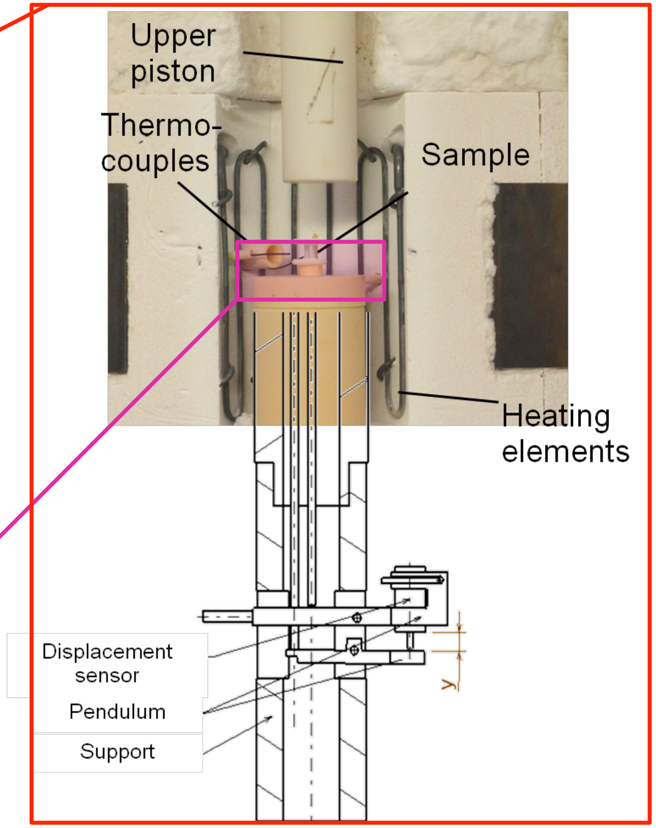
Shear viscosity

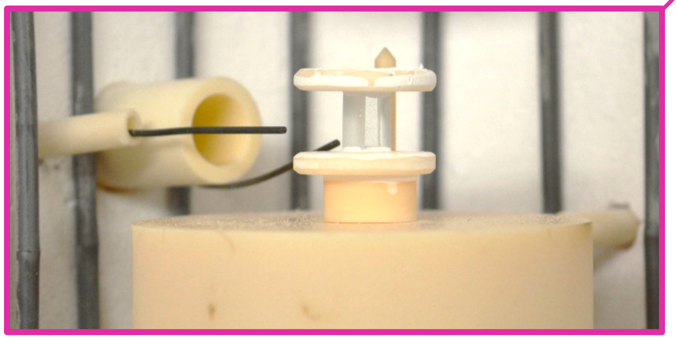
ii) Pourquoi les verres les plus rigides sont souvent très fragiles (au sens d'Angell)

iii) Est-ce que la viscosité linéaire existe vraiment?

Creep testing apparatus

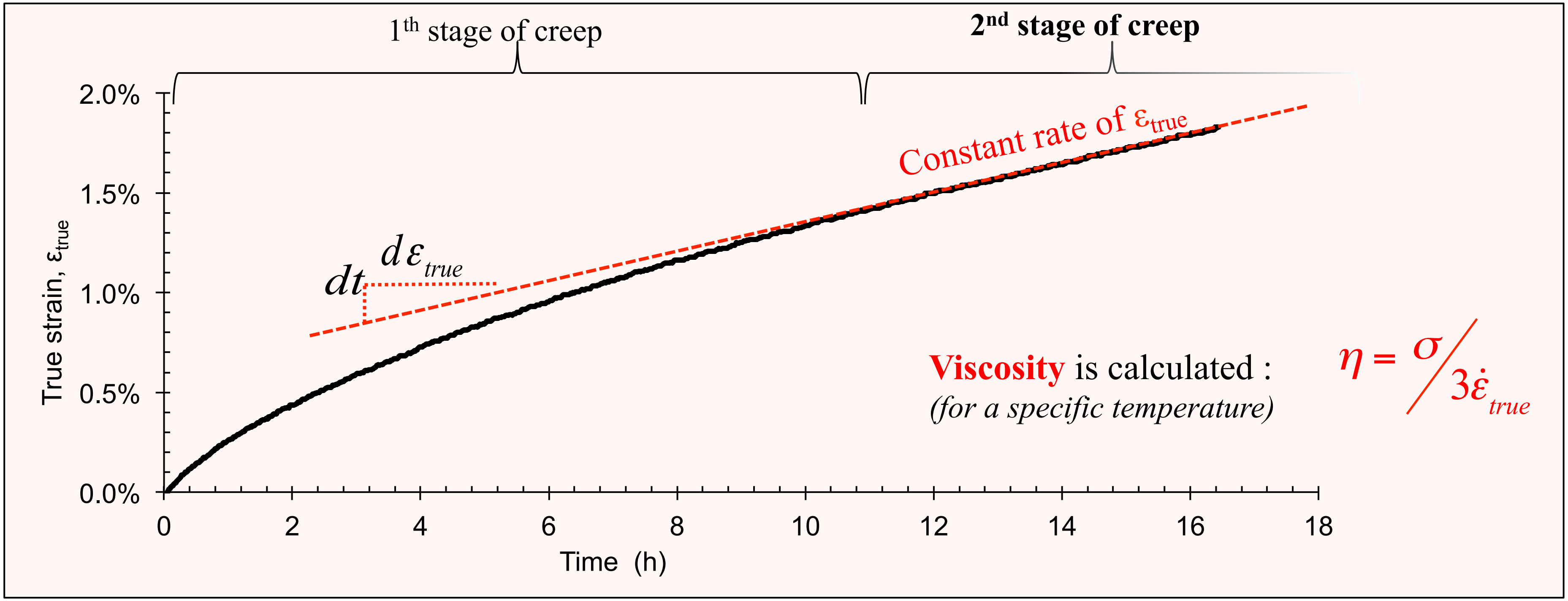






- **Constant load apparatus**
- 2 thermocouples for **thermal** measurements
- Differential measurement of the **displacement**
- **Load cell** located at the bottom of the column

Example : Window Glass / 10 MPa / 0.98 Tg



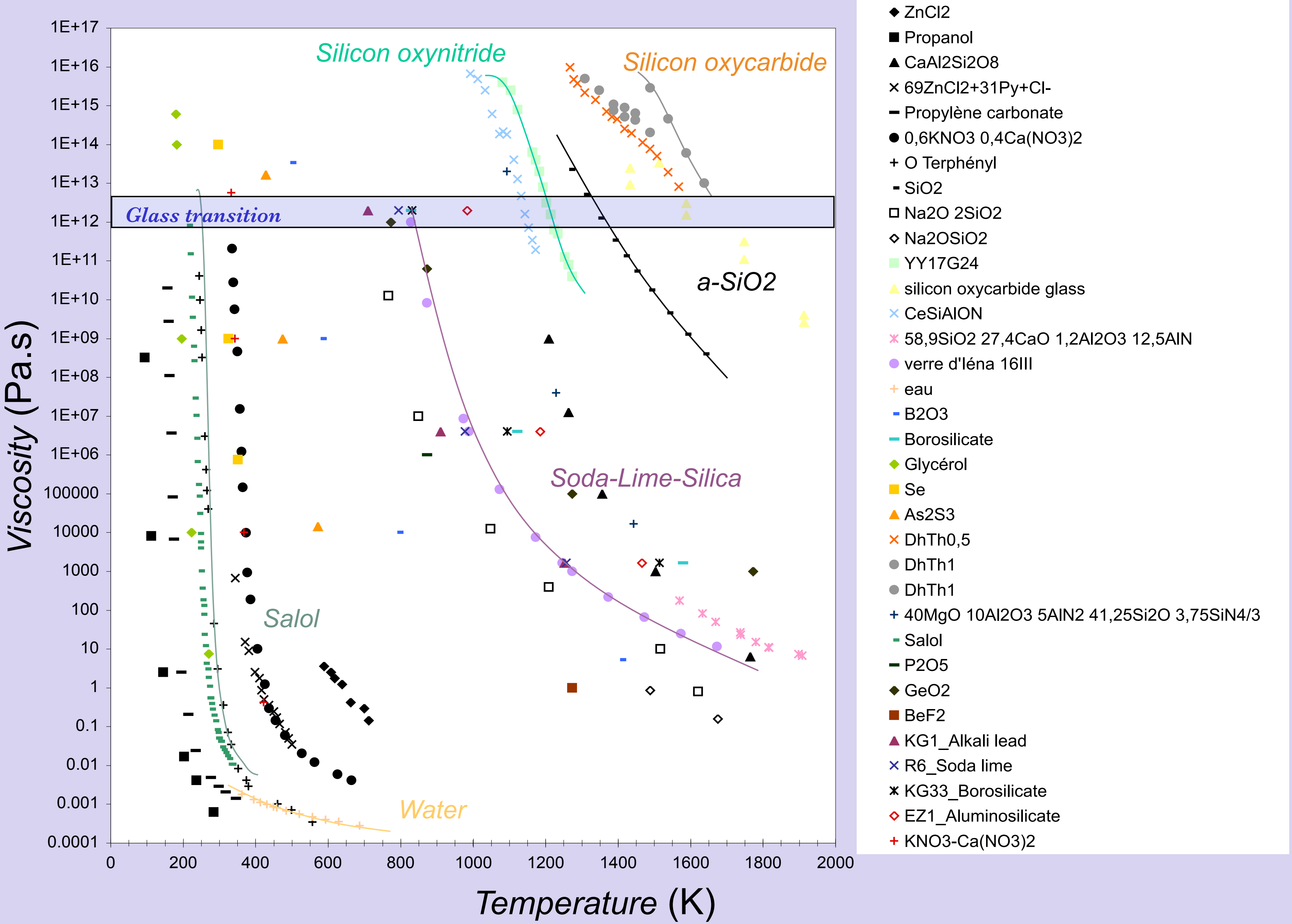
Viscosity is calculated :
(for a specific temperature)

$$\eta = \sigma / 3\dot{\varepsilon}_{true}$$

1 **viscosity** point = Constant temperature + waiting (≈ 5 mins to……….6 days !)

$\eta \approx 10^{8}$ Pa.s

$\eta \approx 10^{14}$ Pa.s


Silicon oxynitride
Silicon oxycarbide
Glass transition
a-SiO2
Soda-Lime-Silica
Salol
Water
Viscosity (Pa.s)
Temperature (K)
1E+17
1E+16
1E+15
1E+14
1E+13
1E+12
1E+11
1E+10
1E+09
1E+08
1E+07
1E+06
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
ZnCl2
Propanol
CaAl2Si2O8
69ZnCl2+31Py+Cl-
Propylène carbonate
0,6KNO3 0,4Ca(NO3)2
O Terphényl
SiO2
Na2O 2SiO2
Na2OSiO2
YY17G24
silicon oxycarbide glass
CeSiAlON
58,9SiO2 27,4CaO 1,2Al2O3 12,5AlN
verre d'Iéna 16III
eau
B2O3
Borosilicate
Glycérol
Se
As2S3
DhTh0,5
DhTh1
DhTh1
40MgO 10Al2O3 5AlN2 41,25Si2O 3,75SiN4/3
Salol
P2O5
GeO2
BeF2
KG1_Alkali lead
R6_Soda lime
KG33_Borosilicate
EZ1_Aluminosilicate
KNO3-Ca(NO3)2

Boltzmann-Arrhenius approach of thermally activated processes:

$$\tau = \tau_o \exp[\Delta G_a /(RT)]$$

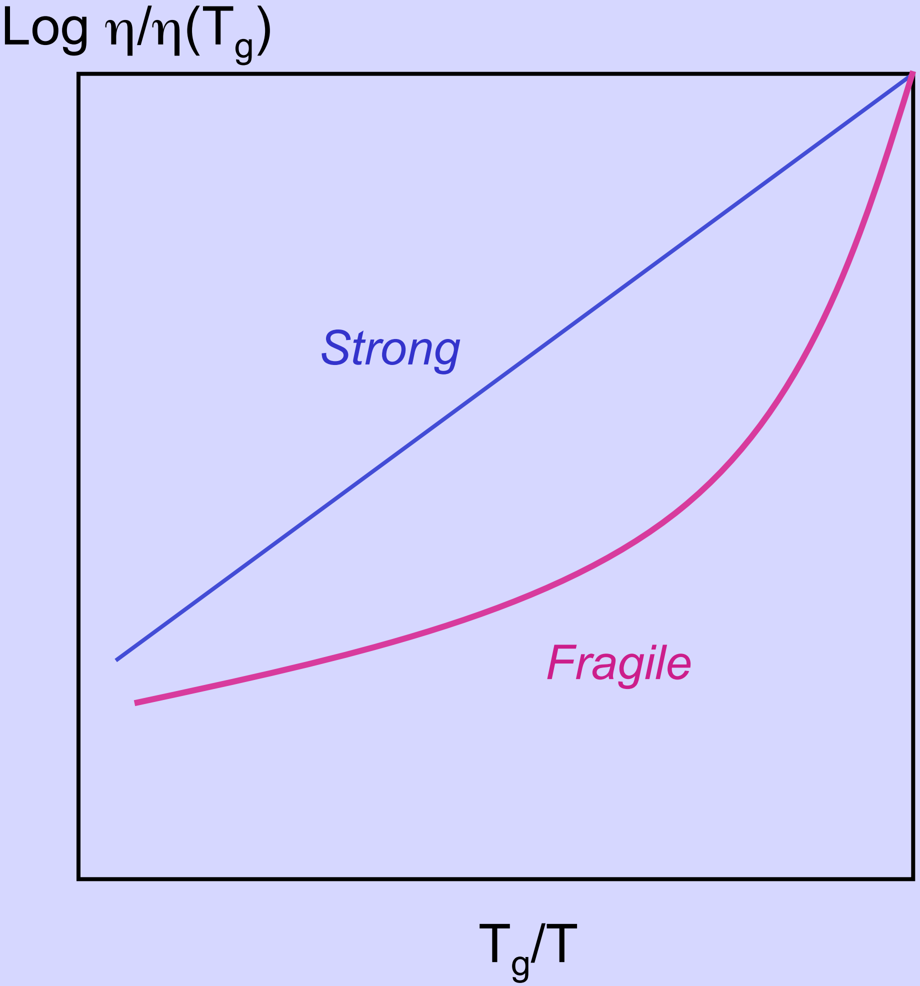
τ: the characteristic relaxation time
τ_o: a constant
T: temperature
R: perfect gas constant
ΔG_a: free activation enthalpy of the flow process

Assuming a simple Maxwell relaxation model

$\eta = \mu \tau_o \exp[\Delta G_a /(RT)]$,

where μ is the shear elastic modulus.

$$\eta = \eta_o \exp[\Delta G_a /(RT)]$$



Observations: the heat for flow is temperature dependent, especially in the case of short glasses ⇨ *VFT, WLF, AM, MYEGA… numerous empirical expressions* *τροπη,τροπη…*

This is where entropy comes into play…

ACTIVATION ENTROPY OF THE VISCOUS FLOW PROCESS

$$\eta = \eta_o \exp[\Delta G_a /(RT)]$$

$$R \left.\frac{\partial \ln \eta}{\partial \frac{1}{T}}\right|_{\tau,\,stru} = \Delta G_a + \frac{1}{T} \left.\frac{\partial \Delta G_a}{\partial \frac{1}{T}}\right|_{\tau,\,stru}$$

$$-\left.\frac{\partial \Delta G_a}{\partial T}\right|_{\tau,\,stru} = \Delta S_a$$

$$R \left.\frac{\partial \ln \eta}{\partial \frac{1}{T}}\right|_{\tau,\,stru} = \Delta G_a + T\Delta S_a = \Delta H_a$$

$$\left.\frac{\partial \Delta G_b}{\partial T}\right|_{\tau,\,stru} = \frac{\Delta G_b}{\mu} \left.\frac{\partial \mu}{\partial T}\right|_{\tau,\,stru}$$

$$\Delta S_a = -\frac{\chi}{T}(\Delta G_a + \tau V_a) + \tau \frac{\partial V_a}{\partial T}$$

ΔS_a^{μ} ΔS_a^{τ}

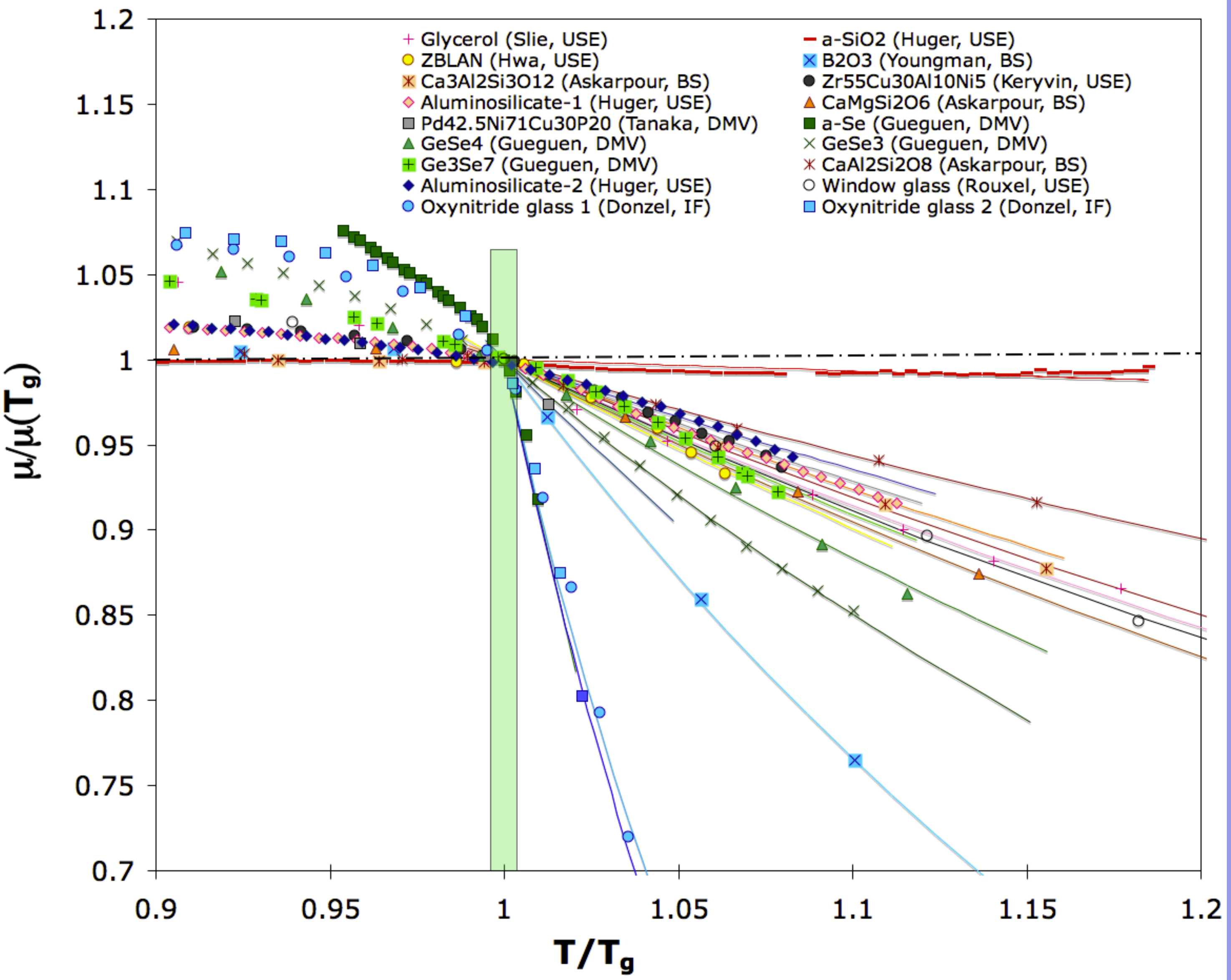
$$\chi = \frac{T}{\mu} \frac{\partial \mu}{\partial T}$$

$$\Delta H_a = R \left.\frac{\partial \ln \eta}{\partial \frac{1}{T}}\right|_{\tau,\,stru}$$

$$\Delta S_a = -\frac{\chi}{(1-\chi)T} \Delta H_a$$

$$\Delta G_a = \frac{1}{(1-\chi)} \Delta H_a$$

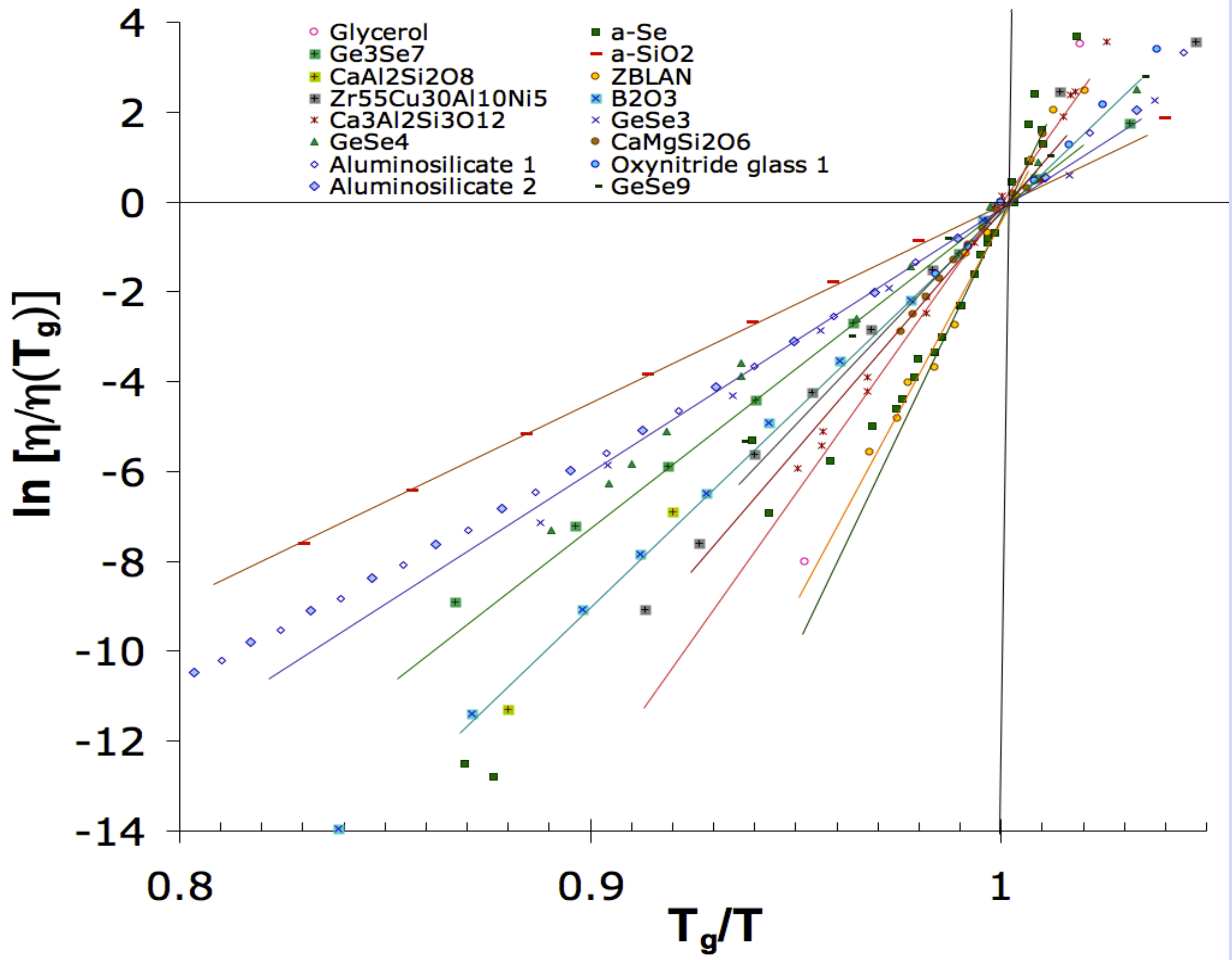
For τ=10 MPa and V_a=50 $cm^3.mol^{-1}$, τV_a=500 $J.mol^{-1}$, to be compared with the order of activation energies, 100 to 1000 $kJ.mol^{-1}$



For T>T$_g$, $\mu/\mu(T_g)=(T_g/T)^\alpha$

where α ranges between 0.07 (a-SiO$_2$) and 10 (a-Se)

J. Chem. Phys., 135, 184501 (2011)



$$\Delta H_a = R\frac{\partial \ln \eta}{\partial (1/T)}\bigg|_{\sigma, stru}$$

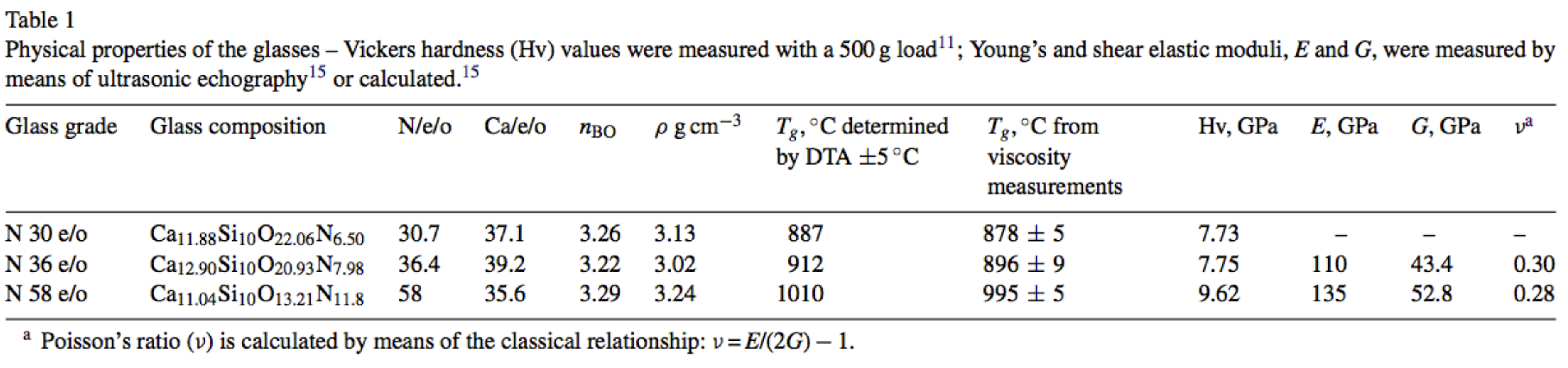


Table 1

Physical properties of the glasses – Vickers hardness (Hv) values were measured with a 500 g load[11]; Young's and shear elastic moduli, *E* and *G*, were measured by means of ultrasonic echography[15] or calculated.[15]

Glass grade	Glass composition	N/e/o	Ca/e/o	n_{BO}	ρ g cm^{-3}	T_g, °C determined by DTA ±5 °C	T_g, °C from viscosity measurements	Hv, GPa	*E*, GPa	*G*, GPa	ν^a
N 30 e/o	$Ca_{11.88}Si_{10}O_{22.06}N_{6.50}$	30.7	37.1	3.26	3.13	887	878 ± 5	7.73	–	–	–
N 36 e/o	$Ca_{12.90}Si_{10}O_{20.93}N_{7.98}$	36.4	39.2	3.22	3.02	912	896 ± 9	7.75	110	43.4	0.30
N 58 e/o	$Ca_{11.04}Si_{10}O_{13.21}N_{11.8}$	58	35.6	3.29	3.24	1010	995 ± 5	9.62	135	52.8	0.28

[a] Poisson's ratio (ν) is calculated by means of the classical relationship: $\nu = E/(2G) - 1$.

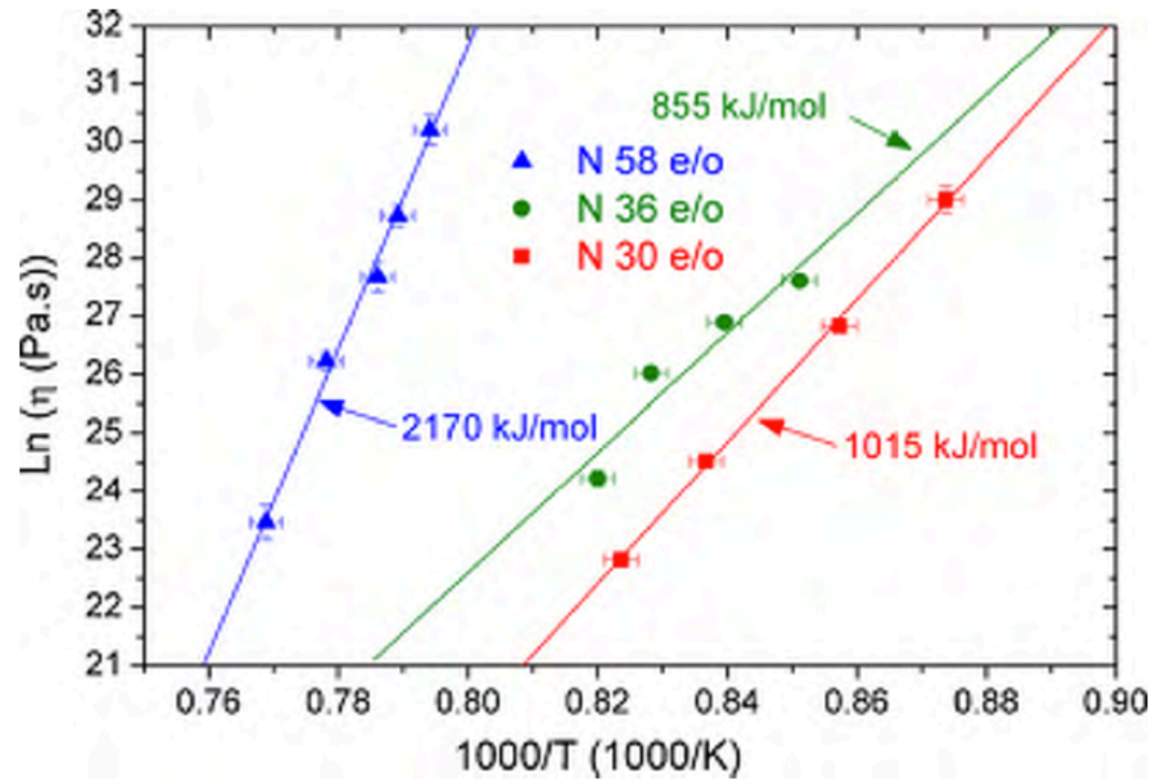
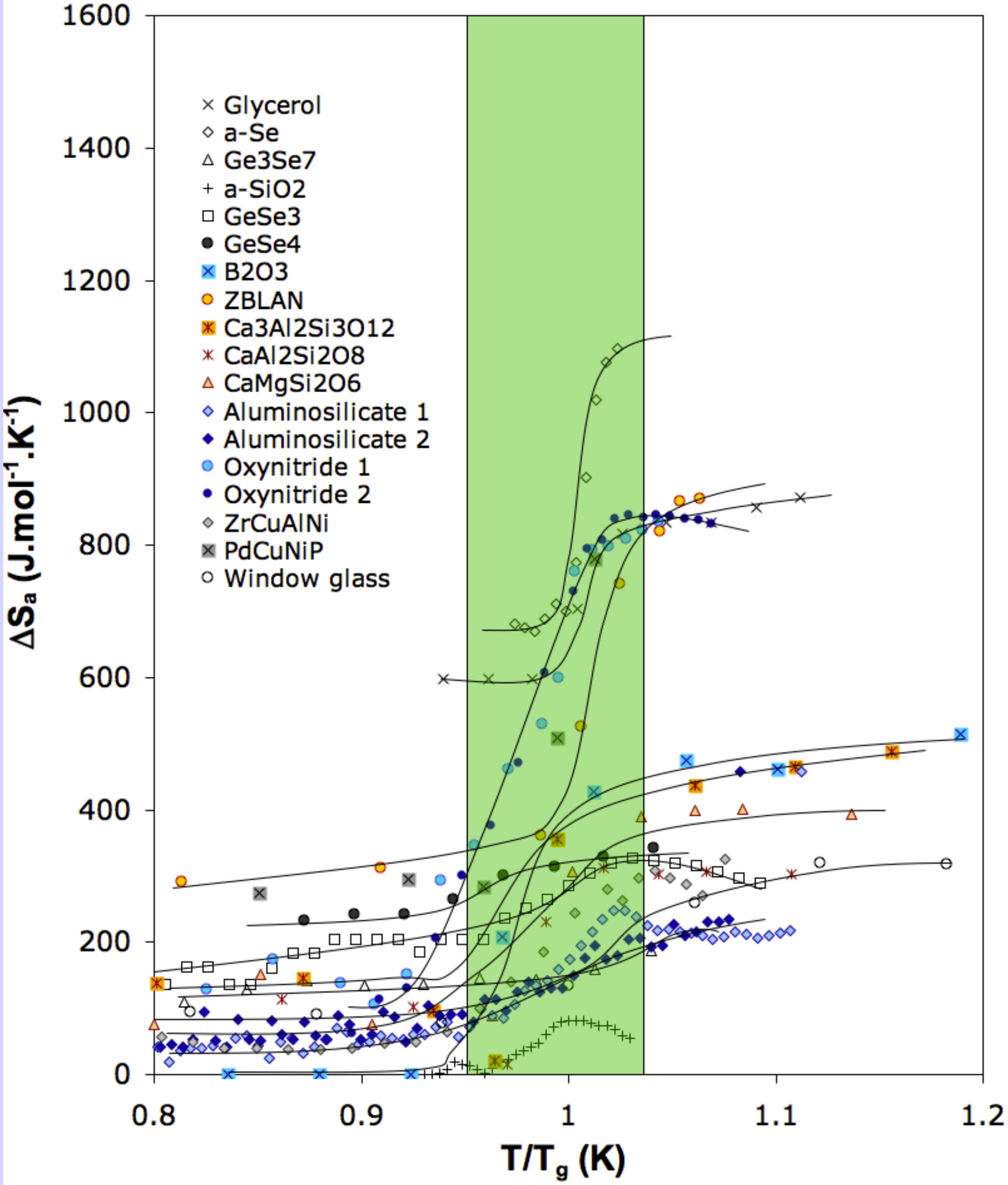
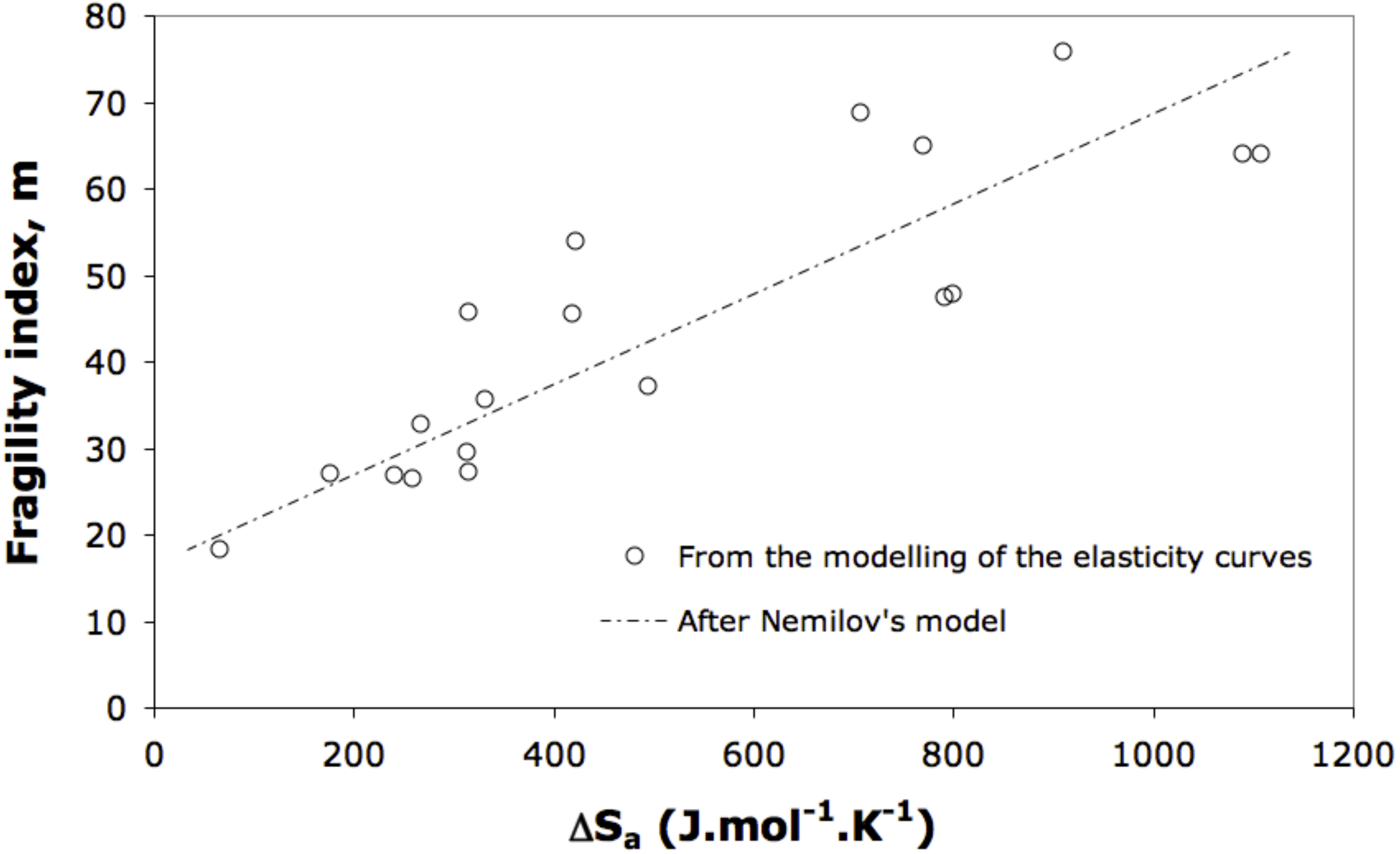


Fig. 2. Logarithm of the viscosity of Ca–Si–O–N glasses as a function of reciprocal temperature. The full lines correspond to the Arrhenius expression for viscosity.

Yes, we believe there is some confinement or some segregation of nitrogen in the network



× Glycerol
◇ a-Se
△ Ge3Se7
+ a-SiO2
□ GeSe3
● GeSe4
B2O3
ZBLAN
Ca3Al2Si3O12
CaAl2Si2O8
CaMgSi2O6
Aluminosilicate 1
Aluminosilicate 2
Oxynitride 1
Oxynitride 2
ZrCuAlNi
PdCuNiP
○ Window glass
ΔS_a (J.mol^{-1}.K^{-1})
1600
1400
1200
1000
800
600
400
200
0
0.8
0.9
1
1.1
1.2
T/T$_g$ (K)


Fragility index, m
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
ΔS_a (J.mol^{-1}.K^{-1})
○ From the modelling of the elasticity curves
-·-·- After Nemilov's model

$$\left\{\begin{array}{l} \left.\dfrac{\partial \Delta G_a}{\partial T}\right|_{\sigma,stru} = \dfrac{\Delta G_a}{\mu}\left.\dfrac{\partial \mu}{\partial T}\right|_{\sigma,stru} \\ \\ \mu/\mu(T_g)=(T_g/T)^{\alpha} \end{array}\right.$$

$$\Delta G_a = \Delta G_a(T_g)(T_g/T)^{\alpha}$$

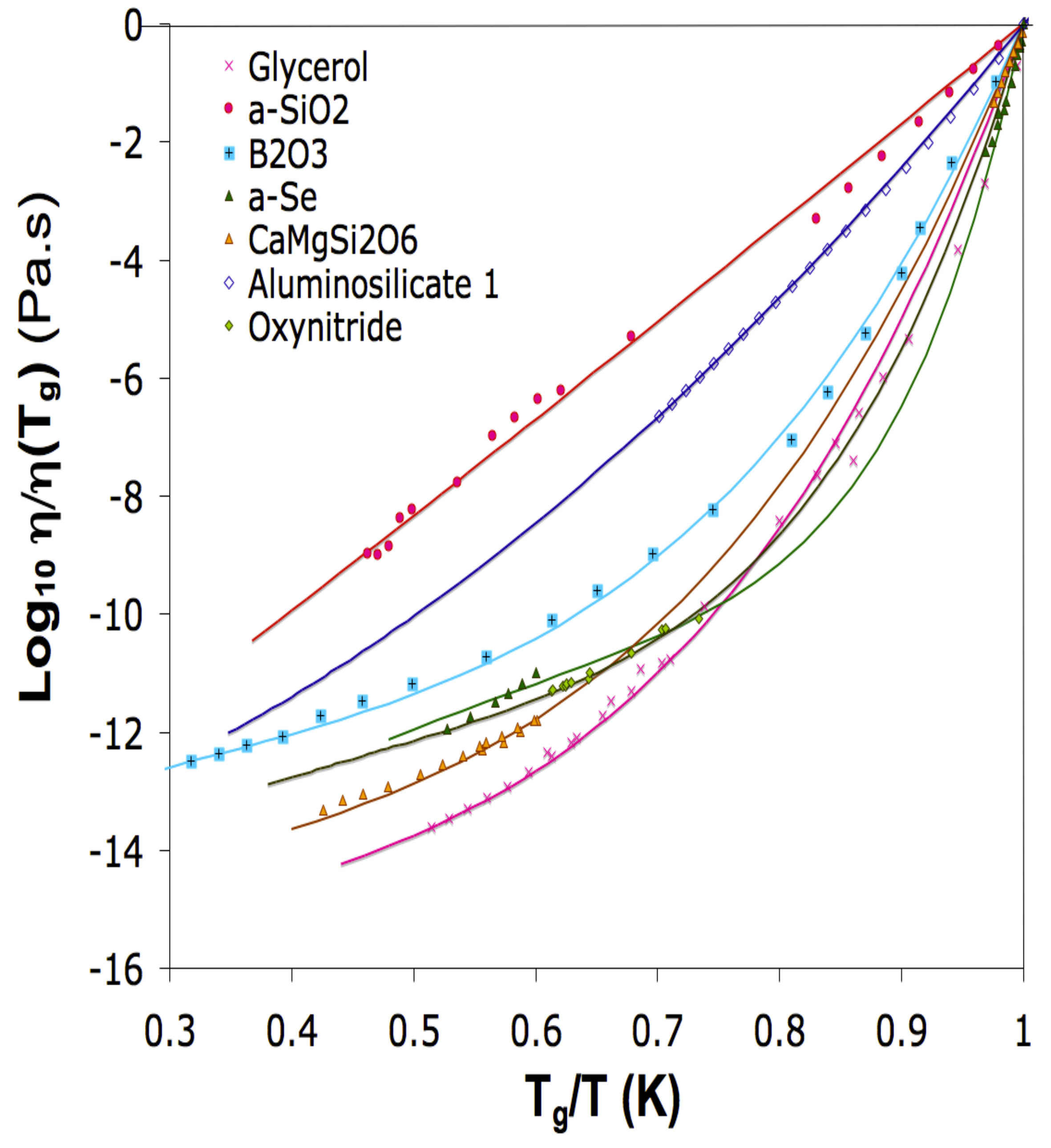
$$\eta = \eta_o \exp\left[\frac{\Delta G_a(T_g)(T_g/T)^{\alpha}}{RT}\right]$$

with
$$\left\{\begin{array}{l} \Delta G_a(T_g) = \dfrac{\Delta H_a(T_g)}{\left(1-\dfrac{T_g}{\mu(T_g)}\left.\dfrac{\partial \mu}{\partial T}\right|_{T_g}\right)} \\ \\ \eta_o = \mu(T)\eta(T_g)/\mu(T_g) \end{array}\right.$$

Equivalent to Avramov-Milchev equation

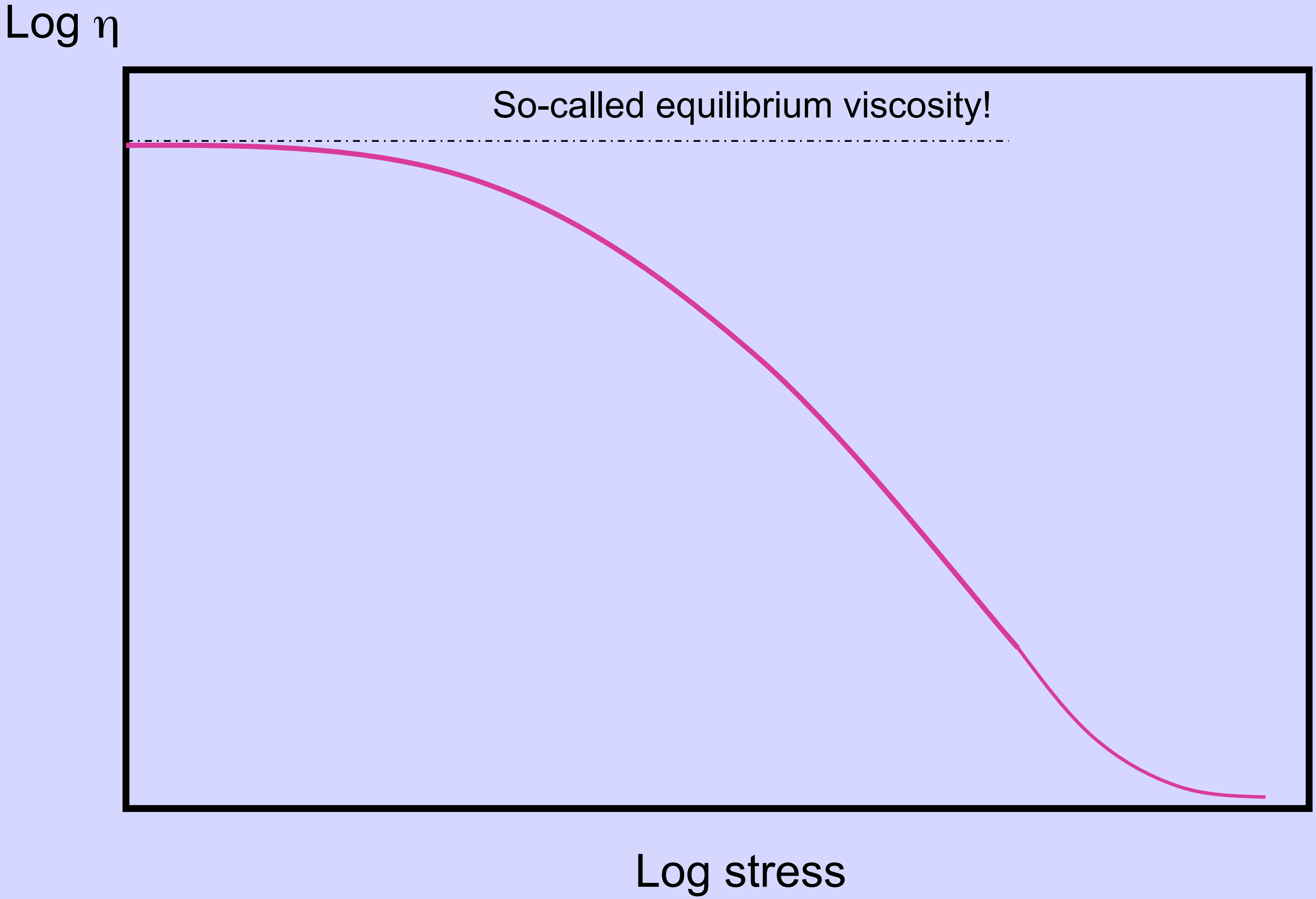
with: $\mu(T)=\mu_{\infty}\exp(E_{\mu}/T)$

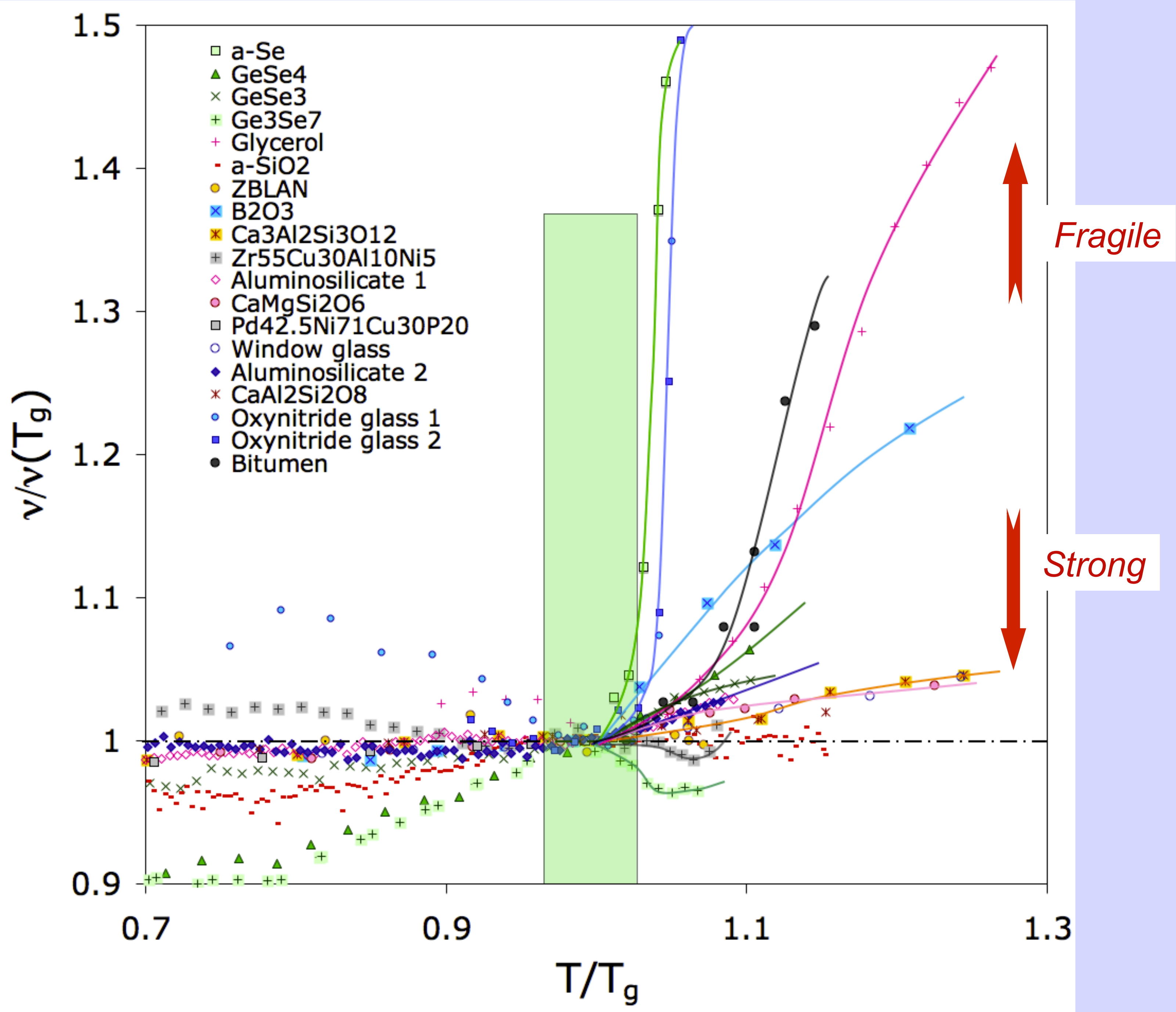
Equivalent to MYEGA equation



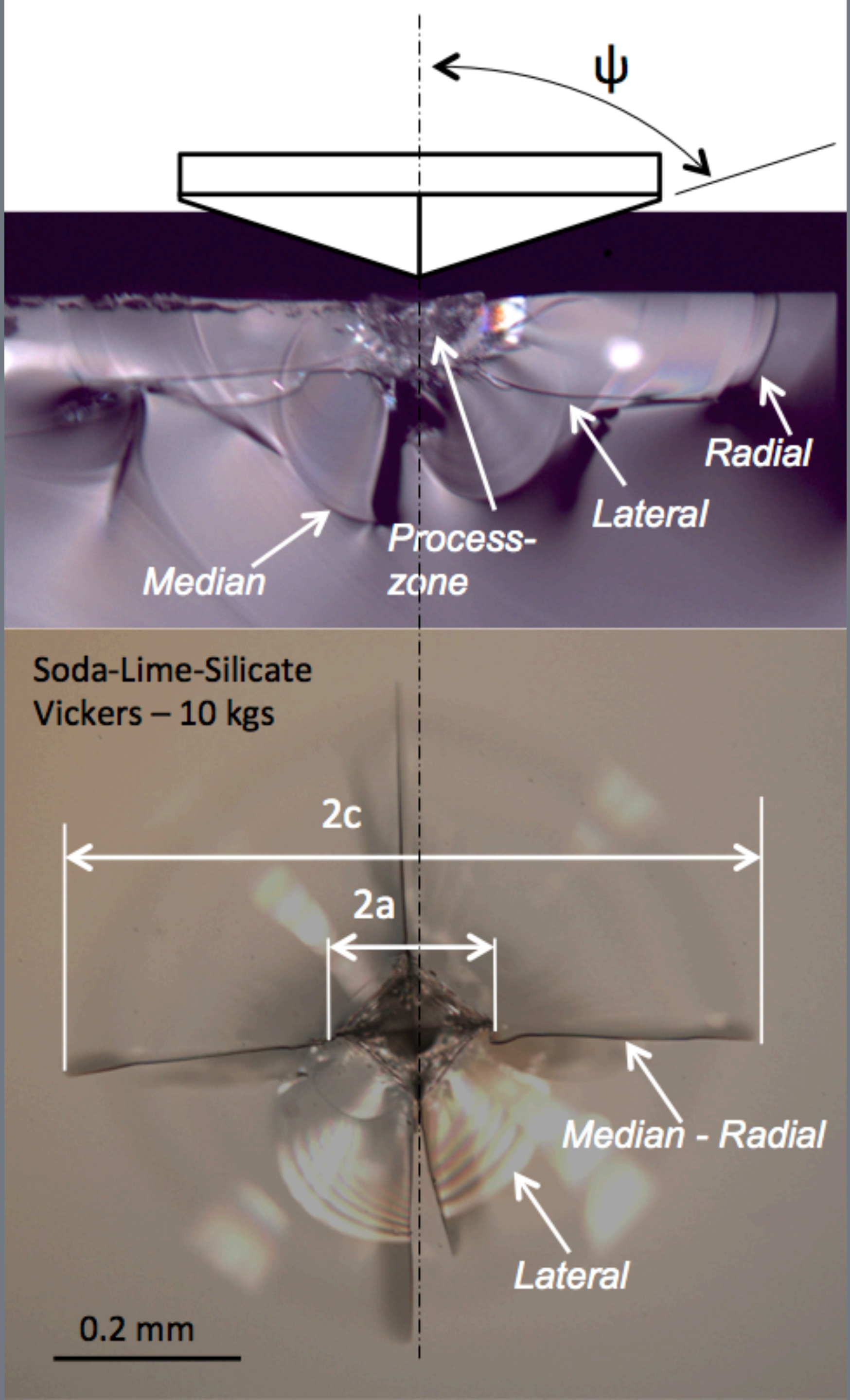
- iii) Est-ce que la viscosité linéaire existe vraiment?

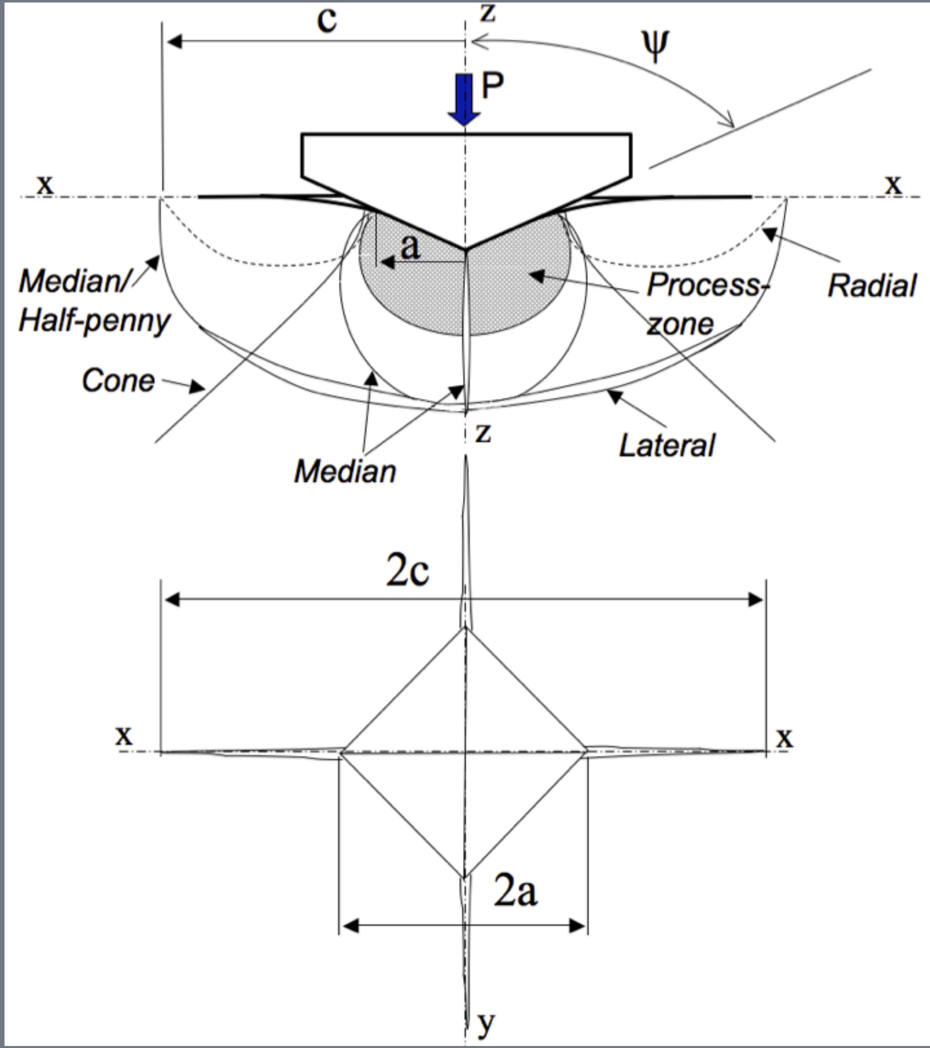
Stress or strain-rate dependence



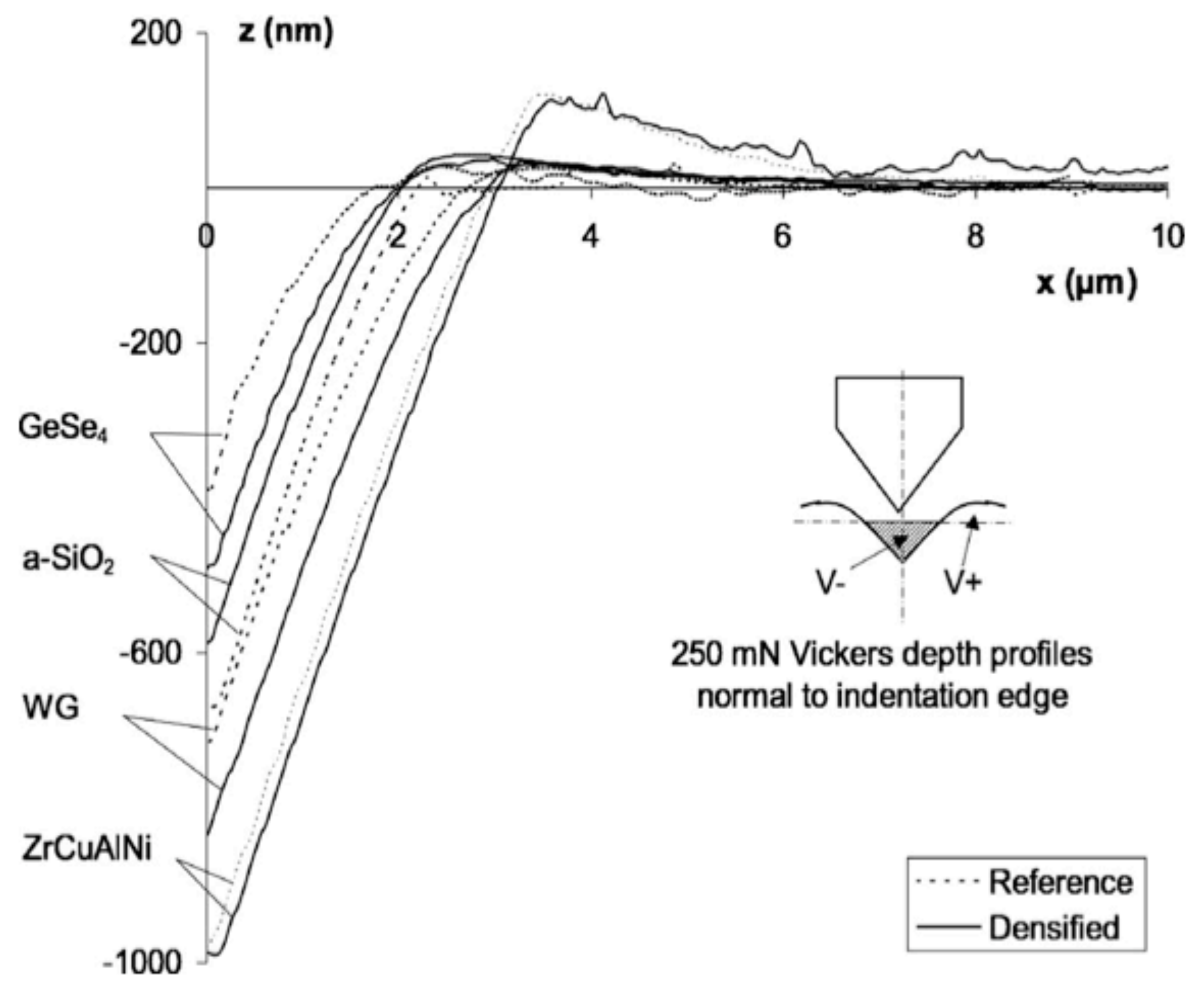

a-Se
GeSe4
GeSe3
Ge3Se7
Glycerol
a-SiO2
ZBLAN
B2O3
Ca3Al2Si3O12
Zr55Cu30Al10Ni5
Aluminosilicate 1
CaMgSi2O6
Pd42.5Ni71Cu30P20
Window glass
Aluminosilicate 2
CaAl2Si2O8
Oxynitride glass 1
Oxynitride glass 2
Bitumen
Fragile
Strong
$\nu/\nu(T_g)$
1.5
1.4
1.3
1.2
1.1
1
0.9
0.7
0.9
1.1
1.3
T/T_g

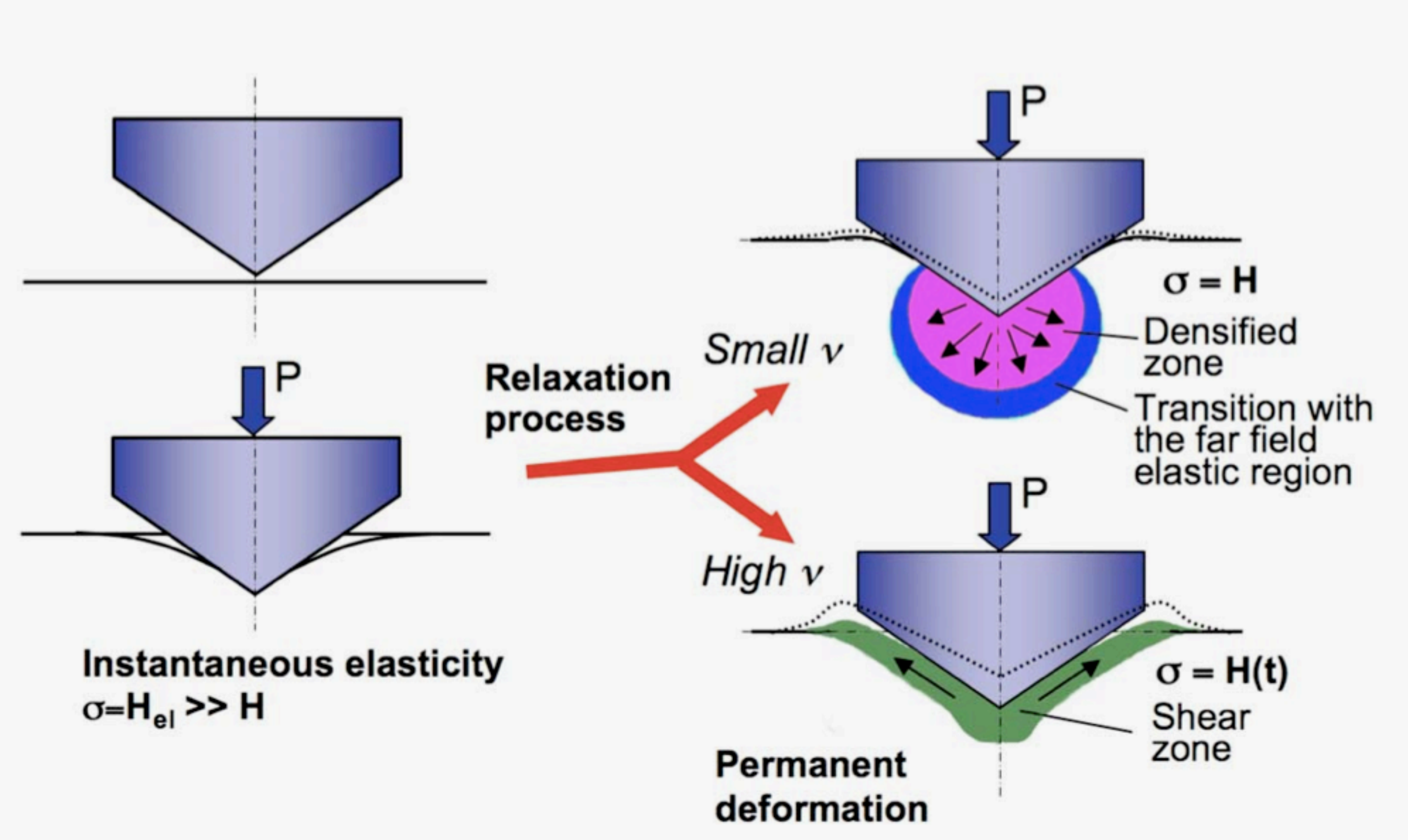
What we know about hardness, indentation cracking, and fracture toughness


ψ
Radial
Lateral
Process-zone
Median
Soda-Lime-Silicate
Vickers – 10 kgs
2c
2a
Median - Radial
Lateral
0.2 mm

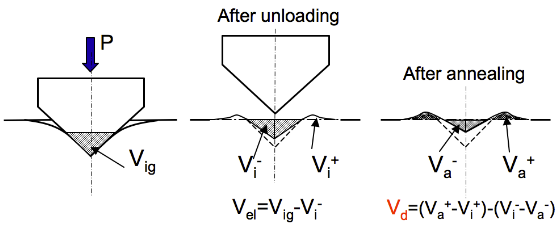

c
z
ψ
P
x
x
a
Median/Half-penny
Process-zone
Radial
Cone
Median
z
Lateral
2c
x
x
2a
y

Isochoric shear flow contribution (pile-up)



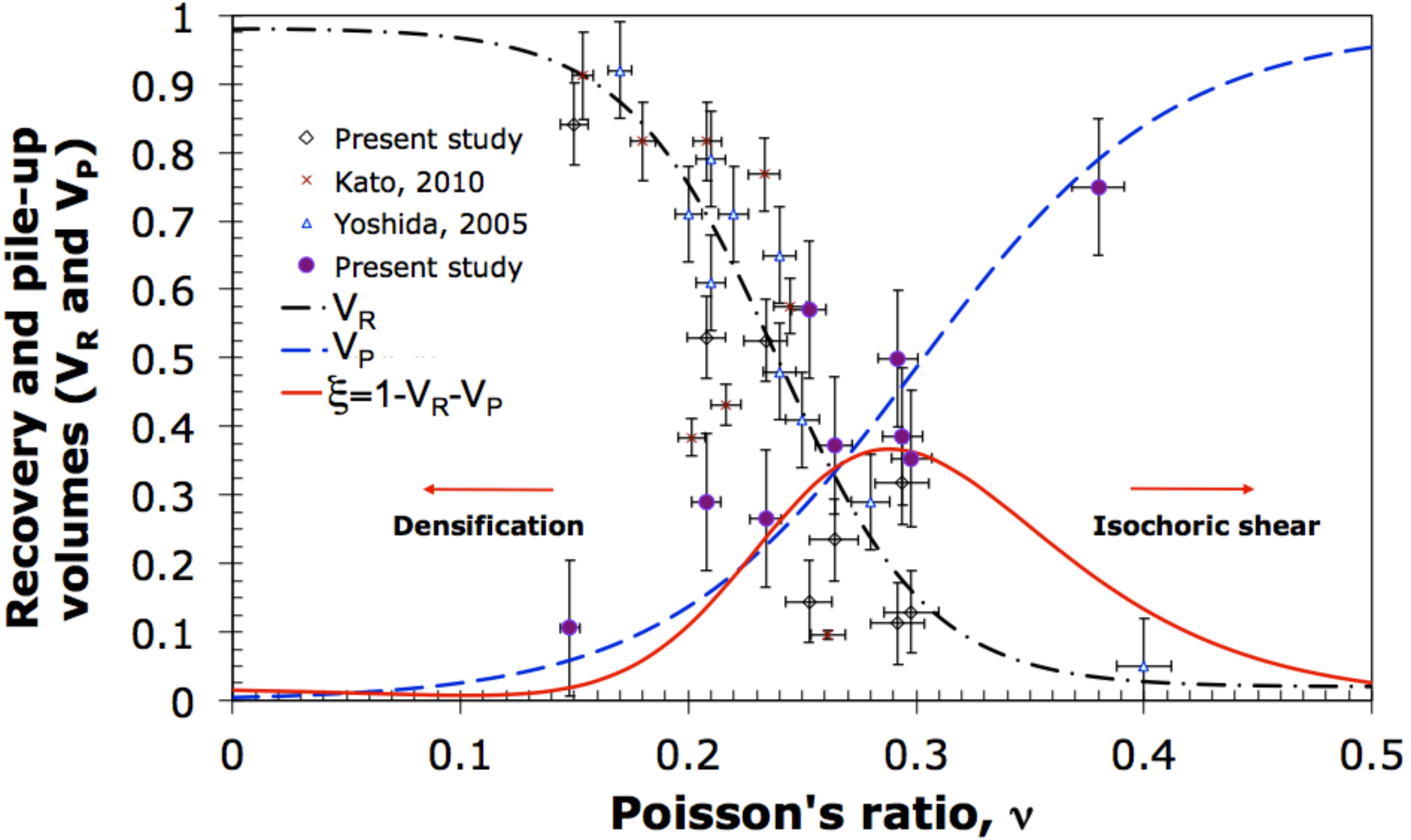

P
Relaxation process
Small ν
P
σ = H
Densified zone
Transition with the far field elastic region
High ν
P
σ = H(t)
Shear zone
Instantaneous elasticity
σ=H_el >> H
Permanent deformation

$$V_R = V_d / V_i^-$$

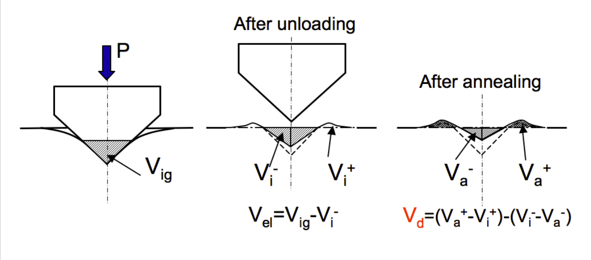


$$V_P = [V_i^+ - (V_a^+ - V_i^+)] / V_i$$

$$V_P = (2V_i^+ - V_a^+) / V_i^-$$

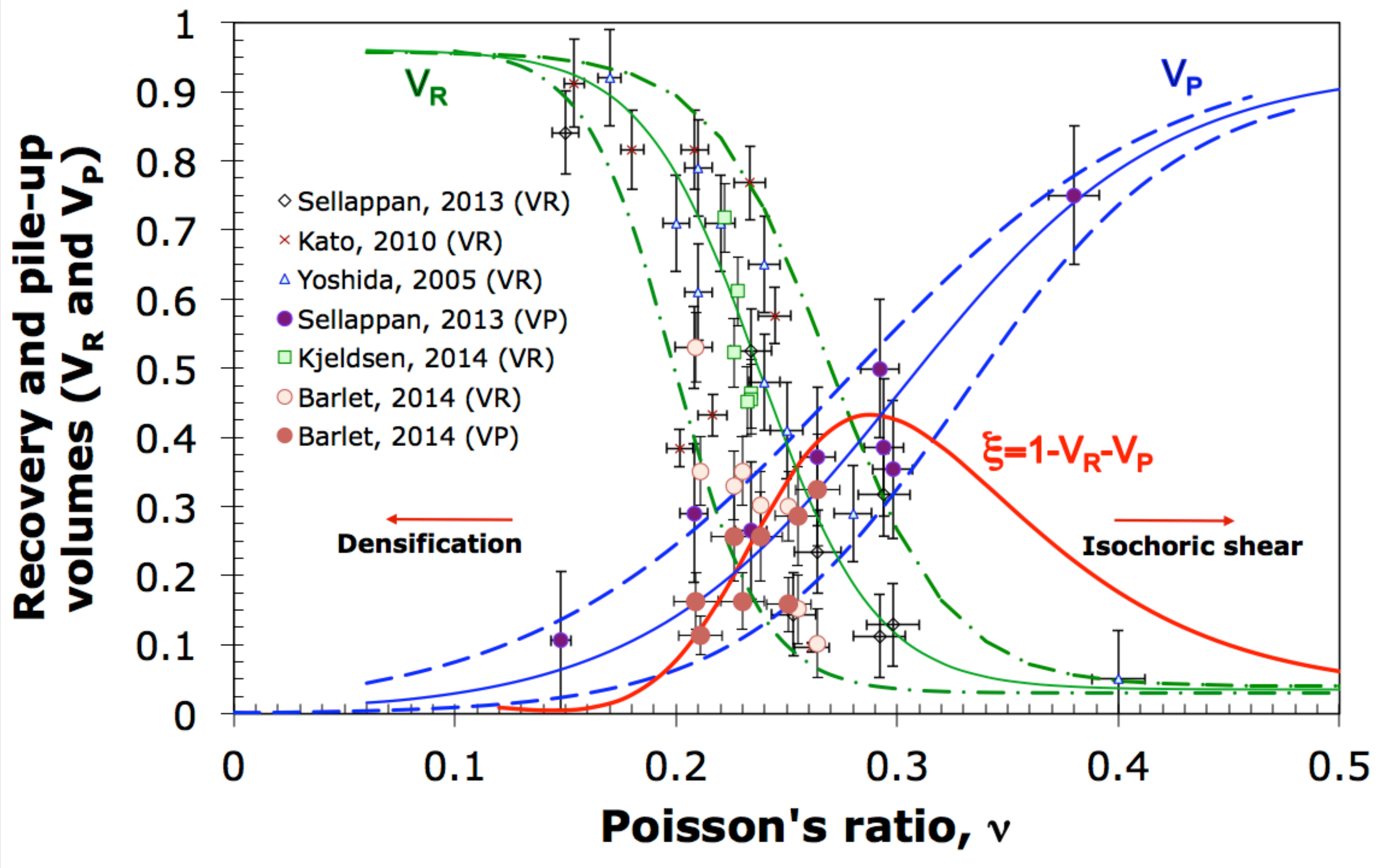


$$V_R = V_d / V_i^-$$



$$V_P = [V_i^+ - (V_a^+ - V_i^+)] / V_i^-$$

$$V_P = (2V_i^+ - V_a^+) / V_i^-$$



$$\sigma_{rr} = \underline{\frac{P}{2\pi r^2}[1-2\nu-2(2-\nu)\cos\theta]} + \underline{\frac{4B}{r^3}[(5-\nu)\cos^2\theta-2+\nu]} \quad (1)$$

$$\sigma_{\theta\theta} = \underline{\frac{P}{2\pi r^2}\frac{(1-2\nu)\cos^2\theta}{1+\cos\theta}} - \underline{\frac{2B}{r^3}(1-2\nu)\cos^2\theta} \quad (2)$$

$$\sigma_{\phi\phi} = \underline{\frac{(1-2\nu)P}{2\pi r^2}[\cos\theta-\frac{1}{1+\cos\theta}]} + \underline{\frac{2B}{r^3}(1-2\nu)(2-3\cos^2\theta)} \quad (3)$$

$$\sigma_{r\theta} = \underline{\frac{P}{2\pi r^2}\frac{(1-2\nu)\sin\theta\cos\theta}{1+\cos\theta}} + \underline{\frac{4B}{r^3}(1+\nu)\sin\theta\cos\theta} \quad (4)$$

$$\sigma_{r\phi} = \sigma_{\theta\phi} = 0 \quad (5)$$

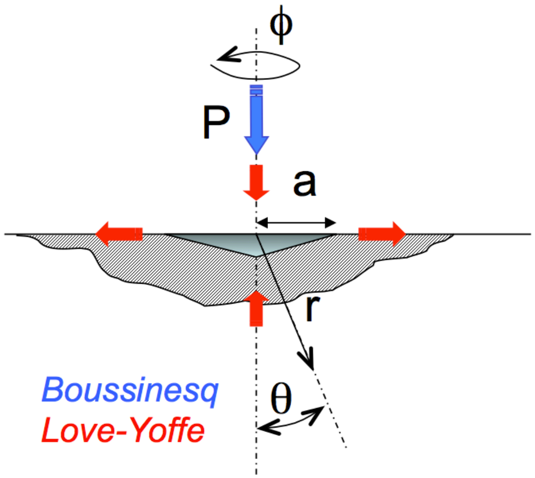
P : indentation load and

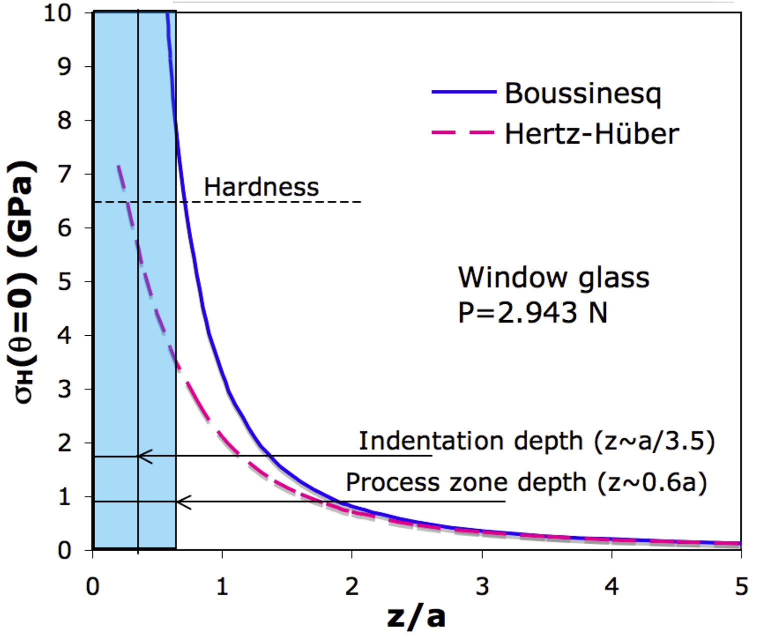
— : Boussinesq's field

— : blister field,

$$B = \frac{3E}{4\pi(1+\nu)(1-2\nu)}(1-V_R-V_P)V_i^- \quad (6)$$

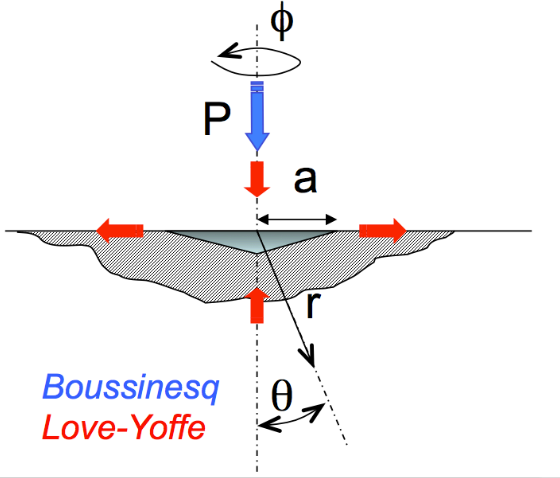
$$(V_i^- = \frac{2a^3}{3\tan\psi}) \quad (7)$$





Paramount importance of Poisson’s ratio ν

For silicate glasses, E/H is typically between 10-15

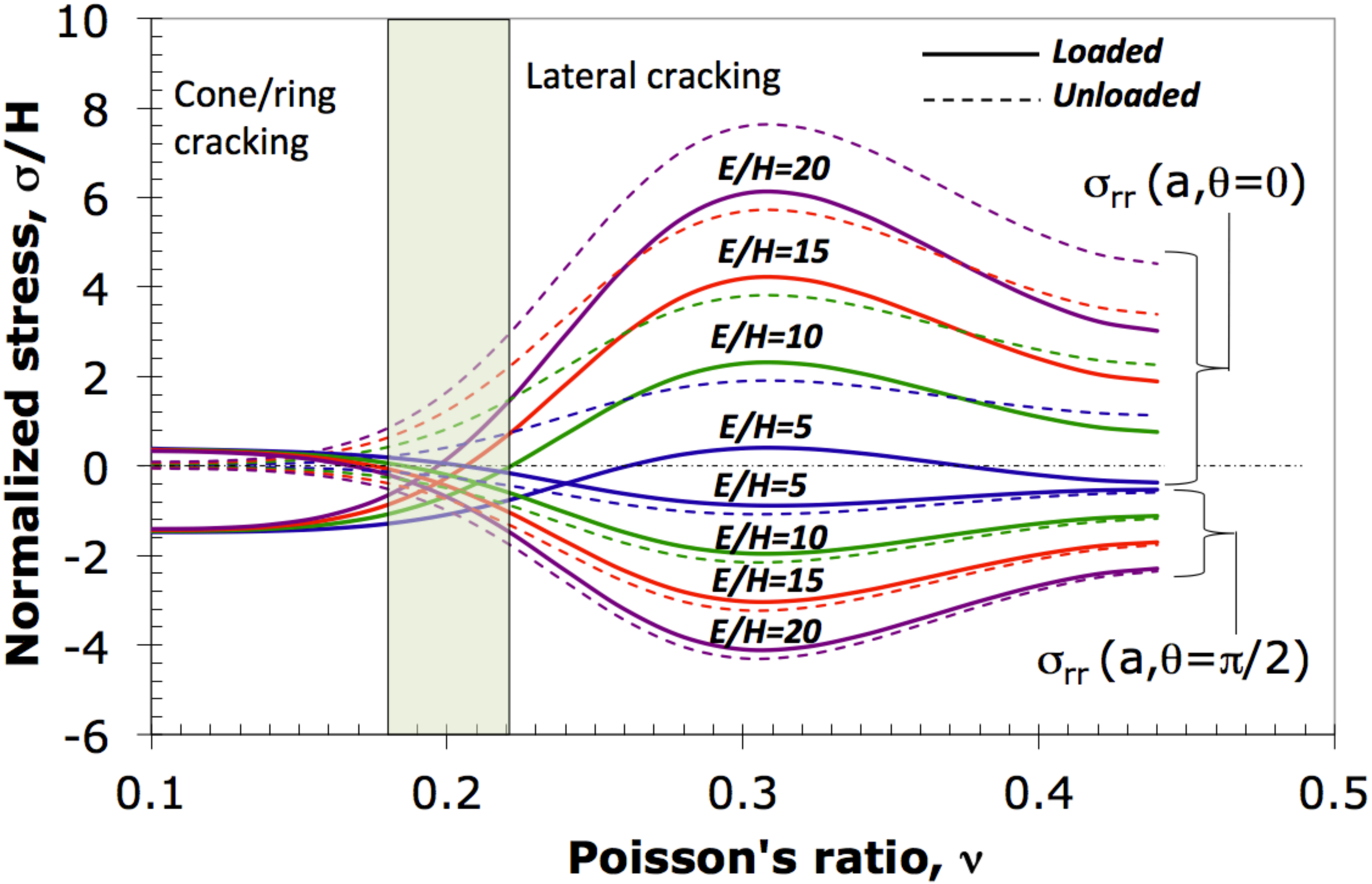


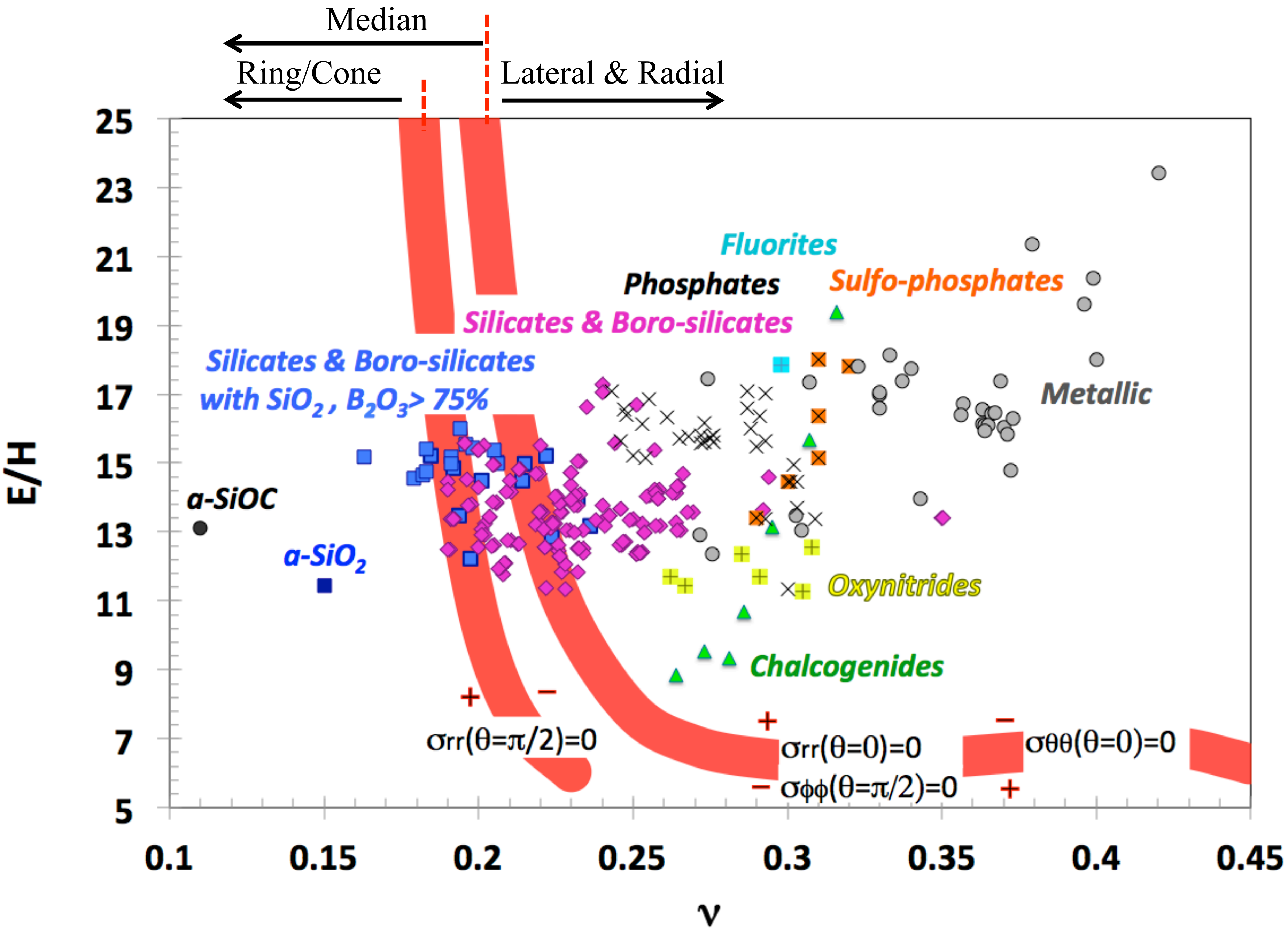
Ring cracks :
$$\sigma_{rr}(r=a,\theta=\pi/2)/H=\frac{1-2\nu}{2}+\frac{2(\nu-2)(1-V_R-V_P)}{\pi(1+\nu)(1-2\nu)\tan\psi}(E/H)$$

Radial cracks :
$$\sigma_{\phi\phi}(r=a,\theta=\pi/2)/H=\frac{2\nu-1}{2}+\frac{2(1-V_R-V_P)}{\pi(1+\nu)\tan\psi}(E/H)$$

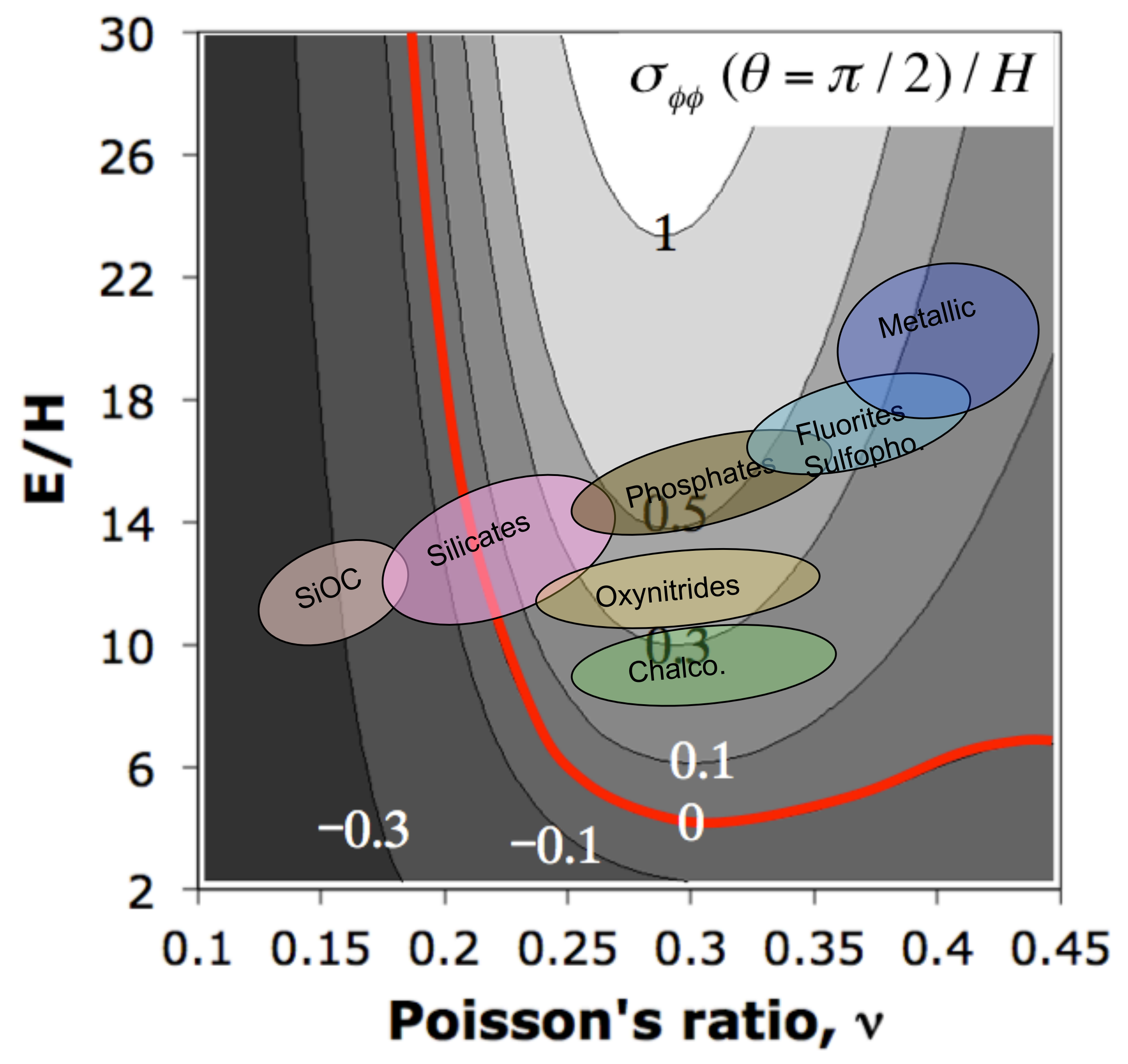
Median cracks :
$$\sigma_{\theta\theta}(r=a,\theta=0)/H=\frac{1-2\nu}{4}-\frac{(1-V_R-V_P)}{\pi(1+\nu)\tan\psi}(E/H)$$

Sub-surface lateral cracks :
$$\sigma_{rr}(r=a,\theta=0)/H=-\frac{3}{2}+\frac{6(1-V_R-V_P)}{\pi(1+\nu)(1-2\nu)\tan\psi}(E/H)$$


Normalized stress, σ/H
Poisson's ratio, ν
10
8
6
4
2
0
-2
-4
-6
0.1
0.2
0.3
0.4
0.5
Cone/ring cracking
Lateral cracking
Loaded
Unloaded
E/H=20
E/H=15
E/H=10
E/H=5
E/H=5
E/H=10
E/H=15
E/H=20
σrr (a,θ=0)
σrr (a,θ=π/2)


Median
Ring/Cone
Lateral & Radial
Fluorites
Phosphates
Sulfo-phosphates
Silicates & Boro-silicates
Silicates & Boro-silicates with SiO_2, B_2O_3> 75%
Metallic
a-SiOC
a-SiO_2
Oxynitrides
Chalcogenides
+
−
σrr(θ=π/2)=0
σrr(θ=0)=0
σϕϕ(θ=π/2)=0
σθθ(θ=0)=0
E/H
25
23
21
19
17
15
13
11
9
7
5
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
ν

Radial cracking



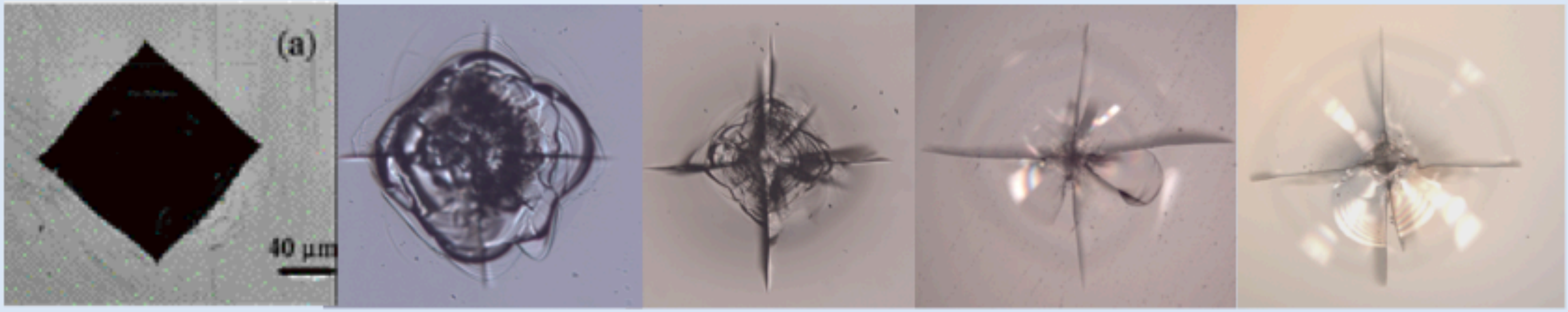
a-SiOC

a-SiO_2

Boro-Silicate ($82\% \ SiO_2$)

Boro-Silicate ($73\% \ SiO_2$)

Soda-Lime-Silicate ($71\% \ SiO_2$)



0.11 *0.15* *0.195* *0.208* *0.234*

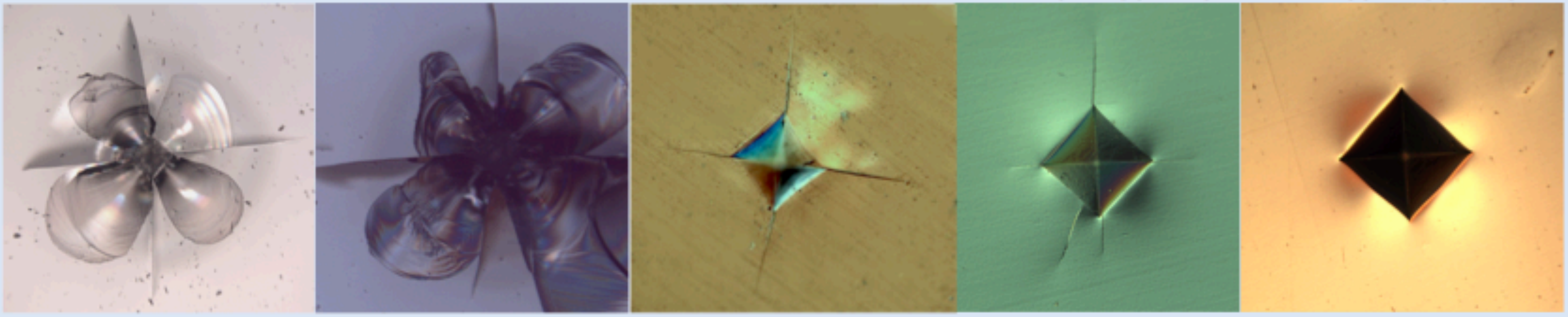
Boro-Lime-Silicate ($37.5\% \ SiO_2$)

Fluorite

Oxynitride Silicate

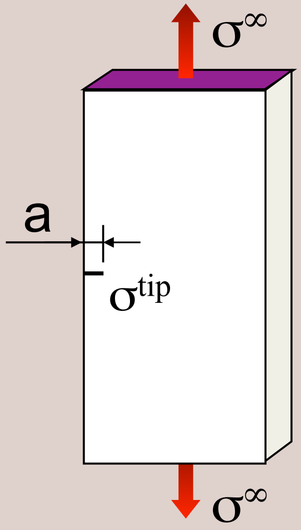
$Zr_{40}Cu_{50}Al_{10}$

$Zr_{60}Cu_{30}Al_{10}$



0.292 *0.298* *0.308* *0.35* *0.373* ν

$K_I \, \alpha \, \sigma^{\infty}\sqrt{a} \, \alpha \, \sigma^{tip}\sqrt{\rho}$



At fracture:

$$K_{Ic} \; \alpha \; \sigma_c \sqrt{\rho} \; \alpha \; \sigma_r \sqrt{a}$$

$$G_{Ic} = \frac{K_{Ic}^2}{E^*} \quad \longrightarrow \quad K_{Ic} = \sqrt{\frac{2\gamma E}{1-\nu^2}}$$

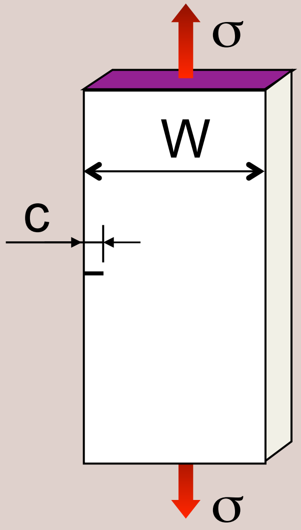
$$\gamma = \frac{1}{2}\left(\frac{\rho}{M_o}\right)^{2/3} \mathcal{N}^{-1/3} \sum_i x_i \, n_i U_{oi}$$

$$\gamma = \frac{1}{2}\left(\sum_i 4/3\pi \, x_i r_i^3\right)^{-2/3} \mathcal{N}^{-1/3} {C_g}^{2/3} \; < U_o >$$

Basic concepts

« As she has the beauty of glass, she has its brittleness » (Polyeucte, Corneille)

Toughness and practical strength:



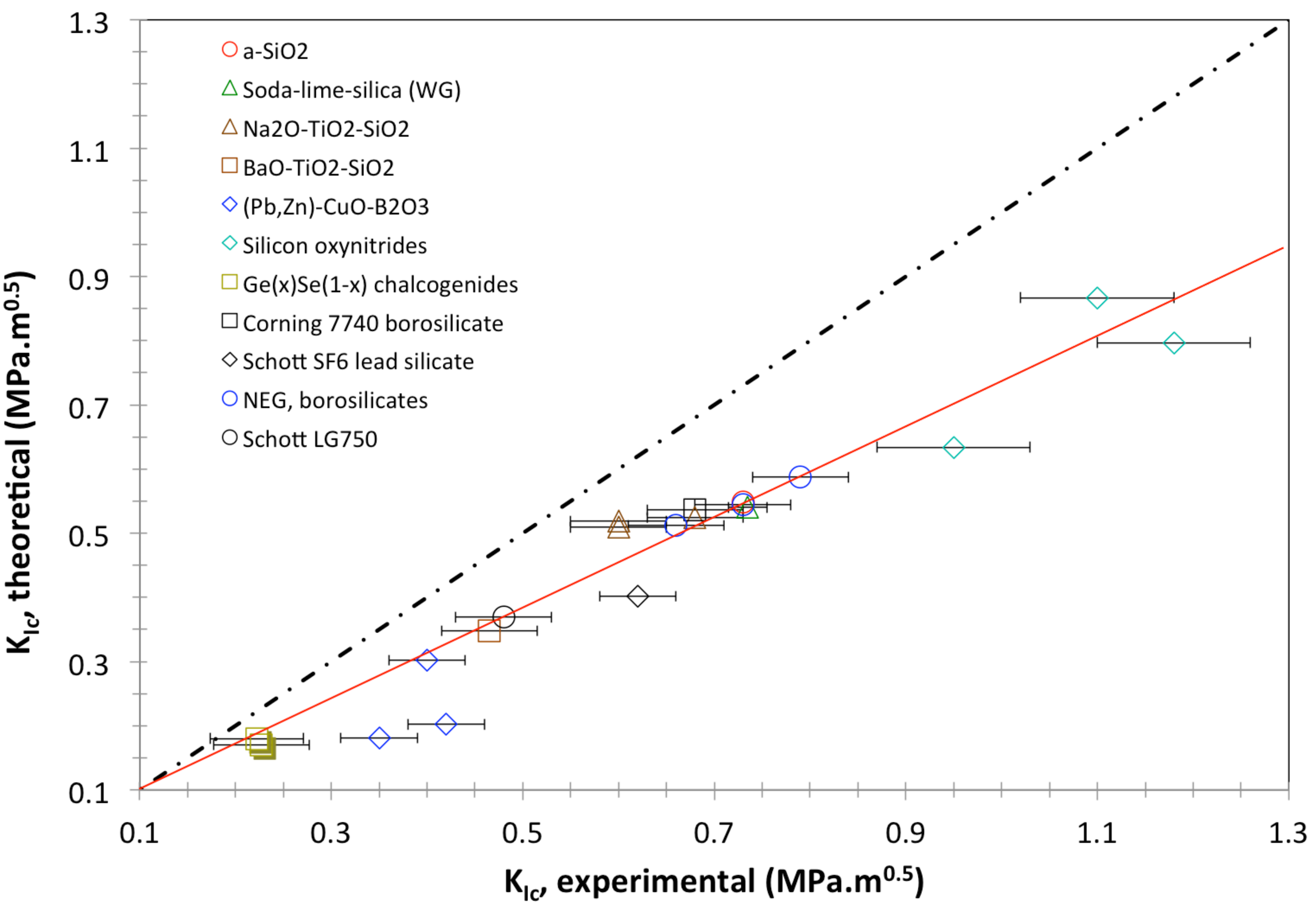
$K_I=\sigma Y\sqrt{c}$ ***with***

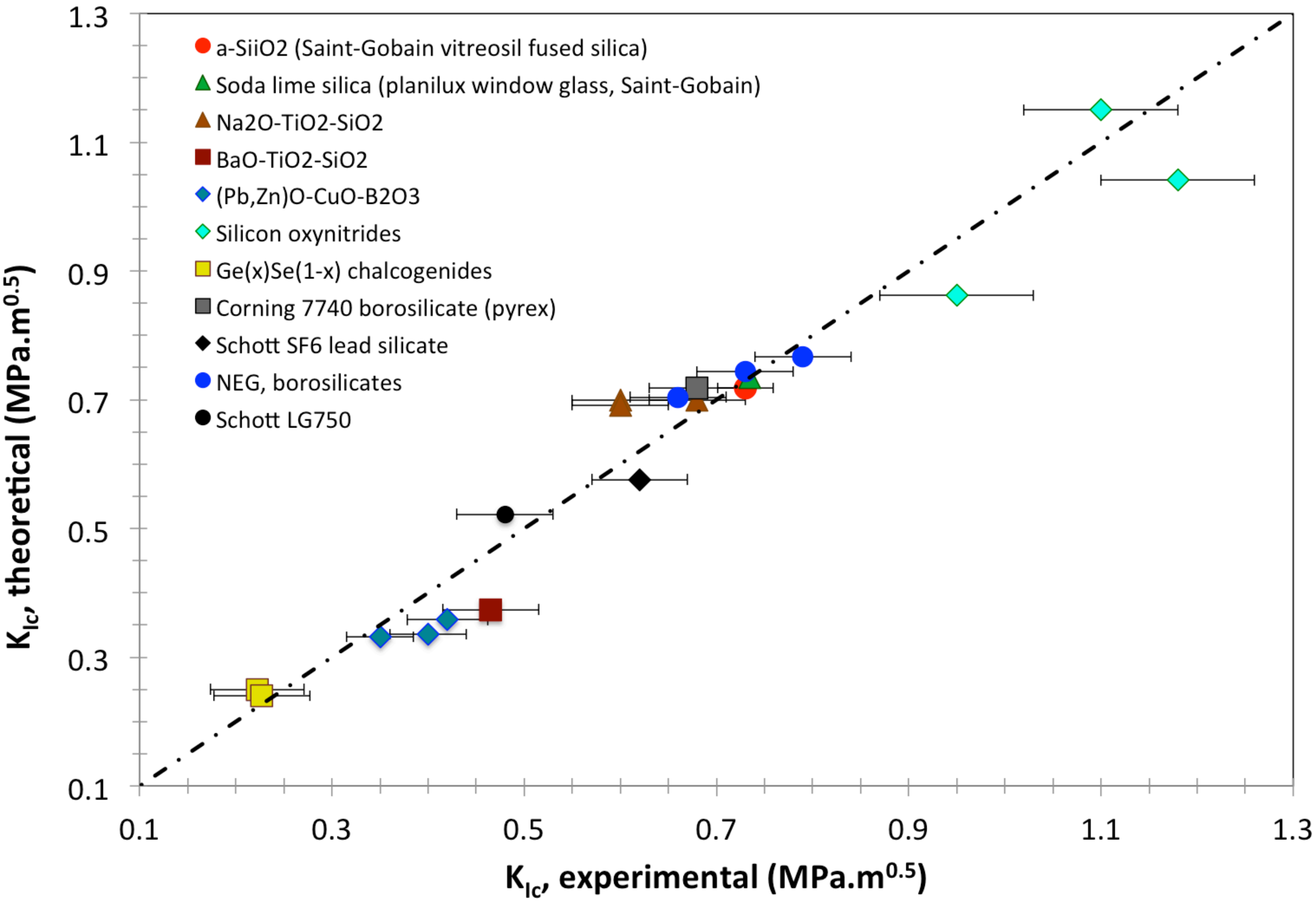
$K_I=1.12\sigma\sqrt{(\pi c)}$

K_I: Stress intensity factor in mode I (opening)
σ: Applied stress
c: Flaw size
Y: Shape factor

At the onset of fracture: $K_I=K_{Ic}$ et $\sigma=\sigma_r$

With σ_r=200 MPa and K_{Ic}=0.7 MPa√m, c=2 μm! → The flaw size is a fact of the problem


○ a-SiO2
△ Soda-lime-silica (WG)
△ Na2O-TiO2-SiO2
☐ BaO-TiO2-SiO2
◇ (Pb,Zn)-CuO-B2O3
◇ Silicon oxynitrides
☐ Ge(x)Se(1-x) chalcogenides
☐ Corning 7740 borosilicate
◇ Schott SF6 lead silicate
○ NEG, borosilicates
○ Schott LG750
1.3
1.1
0.9
0.7
0.5
0.3
0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
K_{Ic}, theoretical (MPa.m$^{0.5}$)
K_{Ic}, experimental (MPa.m$^{0.5}$)


a-SiiO2 (Saint-Gobain vitreosil fused silica)
Soda lime silica (planilux window glass, Saint-Gobain)
Na2O-TiO2-SiO2
BaO-TiO2-SiO2
(Pb,Zn)O-CuO-B2O3
Silicon oxynitrides
Ge(x)Se(1-x) chalcogenides
Corning 7740 borosilicate (pyrex)
Schott SF6 lead silicate
NEG, borosilicates
Schott LG750
1.3
1.1
0.9
0.7
0.5
0.3
0.1
0.1
0.3
0.5
0.7
0.9
1.1
1.3
K_{Ic}, theoretical ($MPa.m^{0.5}$)
K_{Ic}, experimental ($MPa.m^{0.5}$)