CERAMICS IN ORTHOPAEDICS

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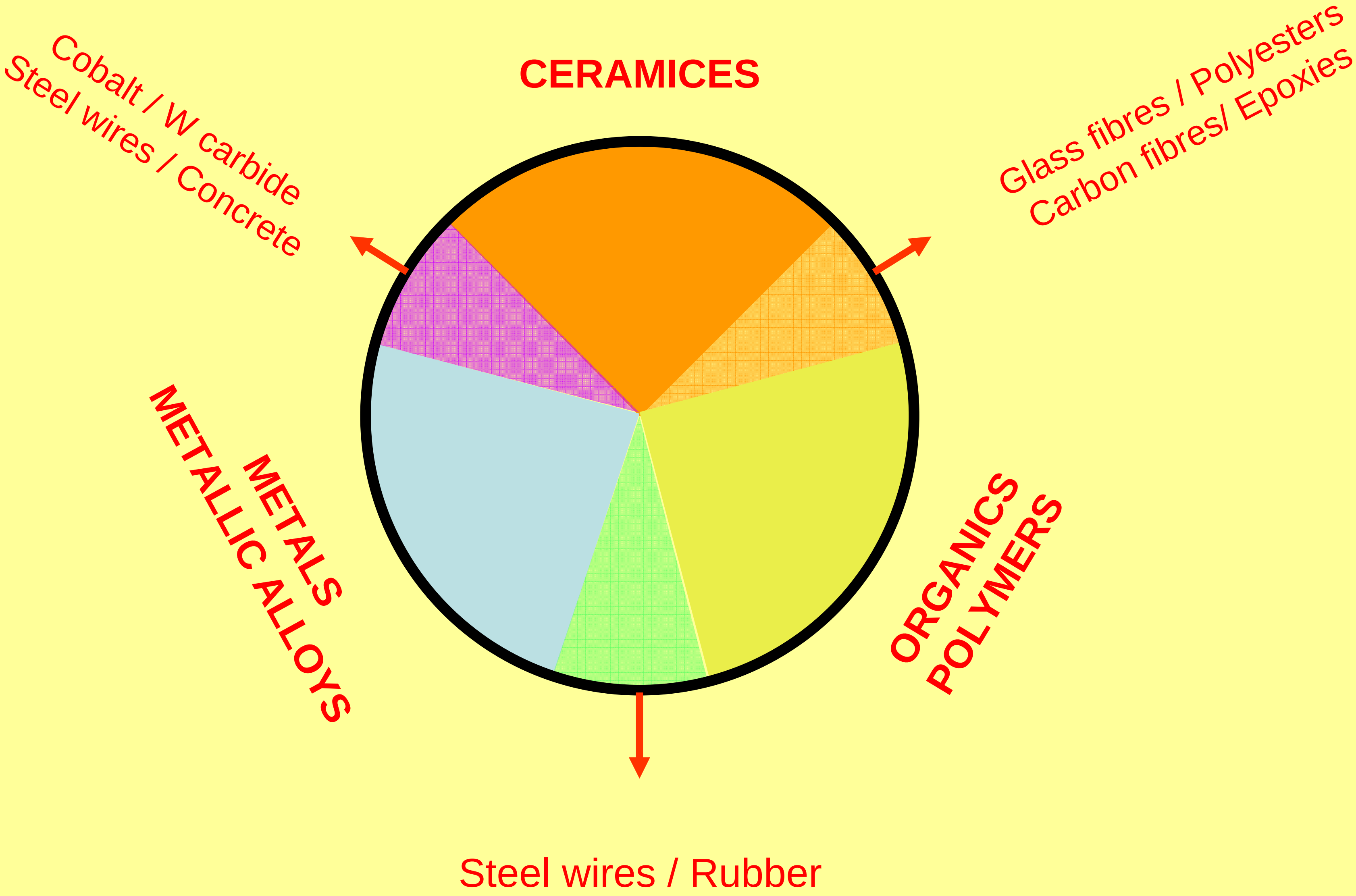
- Outline:
  - What is a ceramic ?
    - Definition
    - Usual properties
    - Processing
  - Applications of bioinert ceramics to orthopaedics
    - Resistance to wear
    - Resistance to fracture
    - The case of zirconia ceramics
    - Current research and perspectives
  - Applications of bioactive ceramics
    - Implants coating
    - Bone substitution
    - Current research and perspectives

Introduction

Bio-compatible materials :
Among the three classes of materials

Metals	Polymers	Ceramics
- Stainless steel	- UHMWPE *(Cups, tibia plates)*	- Alumina *(Hip joint heads, Cups)*
- Titanium (TA6V) *(Hip stems)*	- Acrylic 'cements' *(cemented prostheses)*	- Zirconia *(Hip joint heads)*
- Cobalt-Chromium alloys *(bearing surfaces)*		- Calcium phosphate ceramics *(Coatings, bone substitutes)*

3 classes of materials

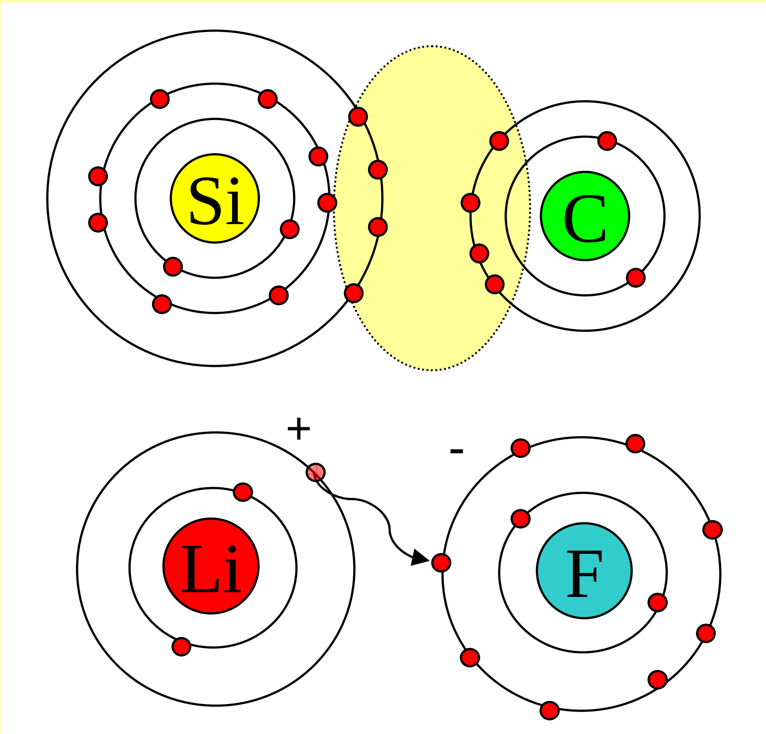


What is a ceramic ? Definition

- **What's a ceramic?**
  - **Inorganic materials** resulting from the combination of metallic (Al, Mg, Ti, Zr …) or inter-metallic (Si) elements with non-metallic ones (O, C, N, B, …) (mostly Oxygen):
    - Oxides — Alumina Al_2O_3, Lime CaO, Zirconia ZrO_2, …
    - Carbides — Tungsten carbide WC, SiC, TiC, …
    - Nitrides — Si_3N_4, TiN, …
    - Borides — TiB_2, …
    - Silicides — $MoSi_2$, …
  - Can be crystallised or amorphous (glasses)
  - Definition with chemical bonds

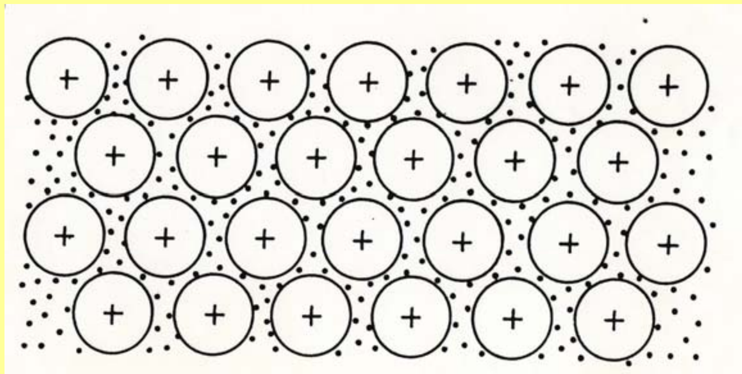
What is a ceramic ? Definition

The properties of materials depend on the nature intensity of chemical bonds between atoms.



Ceramics :

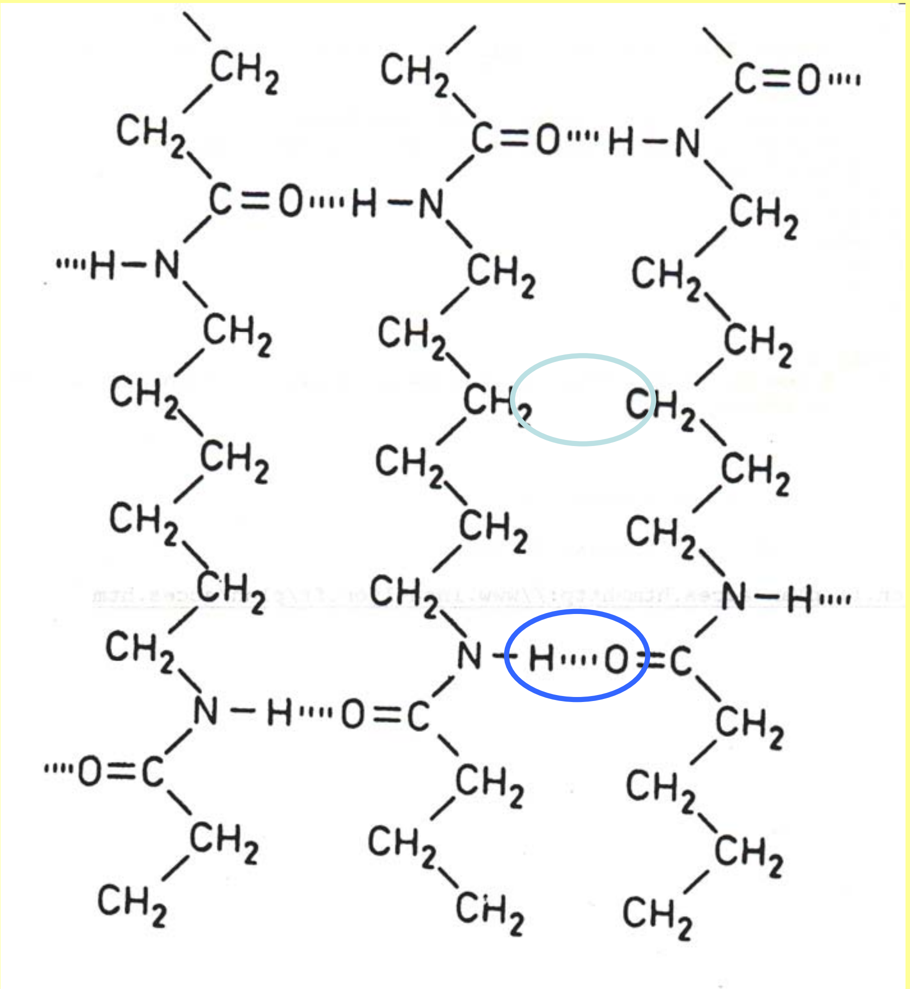
No free electron
Strong bond
Stable bond



Metals:

Free electrons
Weaker bond

What is a ceramic ? Definition



Polyamide (Nylon)

Polymer :

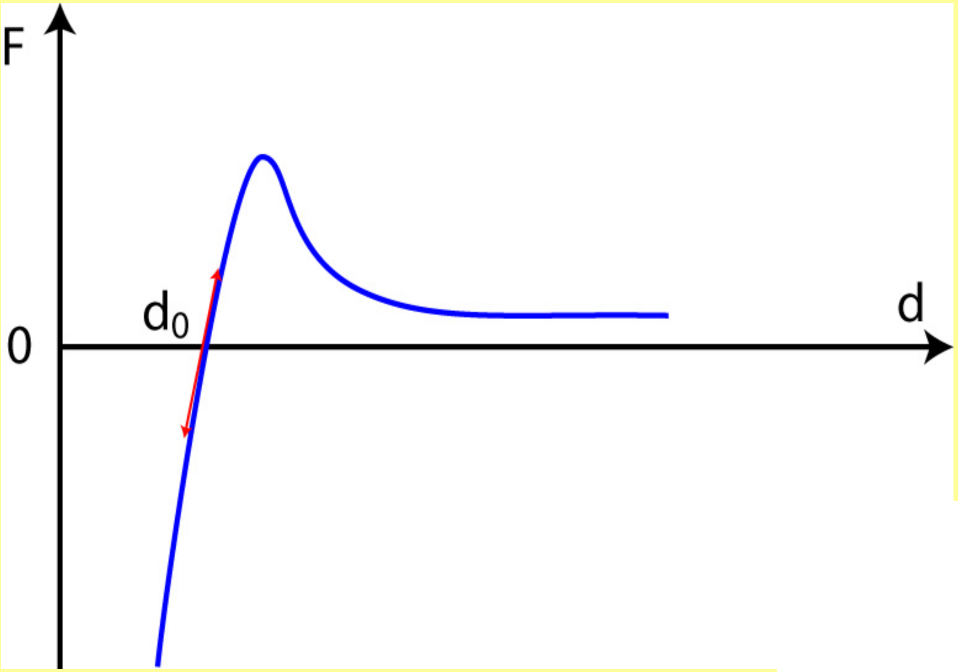
Carbon string (strong bonds)

+

Weak inter-molecular interactions

Van der Waals hydrogen

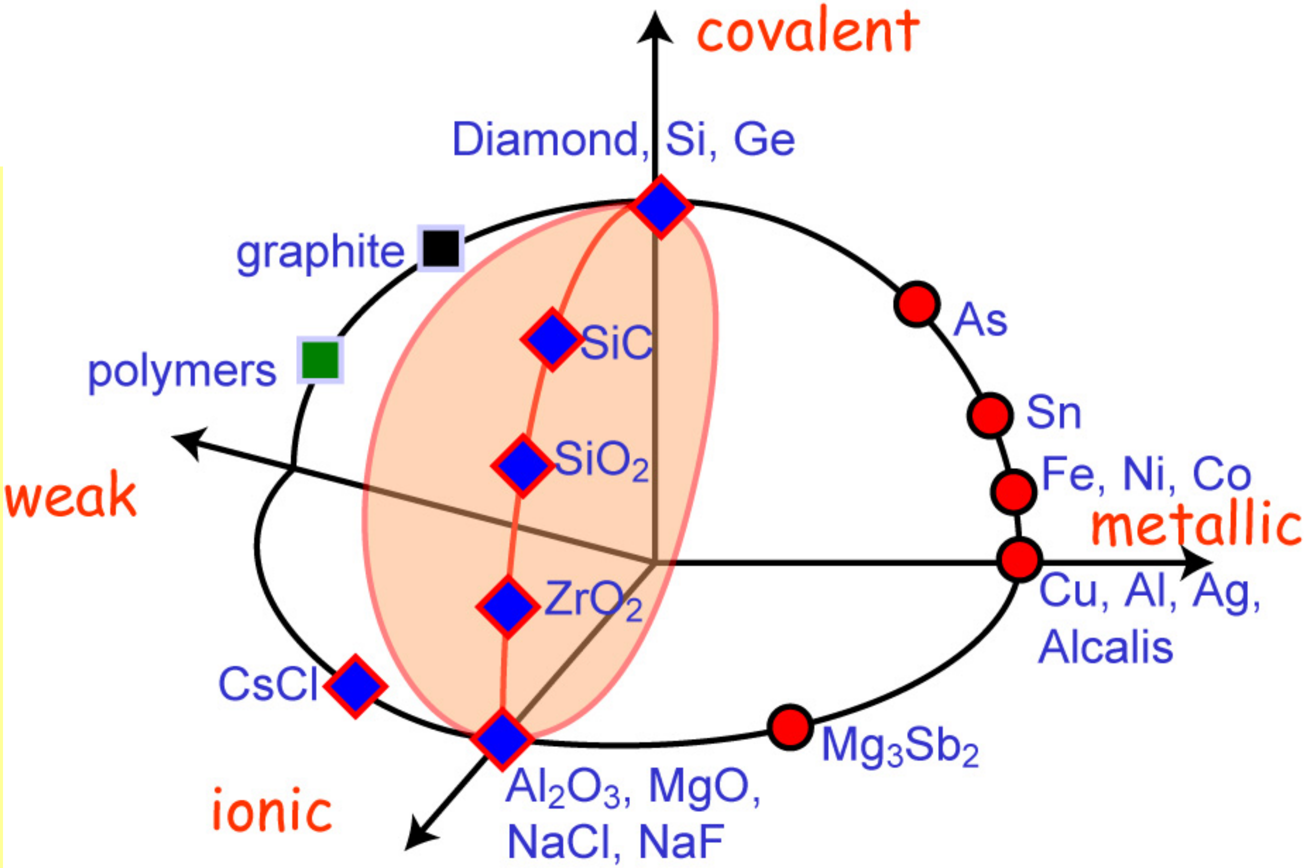
What is a ceramic ? Definition



Atomic bonds

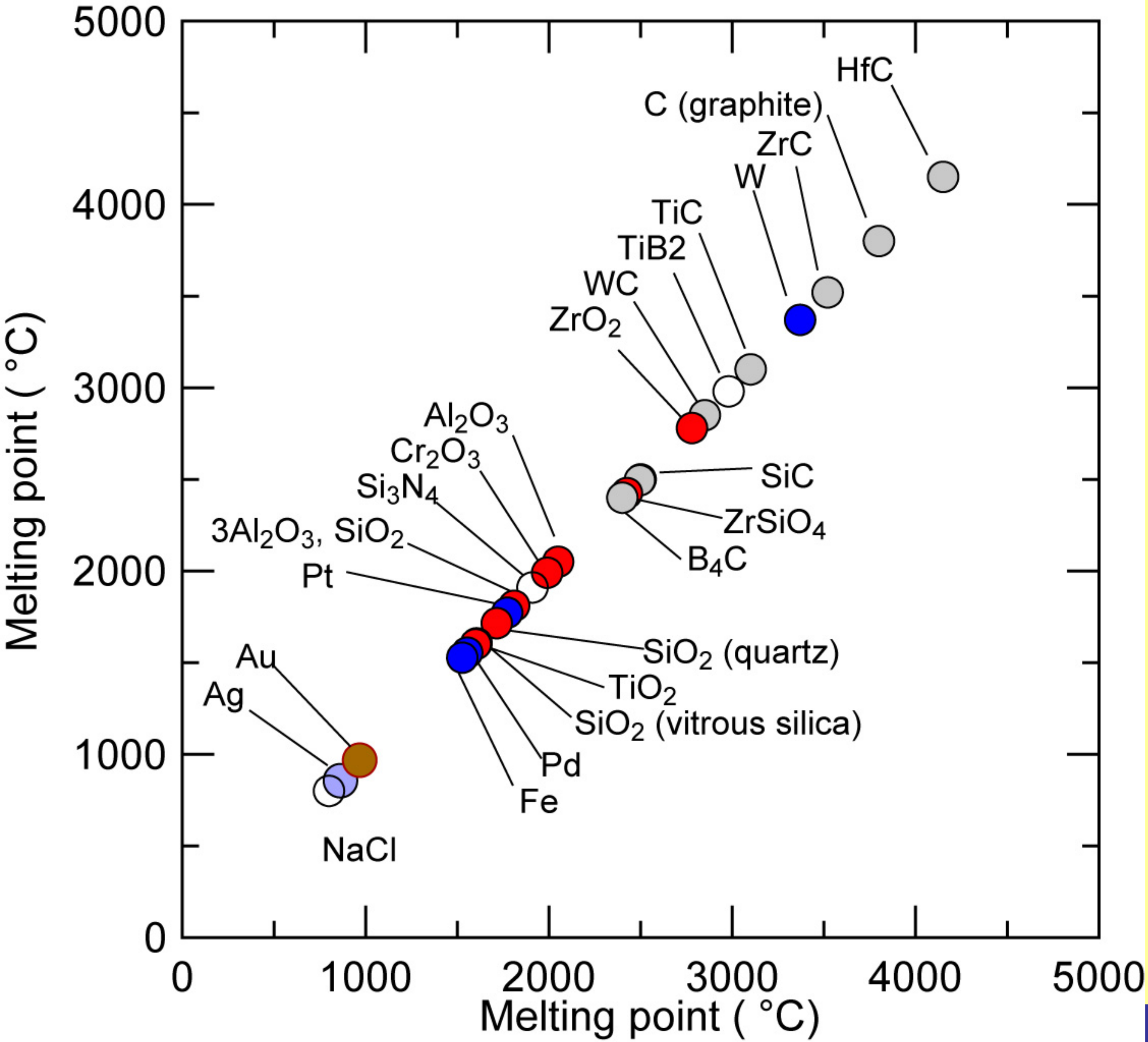
Properties of the material

- d_0: equilibrium distance between two atoms
- Elasticity modulus proportional to the derivative at d_0

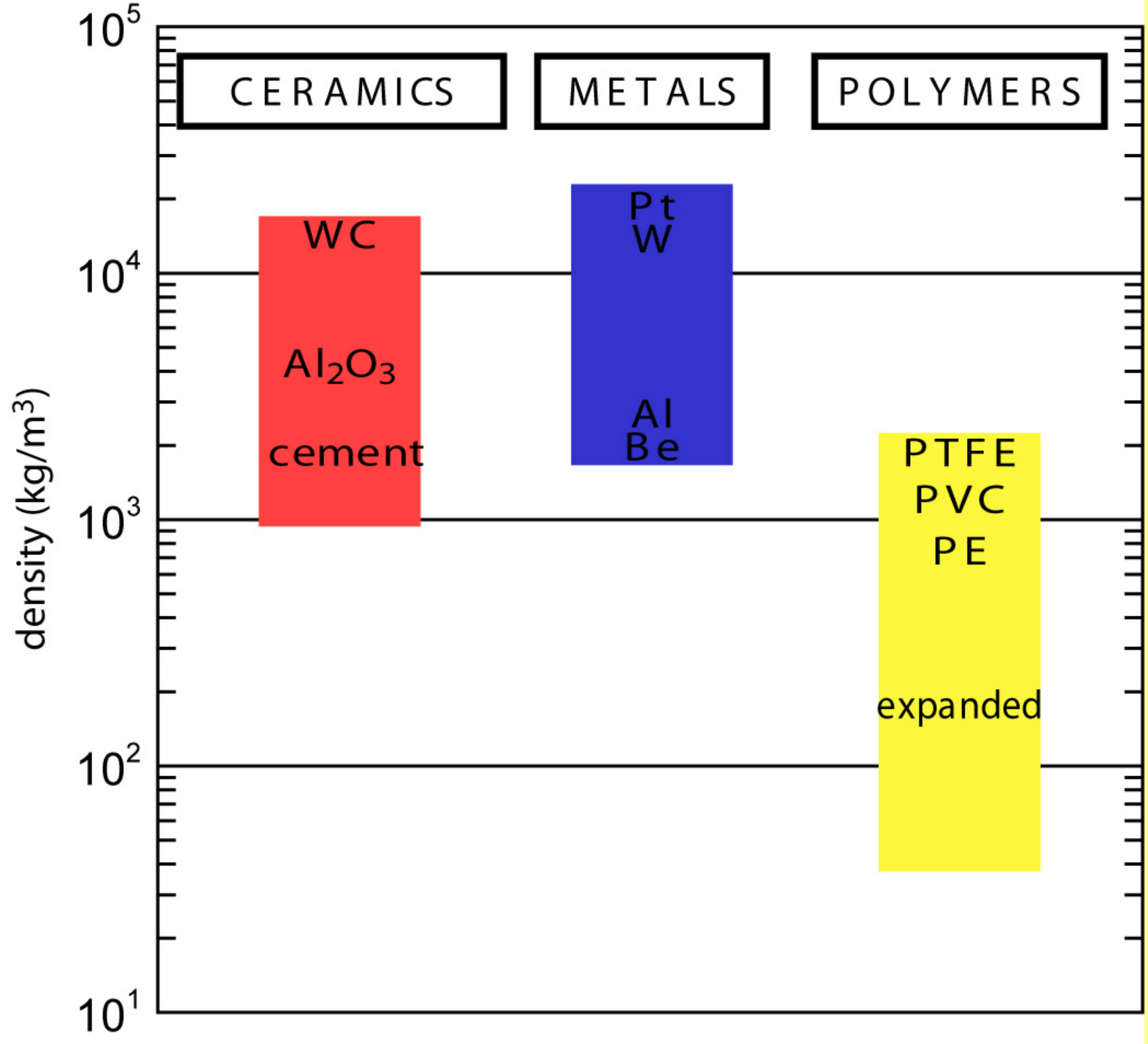


What is a ceramic ? / Properties

- Melting point



What is a ceramic ? / Properties



Oriented bonds

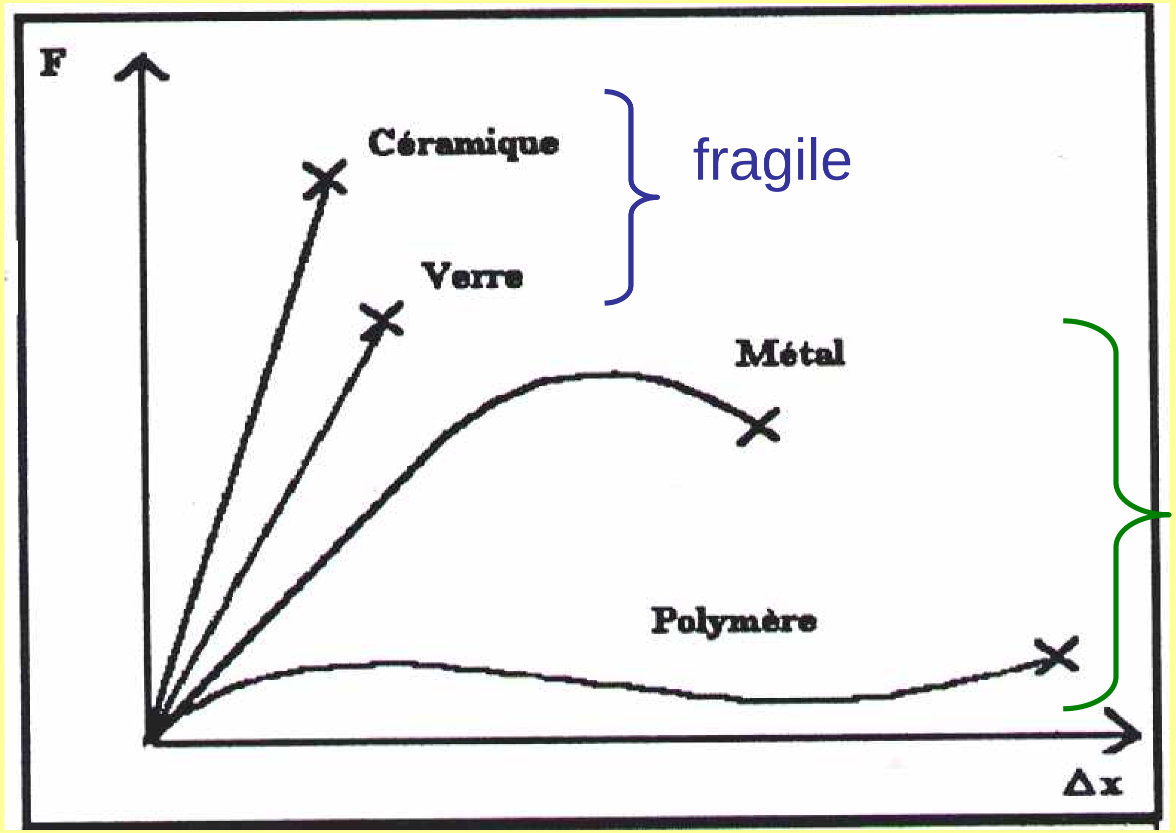
\+

Light elements

↓

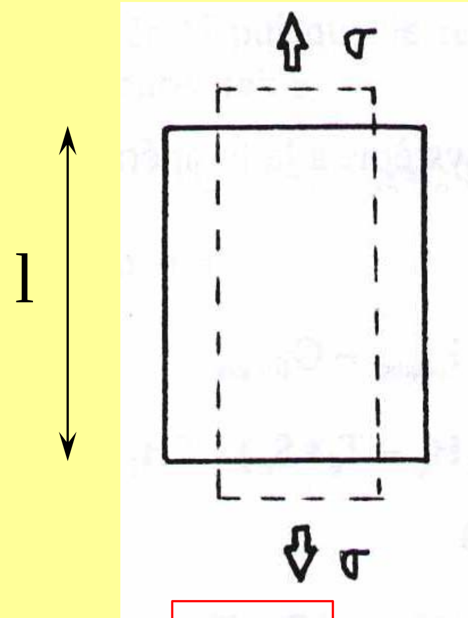
Low density

What is a ceramic ? / Properties



fragile

ductile

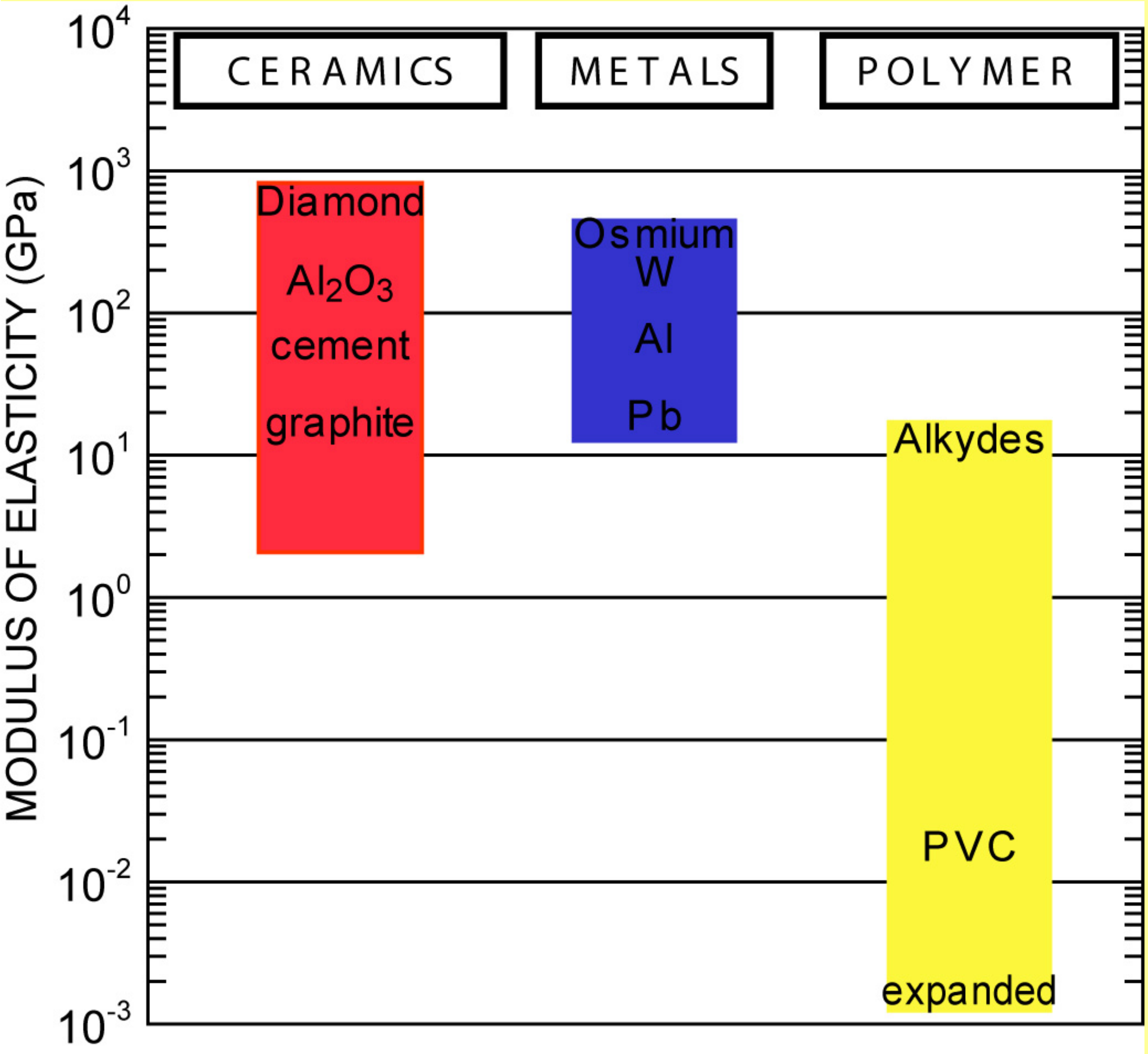


$$E=\frac{\sigma}{\varepsilon}$$

$$\sigma=\frac{F}{S}$$

$$\varepsilon=\frac{dl}{l}$$

What is a ceramic ? / Properties

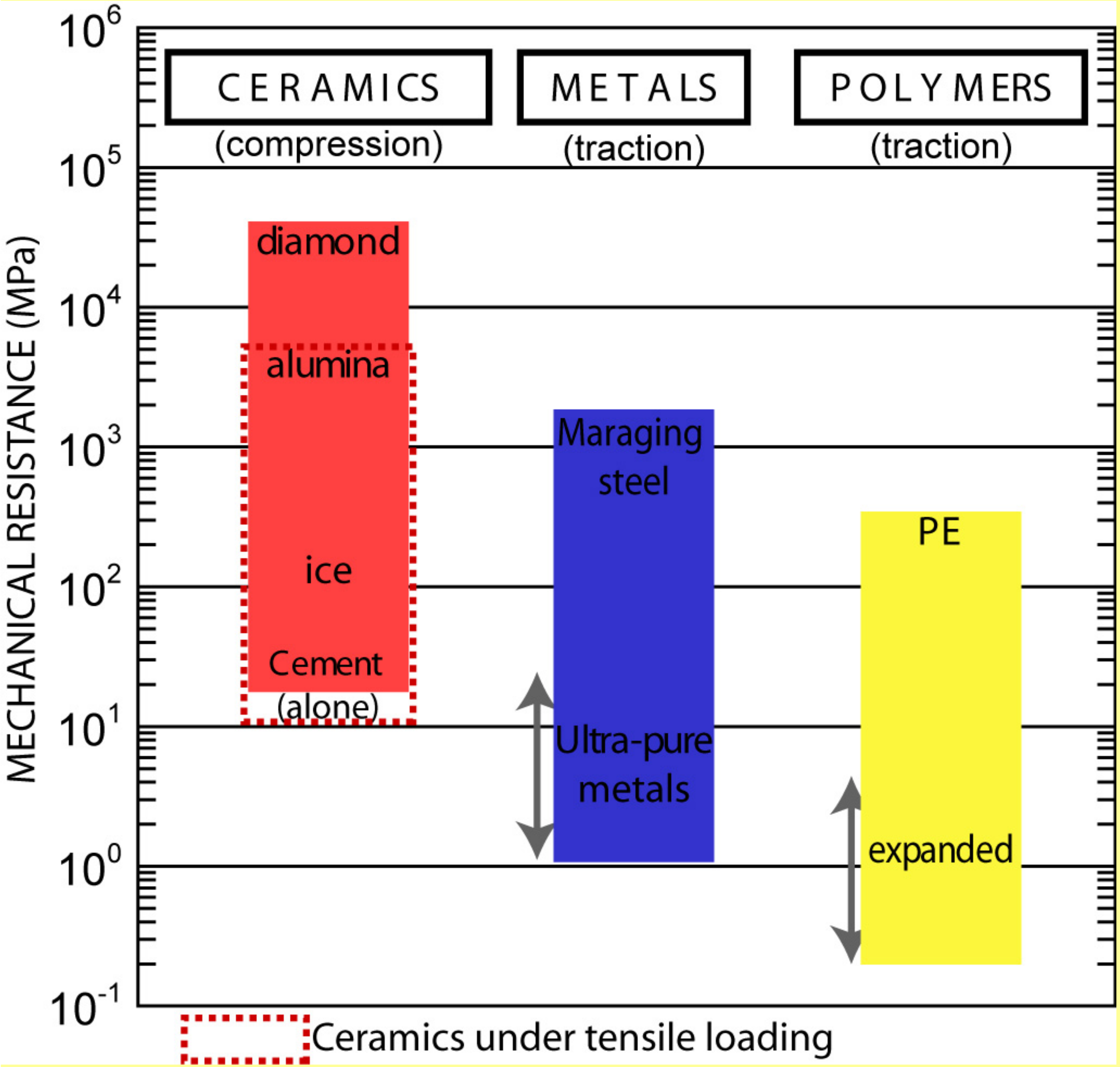


Stiff bonds

↓

High Elasticity (Young's) modulus (E)

What is a ceramic ? / Properties

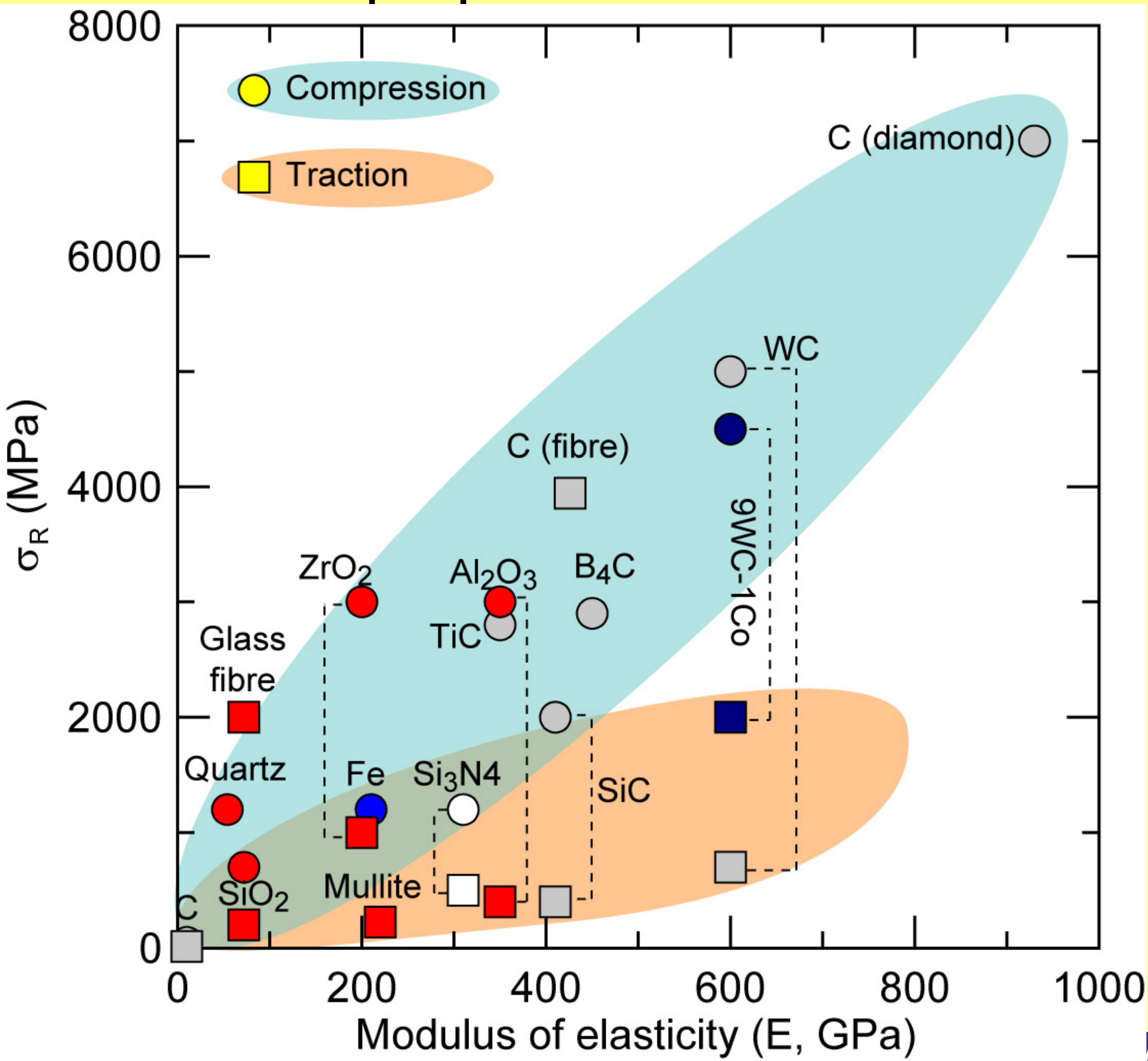


Strong bonds

σ_R High mechanical resistance (σ_R)

IN COMPRESSION

Mechanical properties

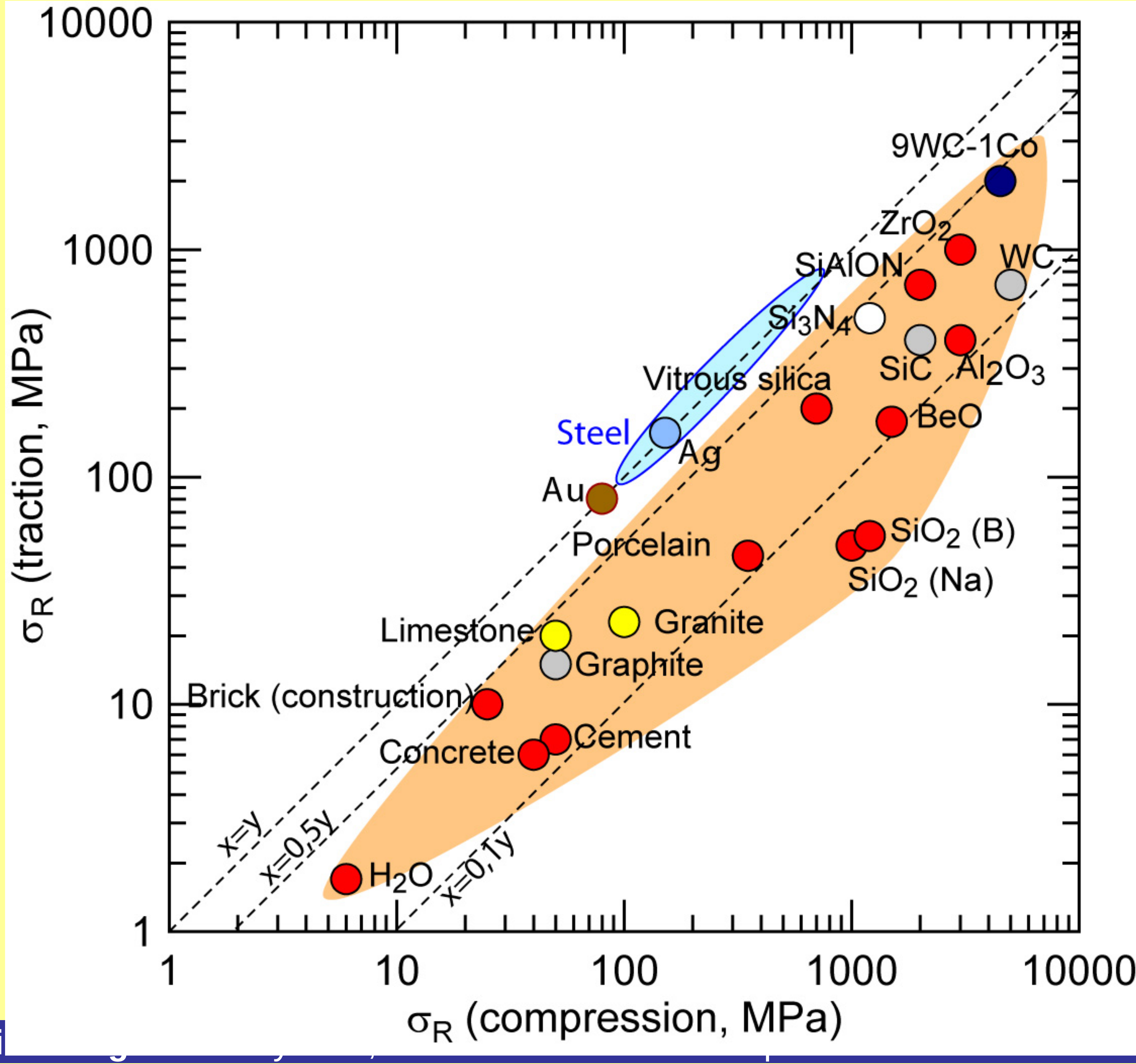


Remarks:

- σ_R in tension lower than σ_R in compression
- Except carbon and glass fibers

Tension – compression asymmetry :

σ_R in tension 2 to 10 times lower than σ_R in compression



What is a ceramic ? Mechanical behaviour

Asymmetry of ceramics mechanical behaviour:

Better resistance to compressive stresses (~10 times)

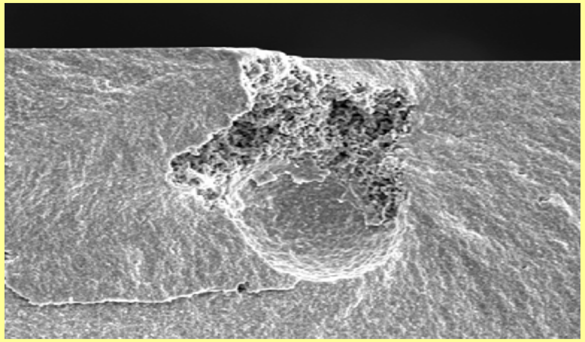
Cause: SENSITIVITY TO DEFECTS

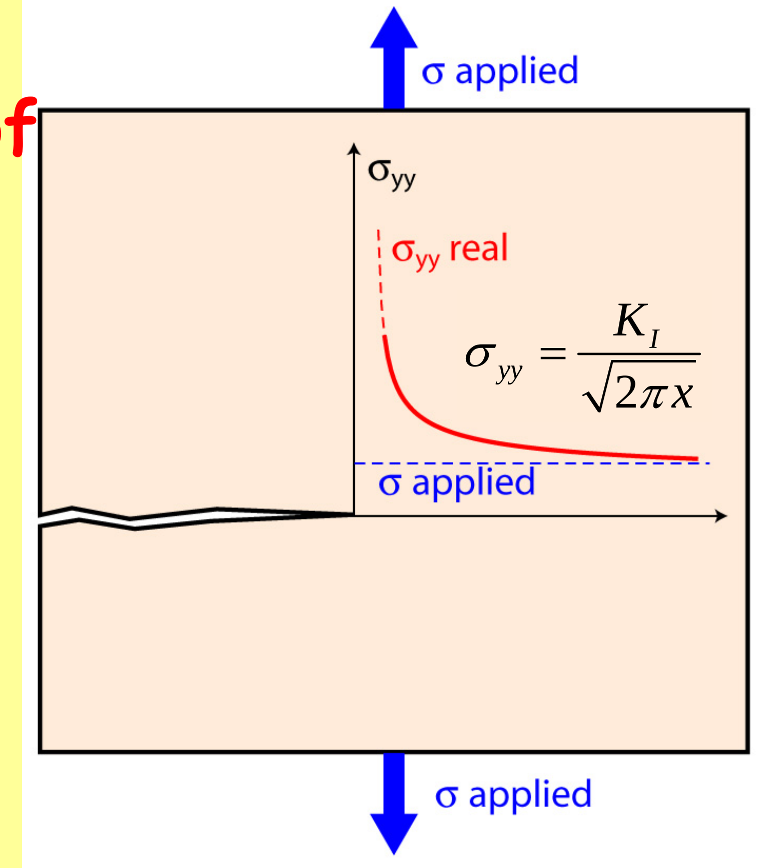
- Characterises by the toughness (= critical stress intensity factor, K_{IC})

What is a ceramic ? Mechanical behaviour

- Stress concentration around the tip of a defect (crack)
- Stress intensity factor K_I: $K_I = \sigma\sqrt{\pi a}$
  - characterises the stress at the crack tip
  - **Crack propagation (fracture) if K_I reaches K_{IC}.**
- ***K_{IC} = toughness: intrinsic property of the material***
- K_{IC} related to the energy (G_{IC}) necessary to break a component:

$G_{IC} \alpha K_{IC}^2 / E$





Bubble resulting from processing, responsible for the fracture of the component

What is a ceramic ? Mechanical behaviour

To simplify:

- Tensile loading : opening of defects
  => Increased K_I

- Compressive loading : closing of defects

- => better behaviour of ceramics under compressive stress than under tensile stress

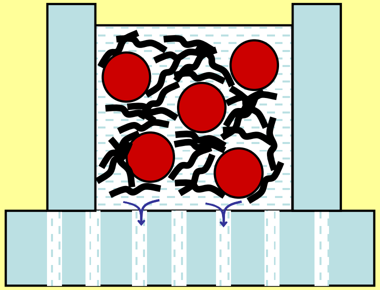
What is a ceramic ? Properties

- Fragile, linear elastic behaviour
  - rupture before plastic (permanent) deformation
- High hardness
  - Most can scratch glass
- Resistance to wear
- Chemical inertness
  - Thanks to strong chemical bonds
- Most of the time insulators
  - Thermal and electrical insulators

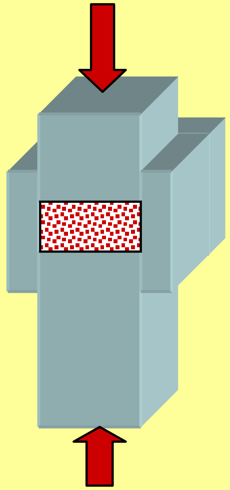
What is a ceramic ? Processing

Ceramic powder

Compaction:

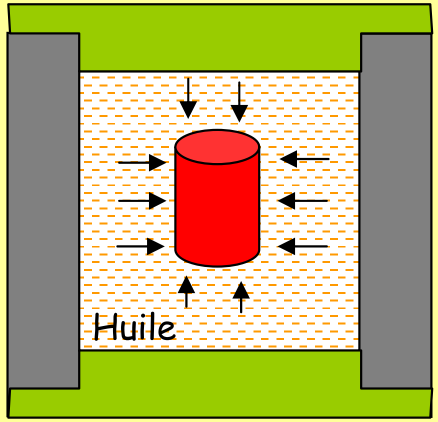


Slip casting



Uniaxial

Pressing



Isostatic

Green ceramic

Thermal treatments:

Debinding → Burn organic compounds

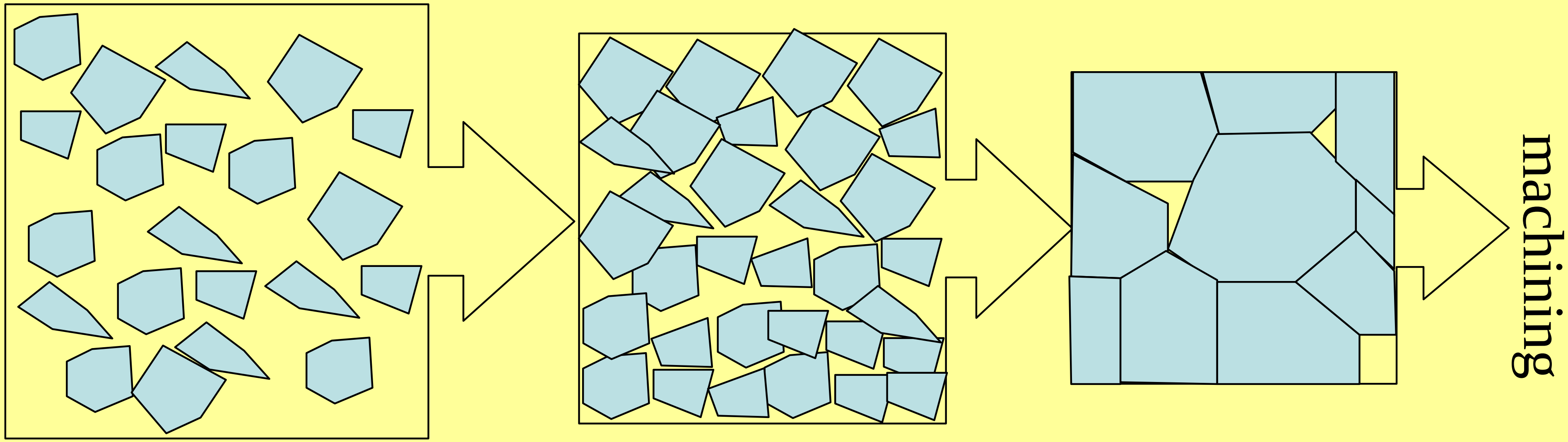
Sintering → Densification, Grain growth

Sintered ceramic

Machining , polishing

Final piece

What is a ceramic ? Processing



Powder (suspension).
synthetic (tech. c.)
Natural ore (trad. c.)

Green product
(after pressing)
Weak bonds
between powder
grains.

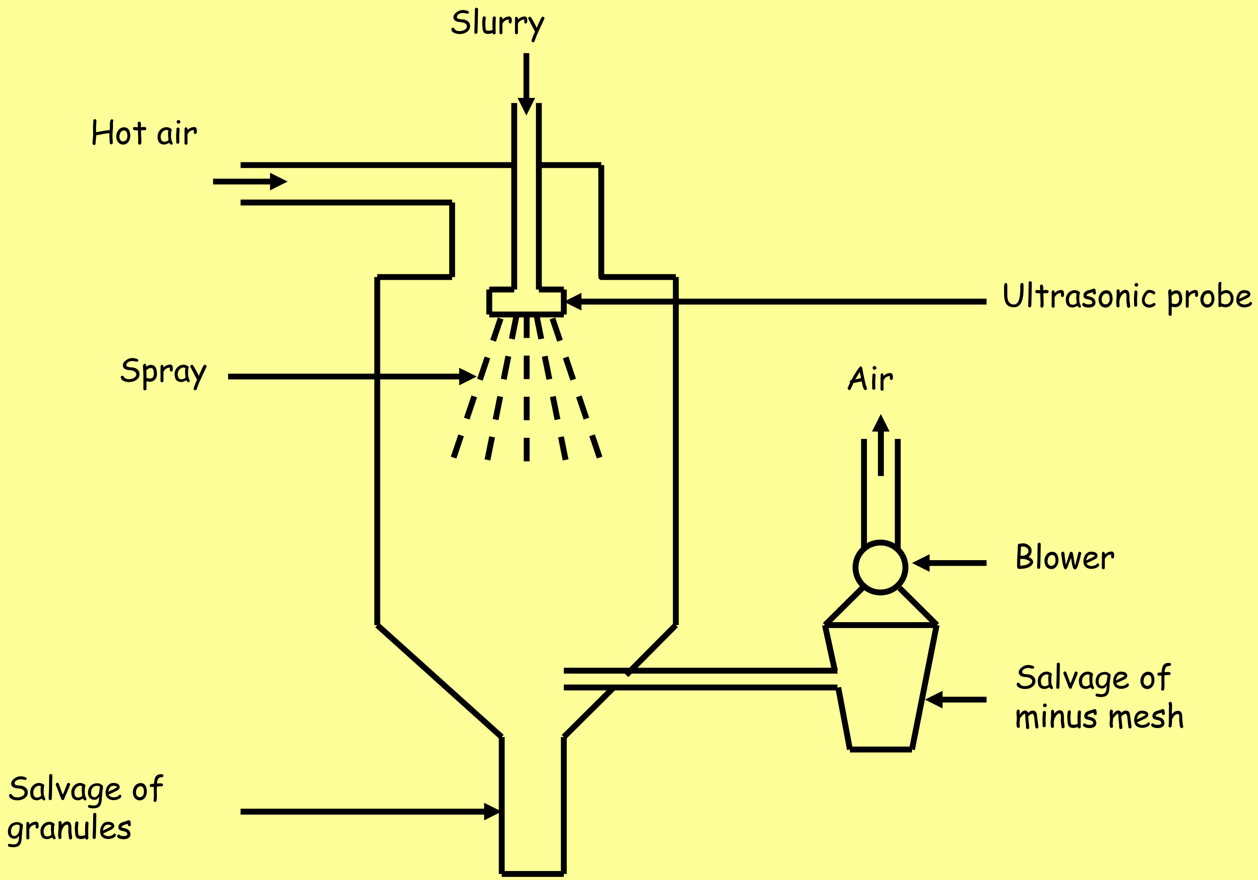
Sintered piece
diffusion in solid
state (~ 1500°C)

Example :Processing of alumina-zirconia composite femoral heads…

Powder preparation

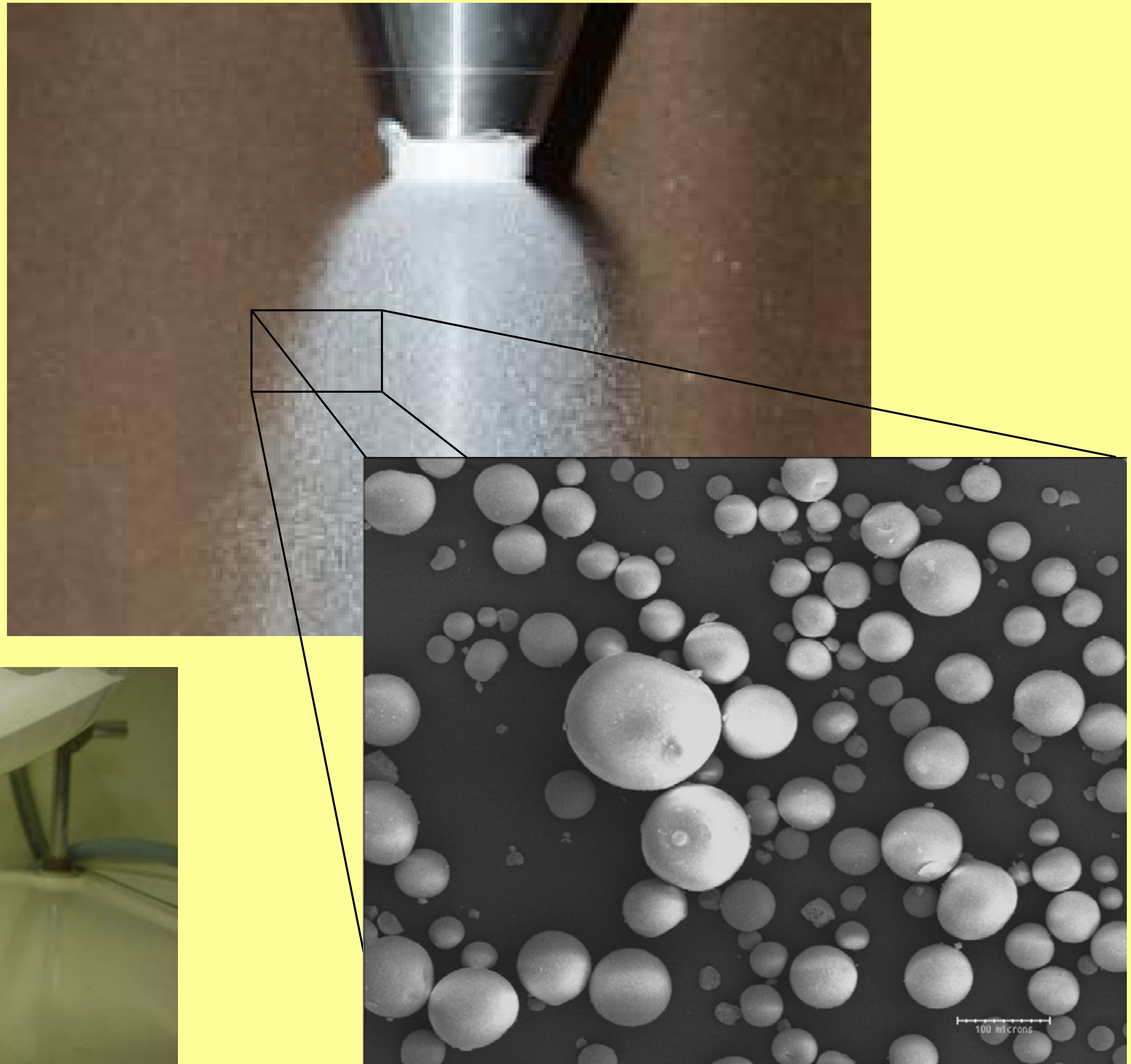
Slurry preparation

Spray - drying of ceramic powders



Powder preparation

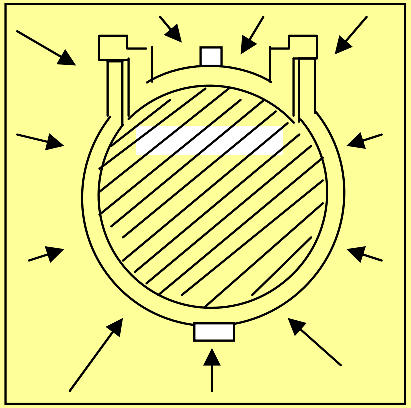
Spray drying



What is a ceramic ? Processing

Forming and sintering

Cold isostatic pressing



Sintering

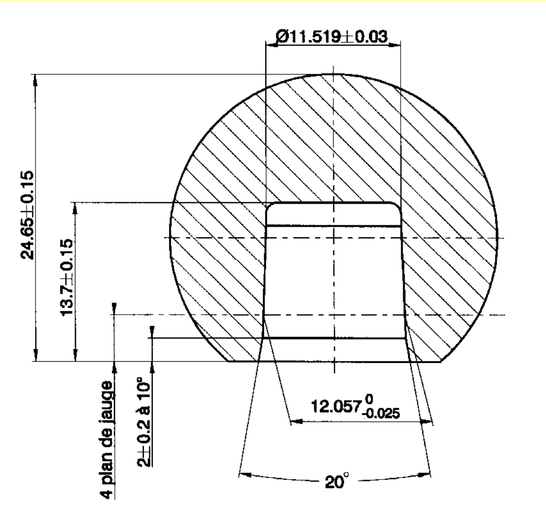
Hot Isostatic pressing and whitening

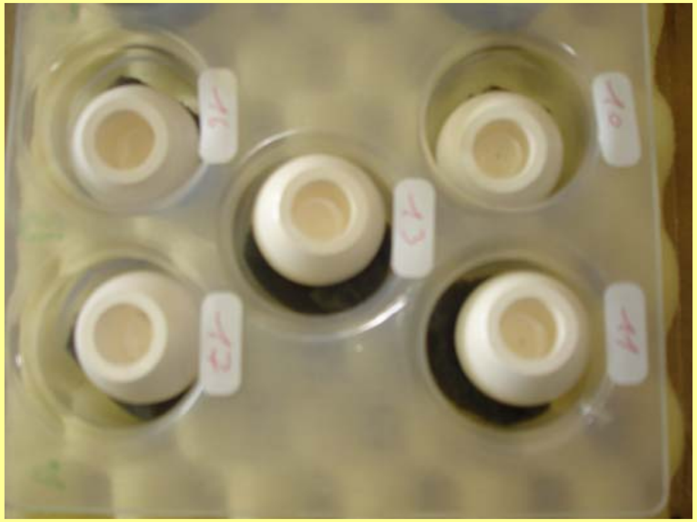
HIP, whitening

Polishing and machining

Polishing

Grinding of the cone

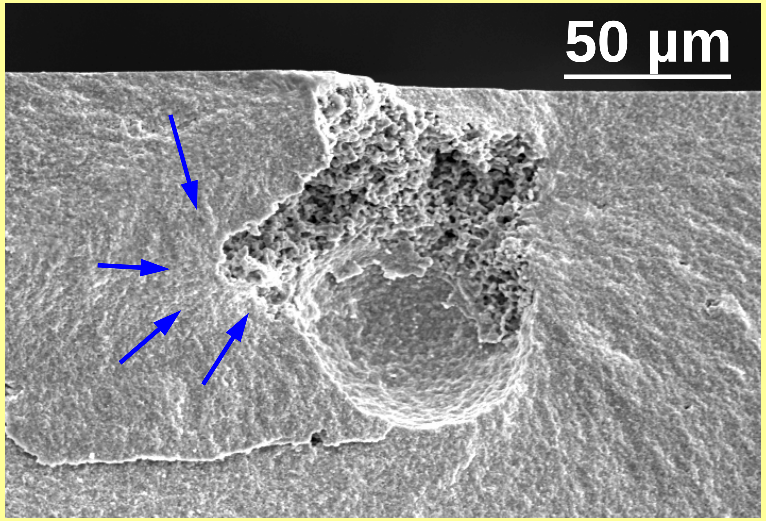




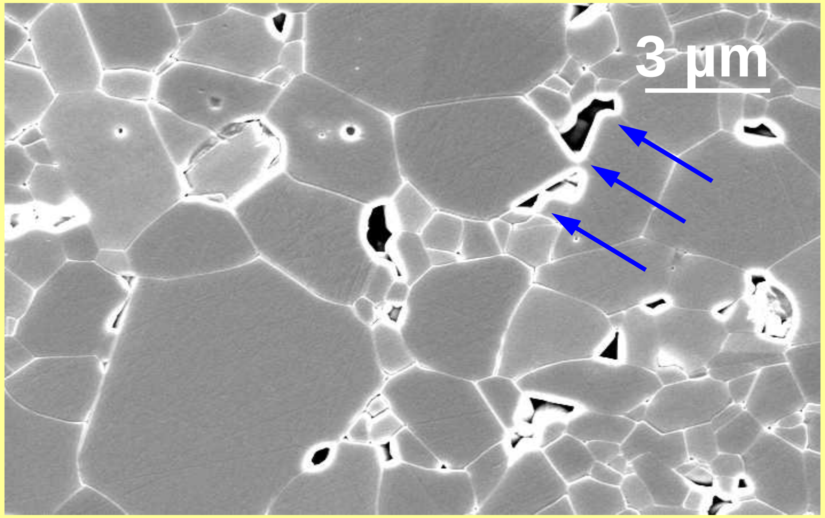
What is a ceramic ? Processing

Flaws in ceramics

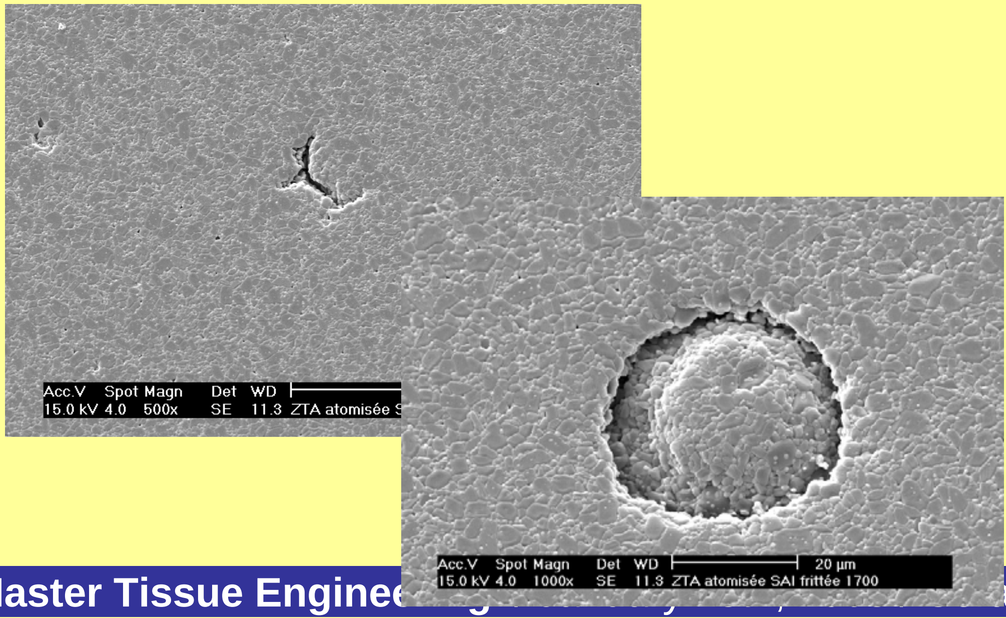
Processing (intrinsic) flaws

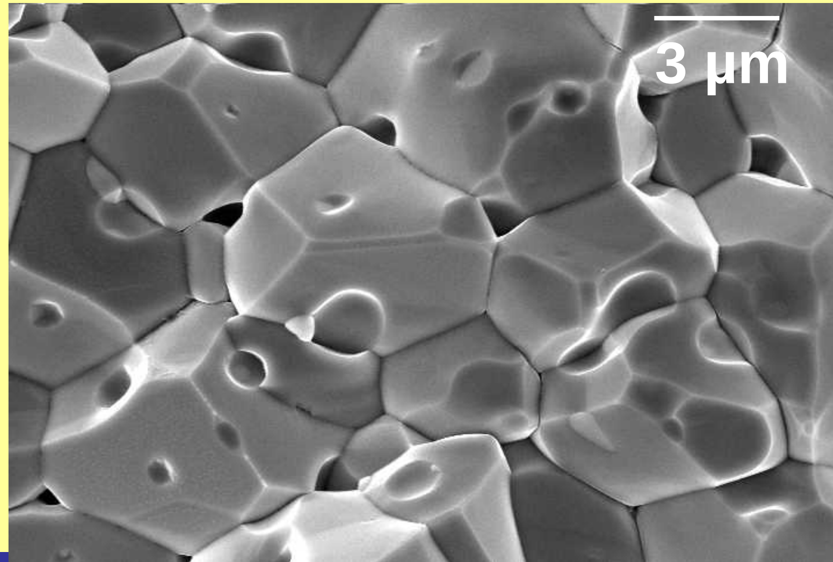


forming



Sintering



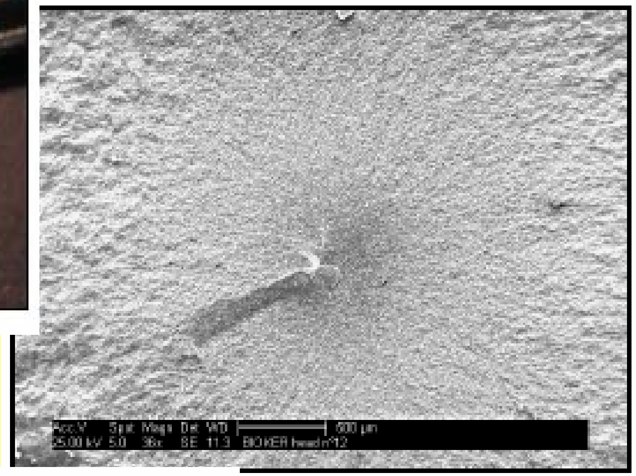


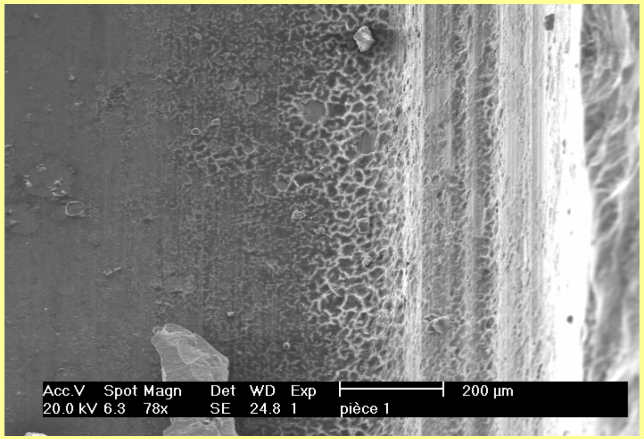
What is a ceramic ? Processing

Flaws in ceramics

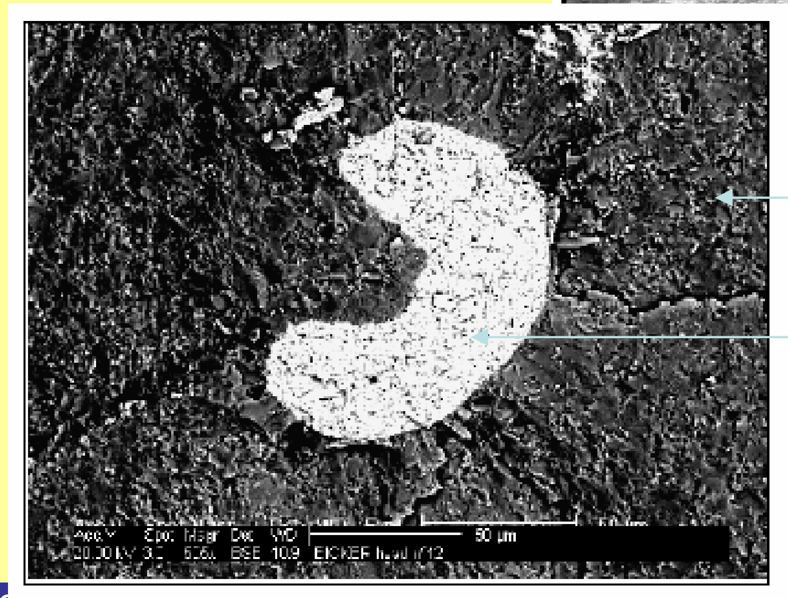
Extrinsic flaws

grinding





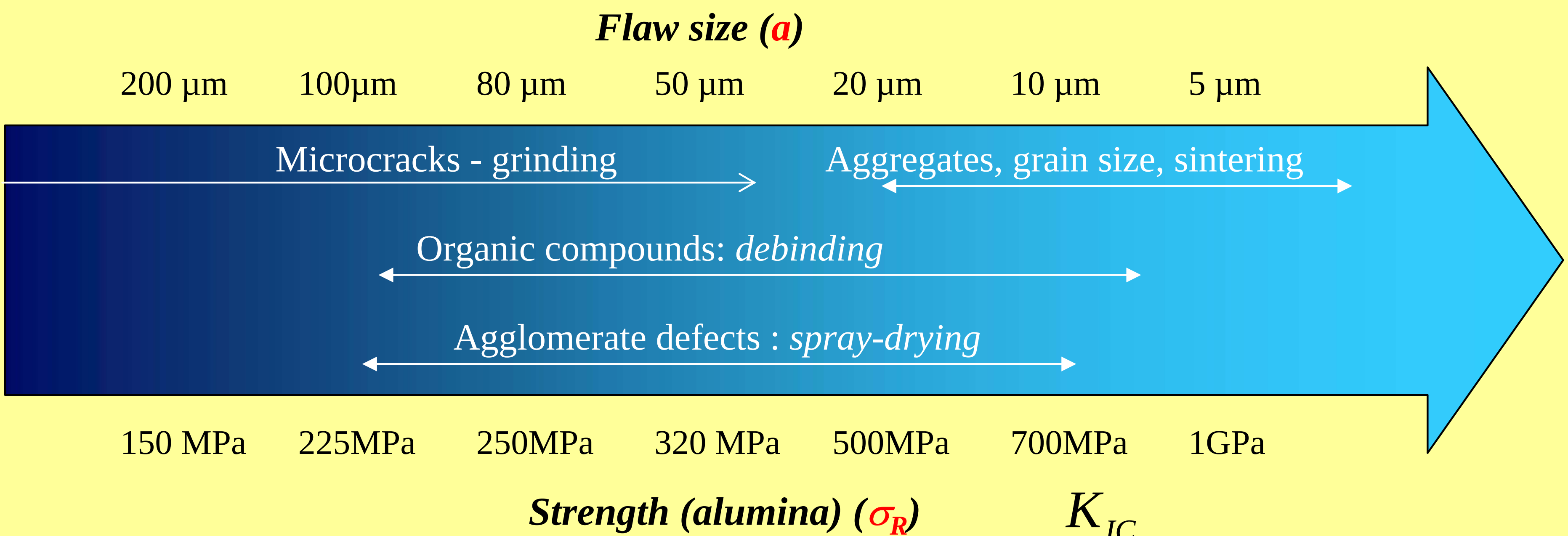
Grinding groove



Processing of ceramics : key role of defects on strength

Each processing step can induce a given type of flaw

Persistance of flaws at the following steps



$$\sigma_R = \frac{K_{IC}}{\sqrt{\pi a}}$$

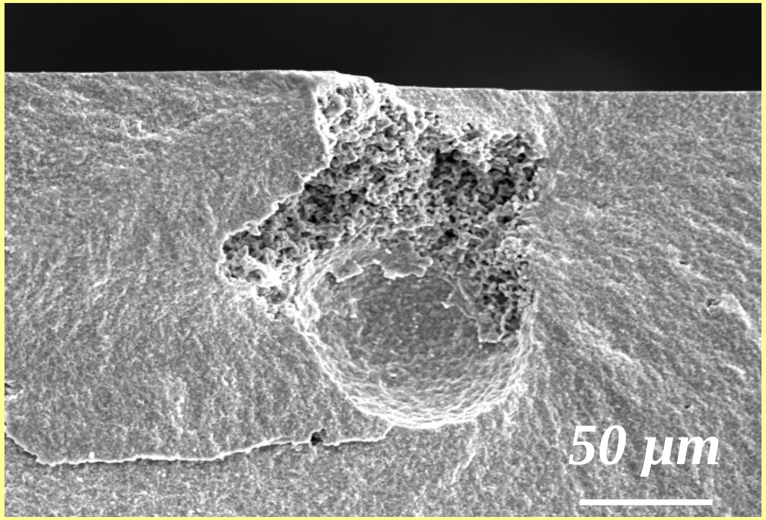
Flaws in ceramics : decrease of strength

What is a ceramic ? Processing

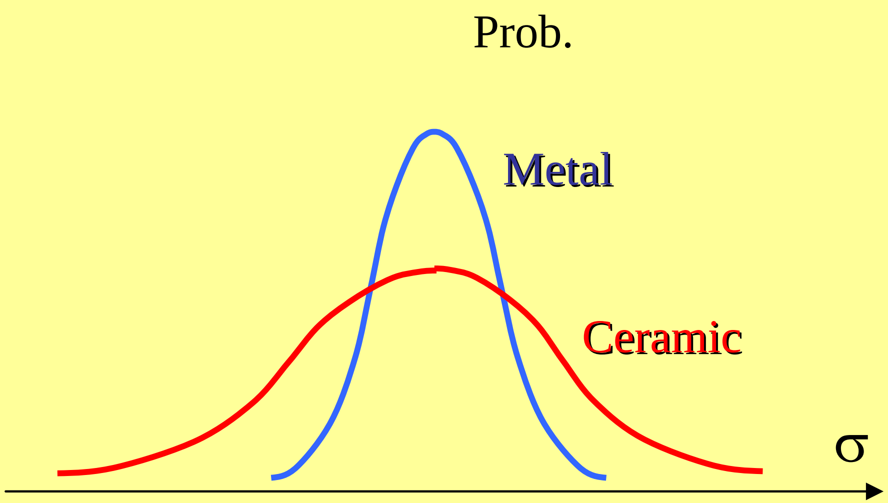
Brittleness of ceramics :
Sensitivity to small defects

metals :	K_{IC} = 100 MPa√m	a_c = 1-10 mm
glasses :	K_{IC} = 0,5 MPa√m	a_c = 100 nm
Alumina :	K_{IC} = 4 MPa √m	a_c = 10 µm

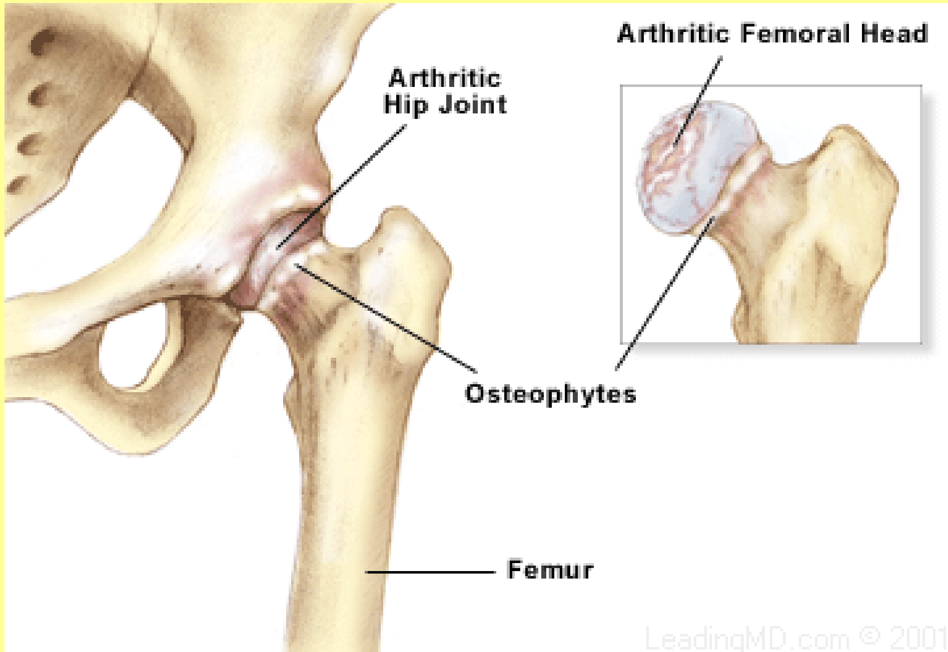
An example of critical flaw

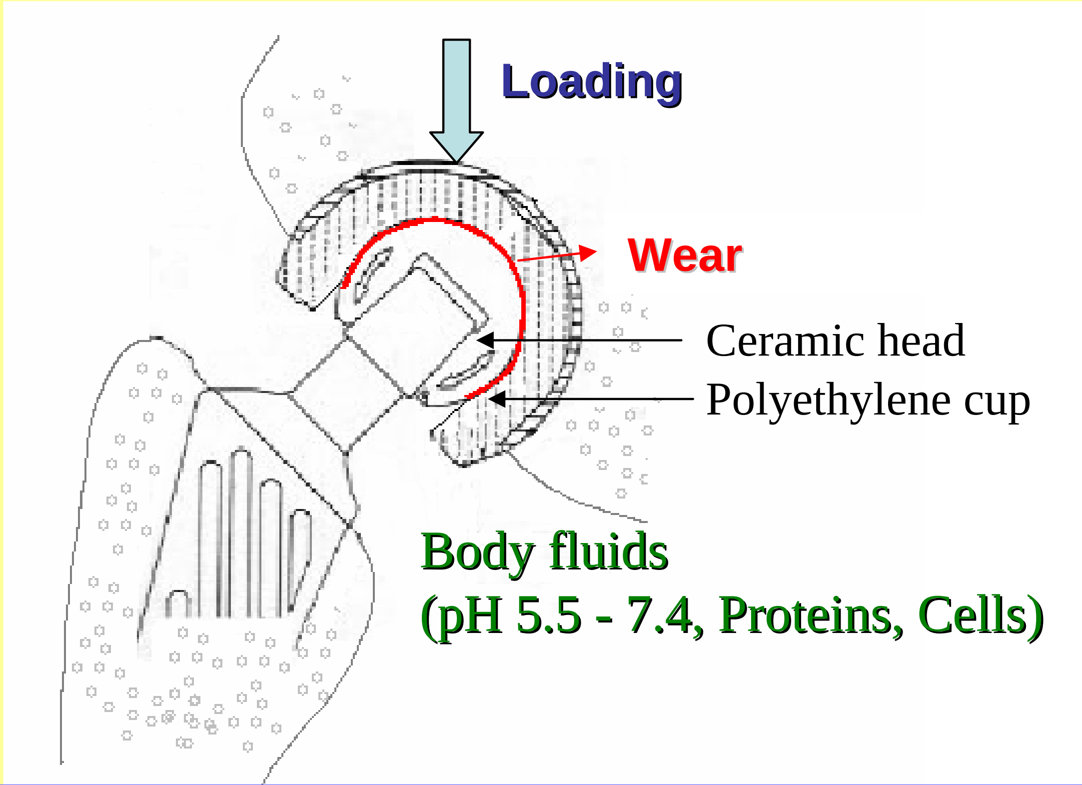


reliability



Application of bio-inert ceramics for orthopaedics





Requirements :	**« Ceramics » issue**
Wear (bearing surfaces)	☺Ceramics : low roughness, ☺Good wettability
Mechanical loading (several times the body weight: *Hip: x 4-10)*	Slow crack growth, Fatigue
Stability (more than 15 years)	Low Temperature Degradation (zirconia) Tribochemical corrosion (alumina)

Chemical inertness : no ion release

Material	Condition	Fe	Ni	Co	Cr	Ti	Al	Zr
316 s.s	Plain	830	190		100			
	Nitrogen Ion implanted	250	95		50			
Co-Cr-Mo	Plain			80	25			
	Nitrogen Ion implanted			130	65			
Ti-6Al-4V	Plain					160	30	
	Nitrogen Ion implanted					185	35	
Al_2O_2	BIOLOX®						0	
ZrO_2	PROZYR®							0
ZrO_2	Monoclinic (coating)							0

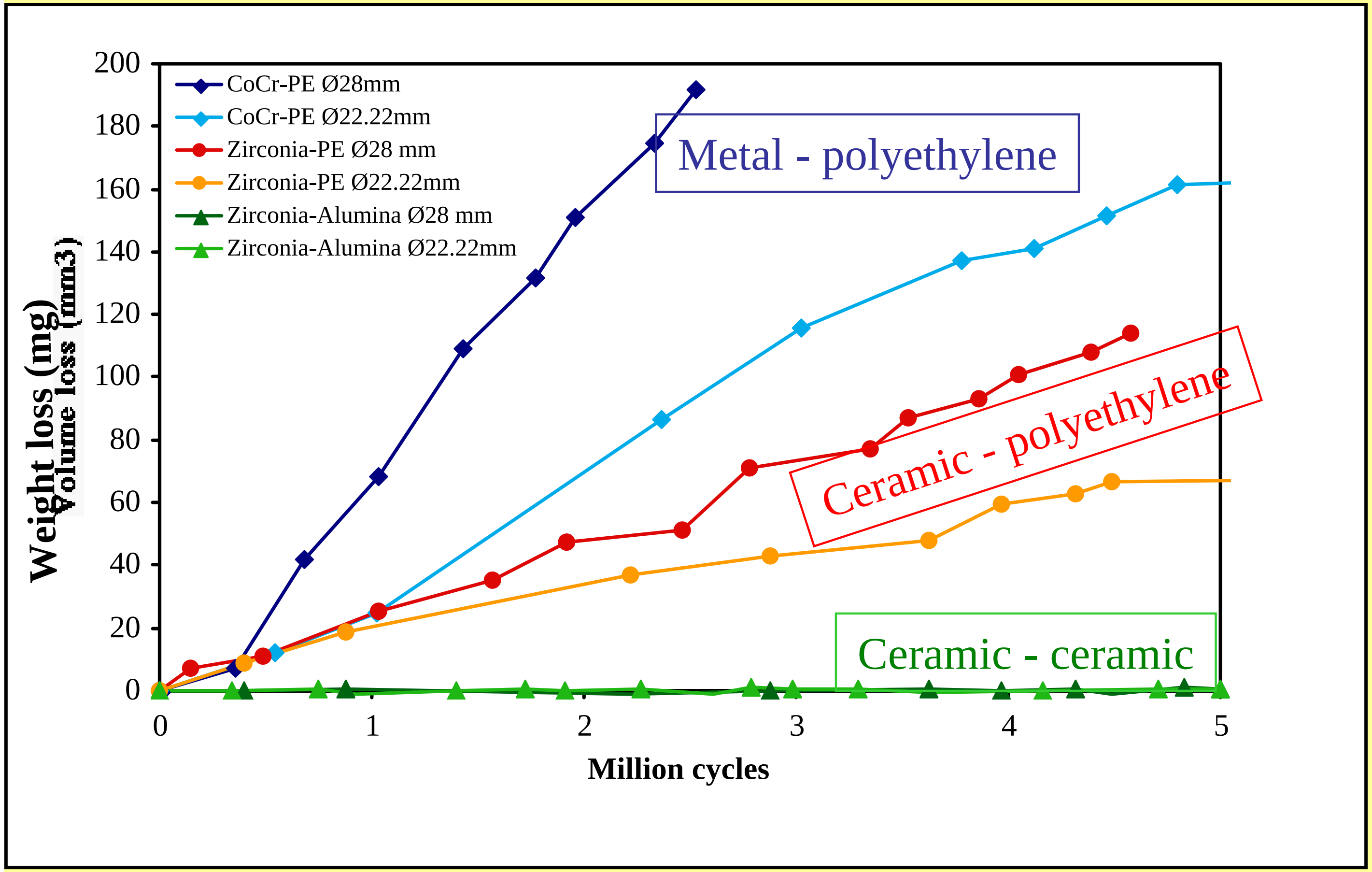
Application of bio-inert ceramics for orthopaedics

- More than 2 millions alumina femoral heads
- 500.000 zirconia heads (yttria stabilized)
- Under strong development (i.e. Biolox Delta) :
  - Alumina-zirconia composites and nano-composites

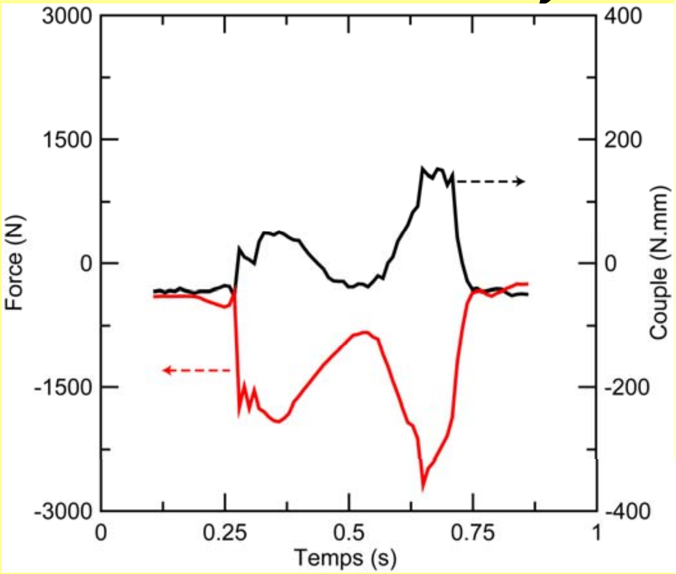
Application of bio-inert ceramics for orthopaedics / wear

Wear is the main issue in orthopaedics

The major advantage of ceramics : low wear debris generation



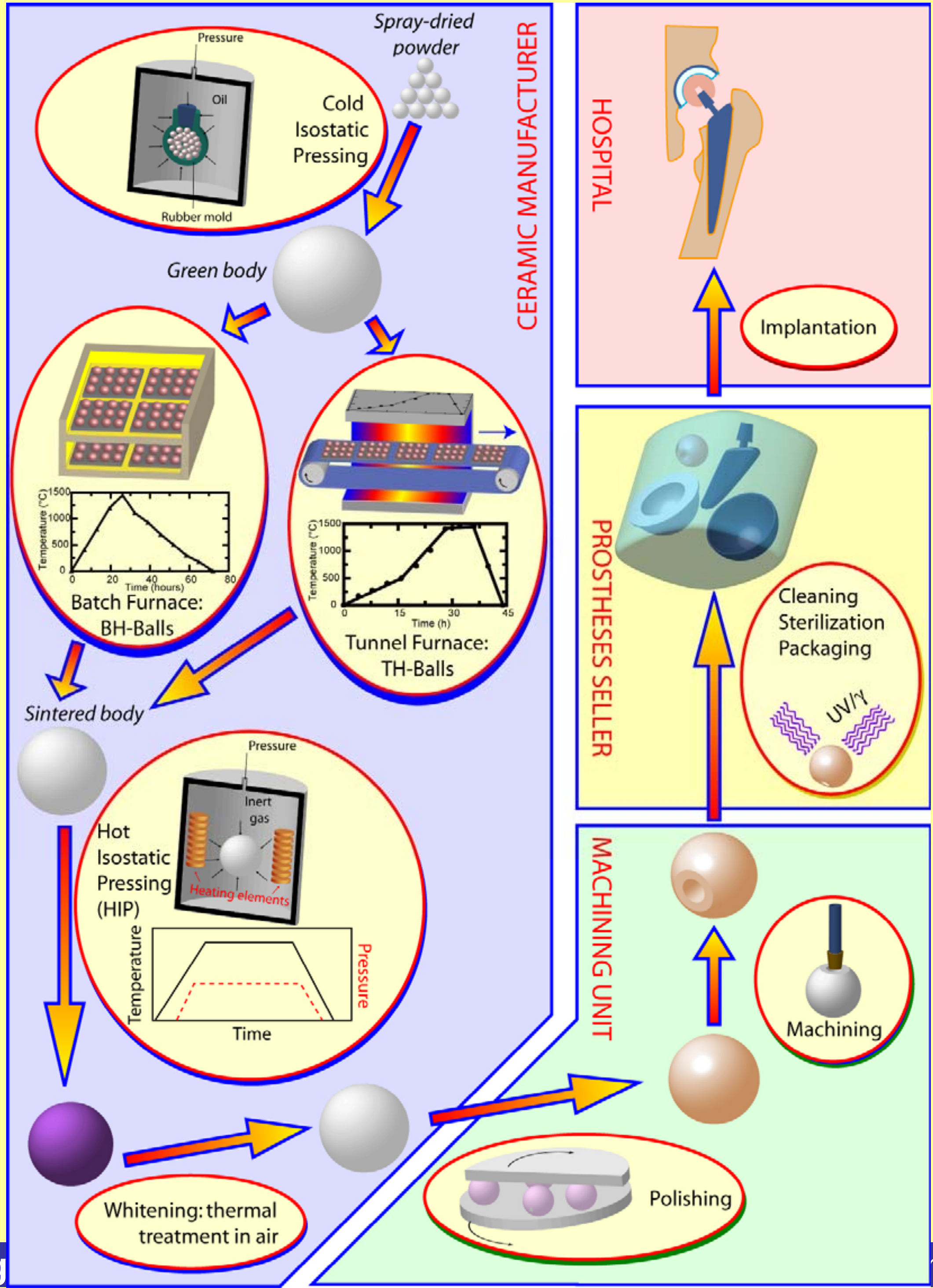
4 Stations Hip simulator of MATEIS Laboratory



Wear testing

- Experimental characterisations of wear :
  - Weigth loss (mass of debris generated)
  - Surface observations (SEM, AFM, Optical interferometry)
  - Surface modifications - phase transformations (X-Ray, Raman spectro.)
  - Analysis of wear debris
- The mass of debris is low (some mg / year), but the number of debris huge (billions)

Application of bio-inert ceramics for orthopaedics / fracture



Application of bio-inert ceramics for orthopaedics / fracture

The major drawback of ceramics : Risk of fracture in vivo

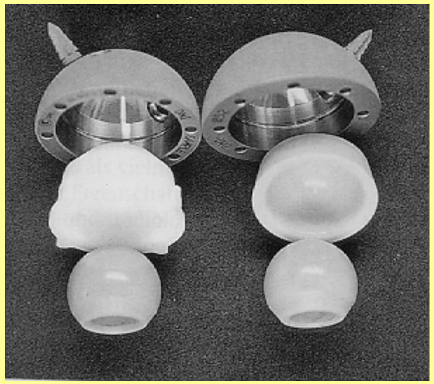
Reminder : failure in vivo is not acceptable !

Heros, Willman

1970 - 1990 : 0,2 % (Biolox) to 13,4 % (9 / 67 - ‘ Rosenthal ’ model)

1990 - 2000 : 0 % (Biolox) to 2,4 % (Ostalox)

Analysis on 1.000.000 Biolox heads (forte) : 0,02%



Fritsch, Gleitz

Alumina - alumina : 0,7%

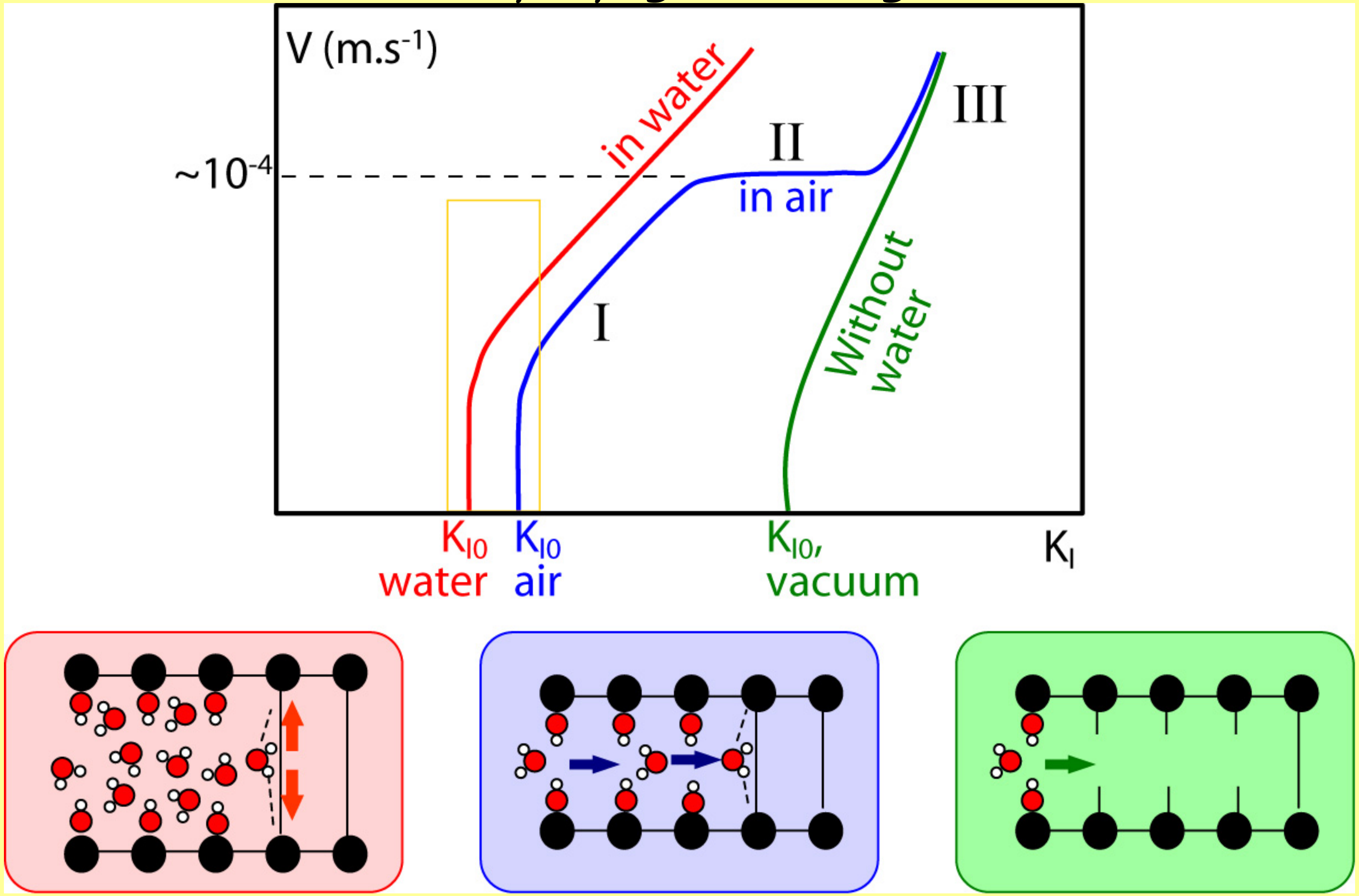
Alumina : K_{IC} = 4 MPa√m

Zirconia : K_{IC} = 6 MPa√m (phase transformation toughening) : increasing use over the 90 ’s

Application of bio-inert ceramics for orthopaedics / fracture

The major drawback of ceramics : Risk of fracture in vivo

*Slow Crack Growth : three propagation stages and **threshold***



Griffith criteria : higher water content means lower threshold

Alumina : K_{IC} = 4 MPa√m **K_{I0} = 2.5 MPa√m** **K_{I0} / K_{IC} ~ 0.6**

Zirconia : K_{IC} = 6 MPa√m **K_{IC} = 3.1 MPa√m** **K_{I0} / K_{IC} ~ 0.5**

Application of bio-inert ceramics for orthopaedics / fracture

Durability and reliability of ceramic implants

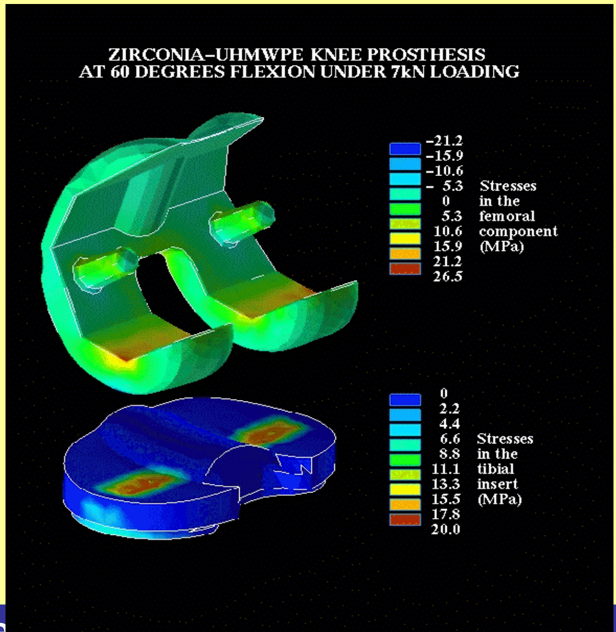
Threshold, defect size, and safety stress limit

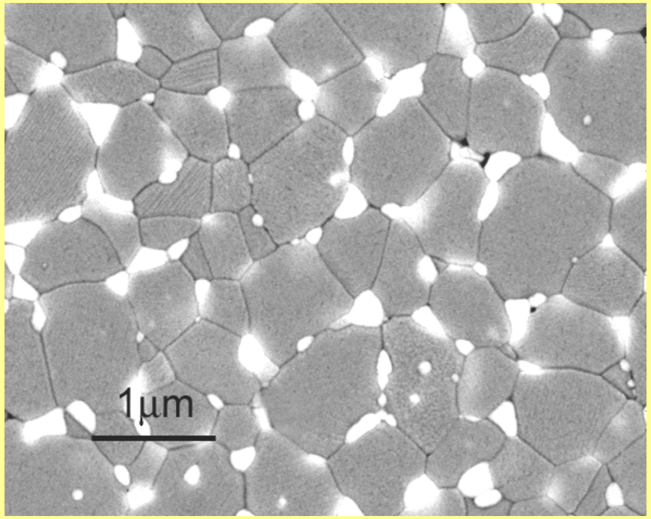
No fracture in-vivo if :

$$\sigma_{applied} < \sigma_{threshold}$$

with : $$\sigma_{threshold} = \frac{K_{I0}}{\sqrt{\pi \cdot a}}$$

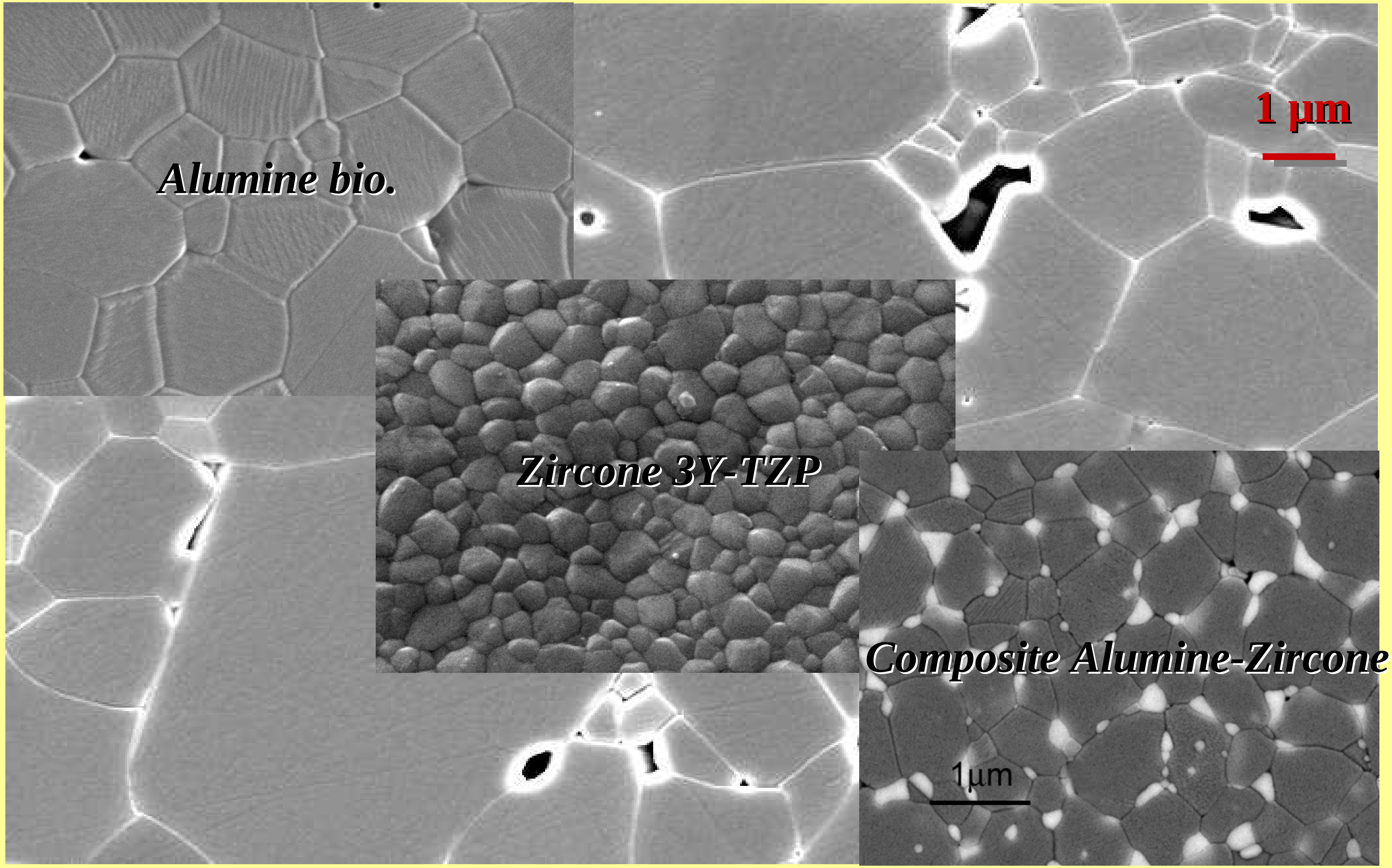
Defect size (a)





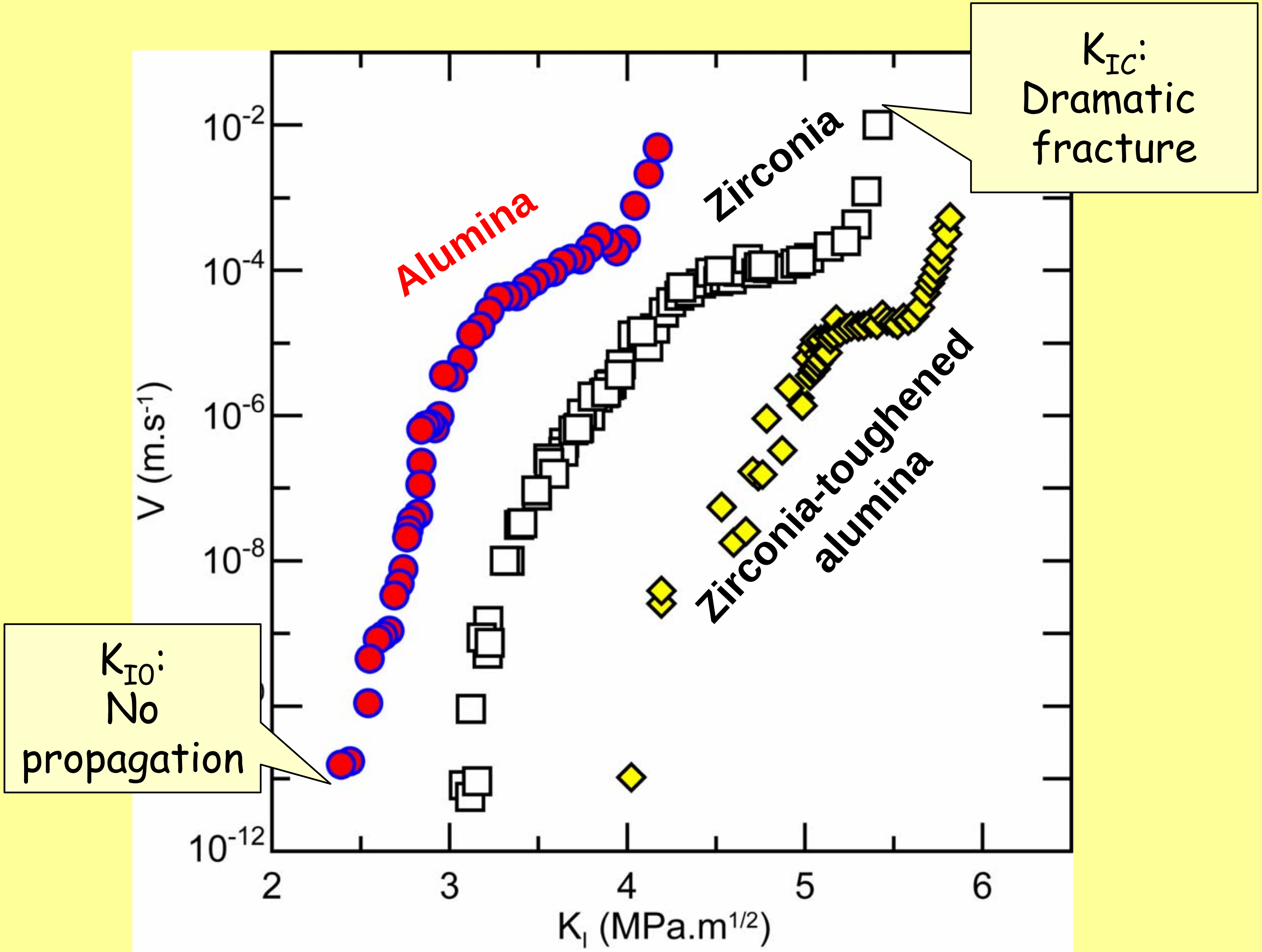
ZTA composite for biomedical applications obtained via colloidal processing

Application of bio-inert ceramics for orthopaedics / fracture



Application of bio-inert ceramics for orthopaedics / fracture

Comparison of current bio-inert ceramics

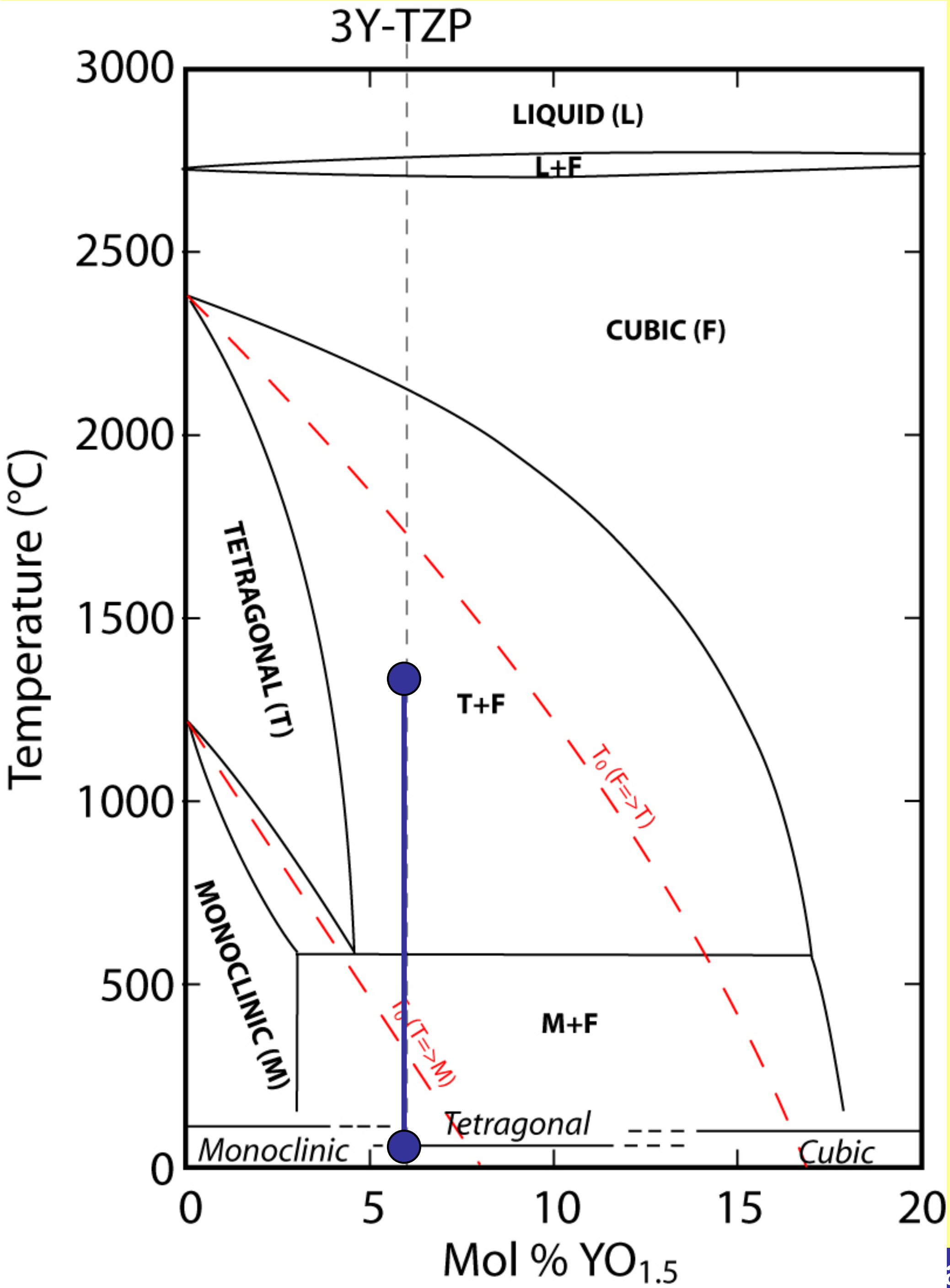


Zirconia Toughened alumina composites offer today the largest threshold

Main reasons for failure of zirconia hip prostheses:

- Fracture:
  - very low rate until 2001 (< 0.1% ?)
  - ~400 fractures since 2001
  - due to:
    - shock
    - accelerated aging
- Aseptic loosening
  - main cause of revision surgery
  - due to osteolysis triggered by wear debris

Application of bio-inert ceramics for orthopaedics / Zirconia



Stable phase at room temperature : monoclinic phase

↓

processing : t – m transformation => fracture

⇓

yttria addition :

3Y-TZP : t phase + cubic (~ 14 %); metastable

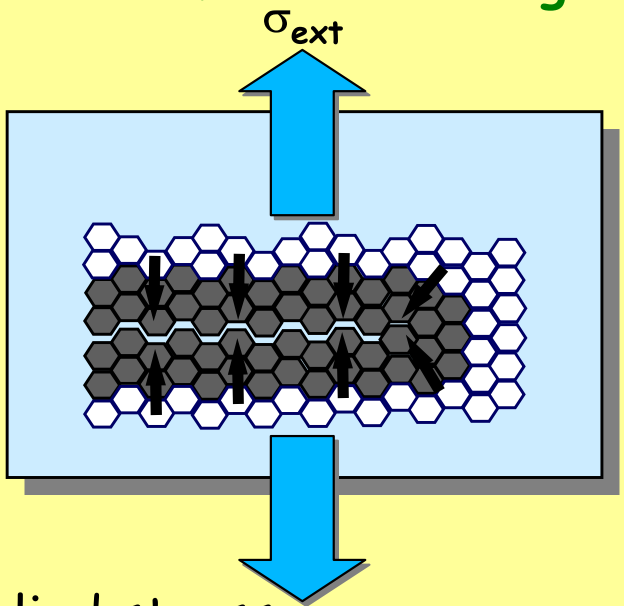
↓ *stresses* *water*

m phase

Application of bio-inert ceramics for orthopaedics / Zirconia

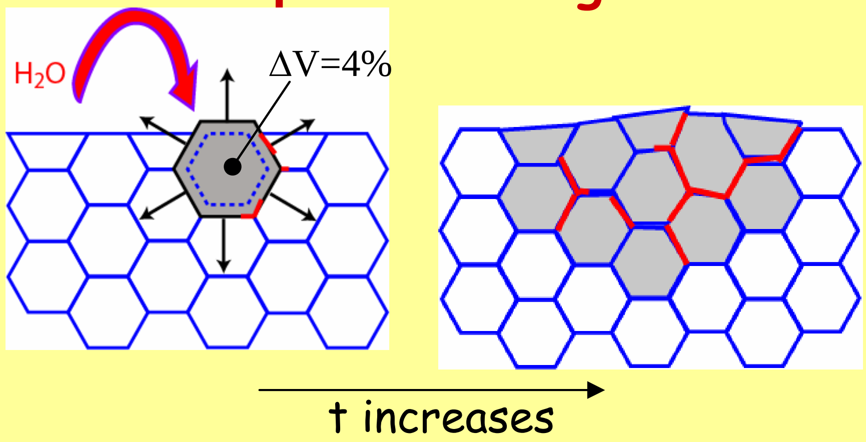
2 faces of zirconia phase transformation

Phase transformation toughening:



- Applied stress
- Stress concentration around the crack tip
- t-m transformation around the crack tip
- Crack tip under compression
- **The crack slows down**

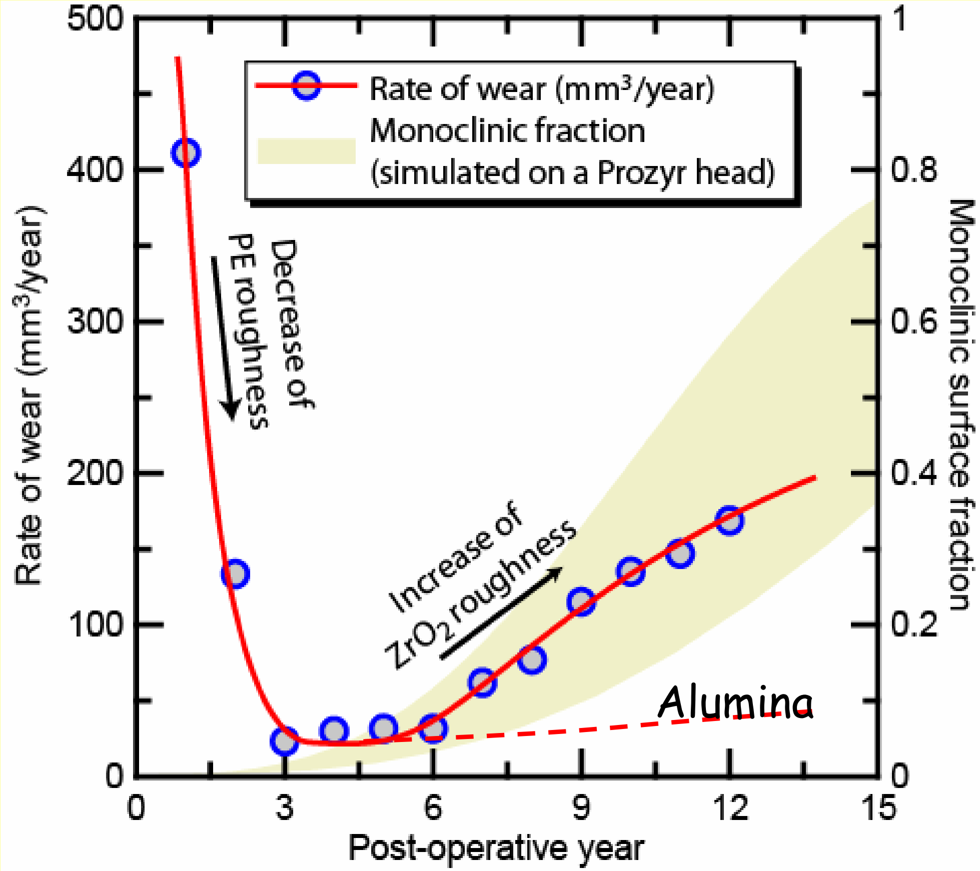
Low temperature degradation



- Presence of water
- Transformation of surface grains
- **Surface uplift**
- **Microcracking**
- Access of water to deeper grains
- Extension of the transformation toward the bulk
- Apparition of bigger surface defects
- Roughening and production of wear debris

Material	Cubic zirconia	Mullite	Alumina	Y-TZP	Ce-TZP
Toughness (SENB)	1.5 $MPa.m^{1/2}$	2 $MPa.m^{1/2}$	4 $MPa.m^{1/2}$	6 $MPa.m^{1/2}$	10 $MPa.m^{1/2}$

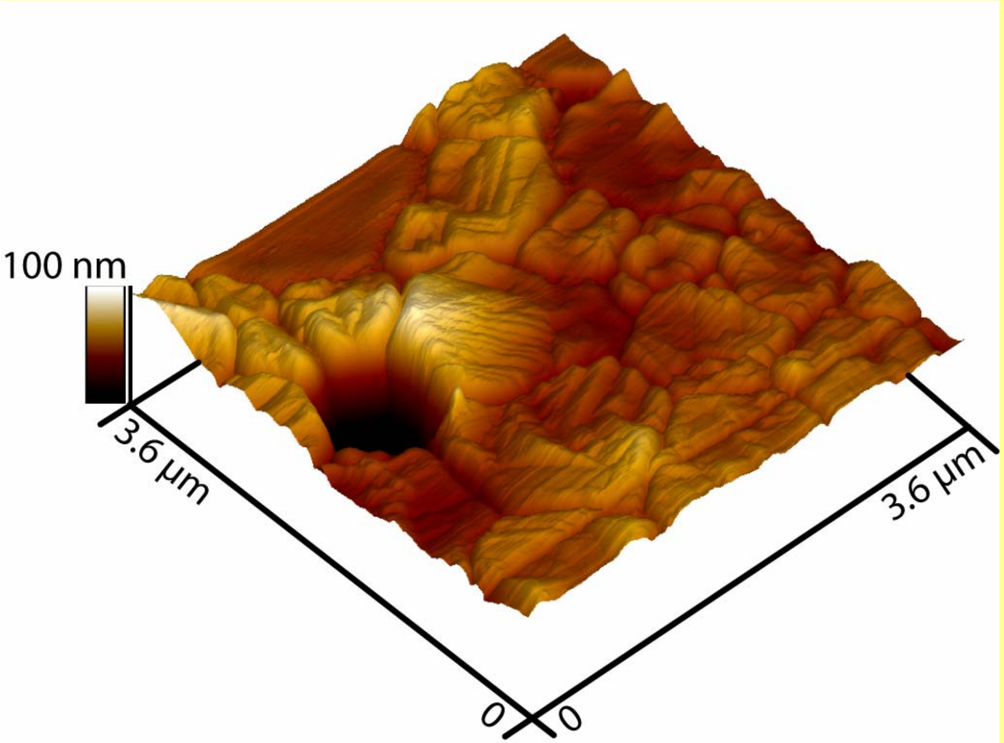
Evolution of wear in zirconia – PE hip prostheses



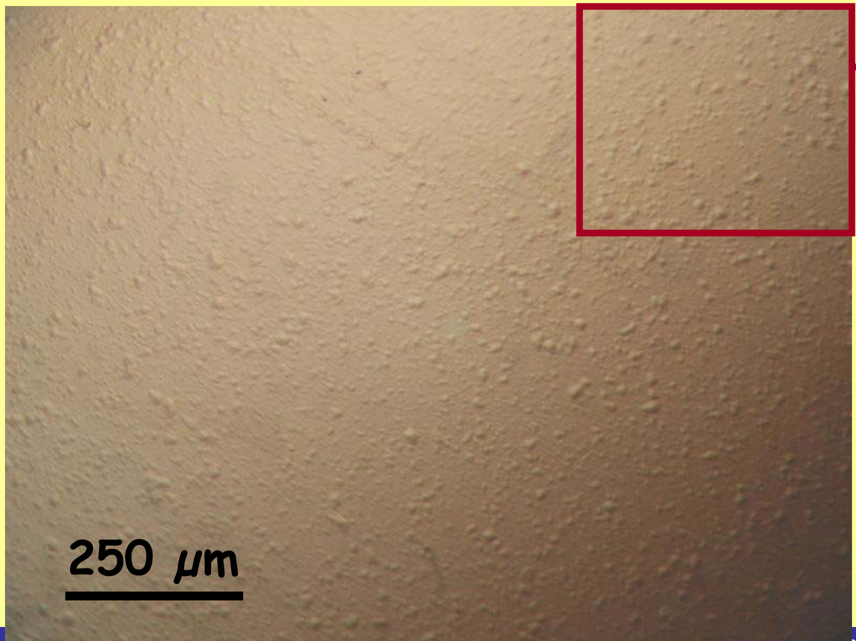
After Hernigou et al. J. Bone Joint Surg Br 2003

- Correlation between
  - the degradation of the wear behaviour after 5-6 years and
  - the increase of Zirconia roughness due to aging.

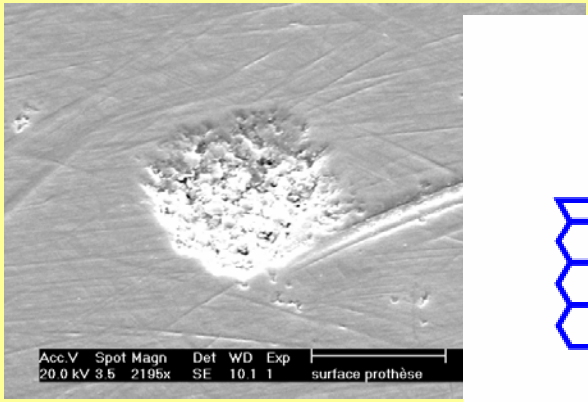
Application of bio-inert ceramics for orthopaedics / Zirconia

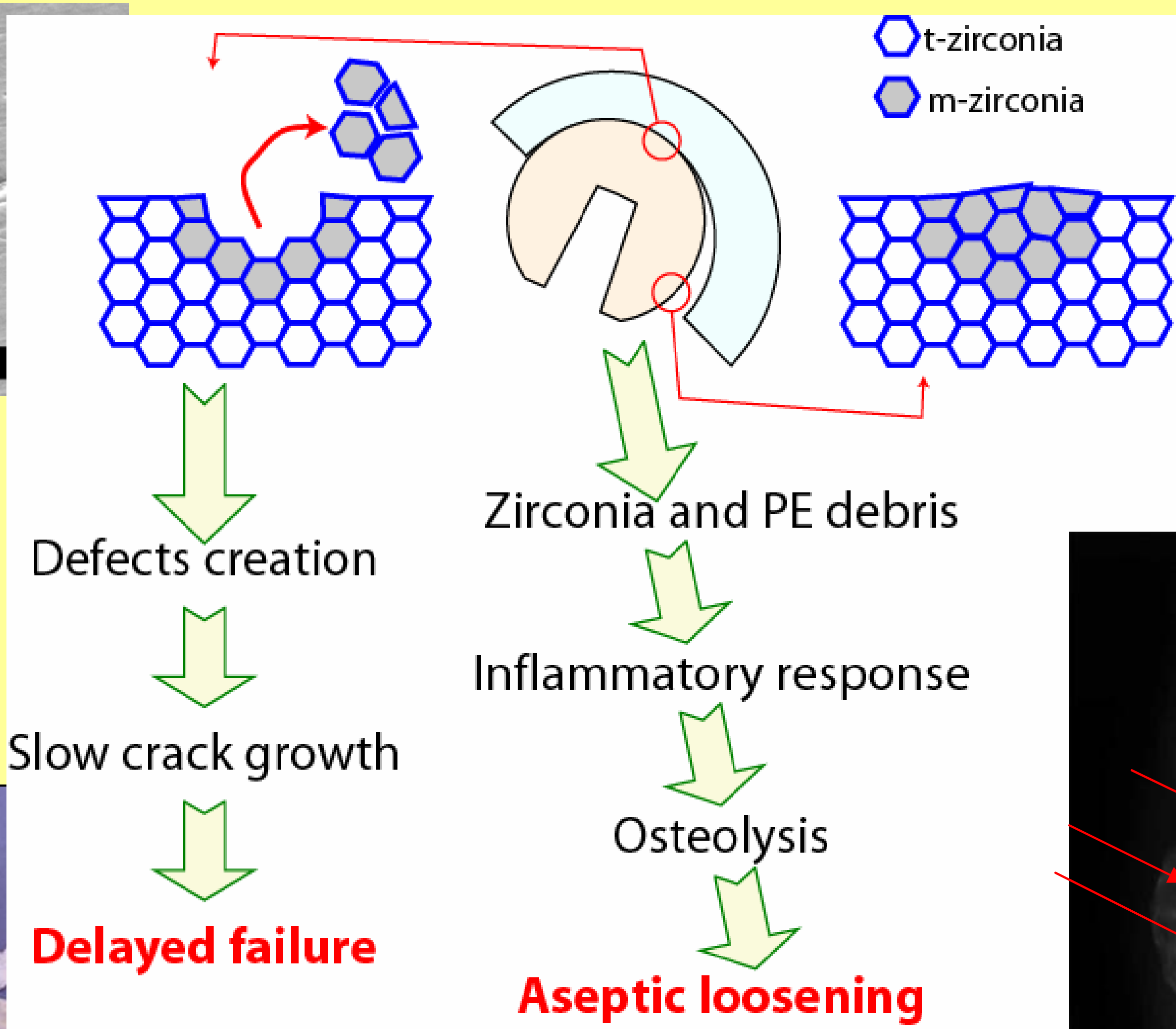


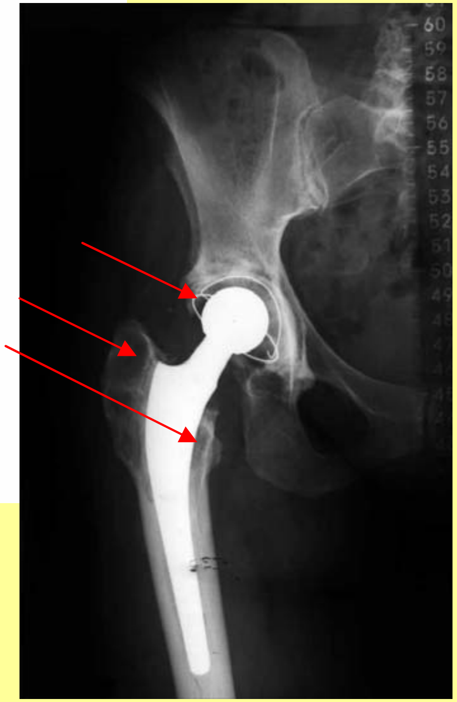
- Evidences for roughening
  - extensive grain pull out
  - surface uplifts



Consequences of aging on zirconia implants

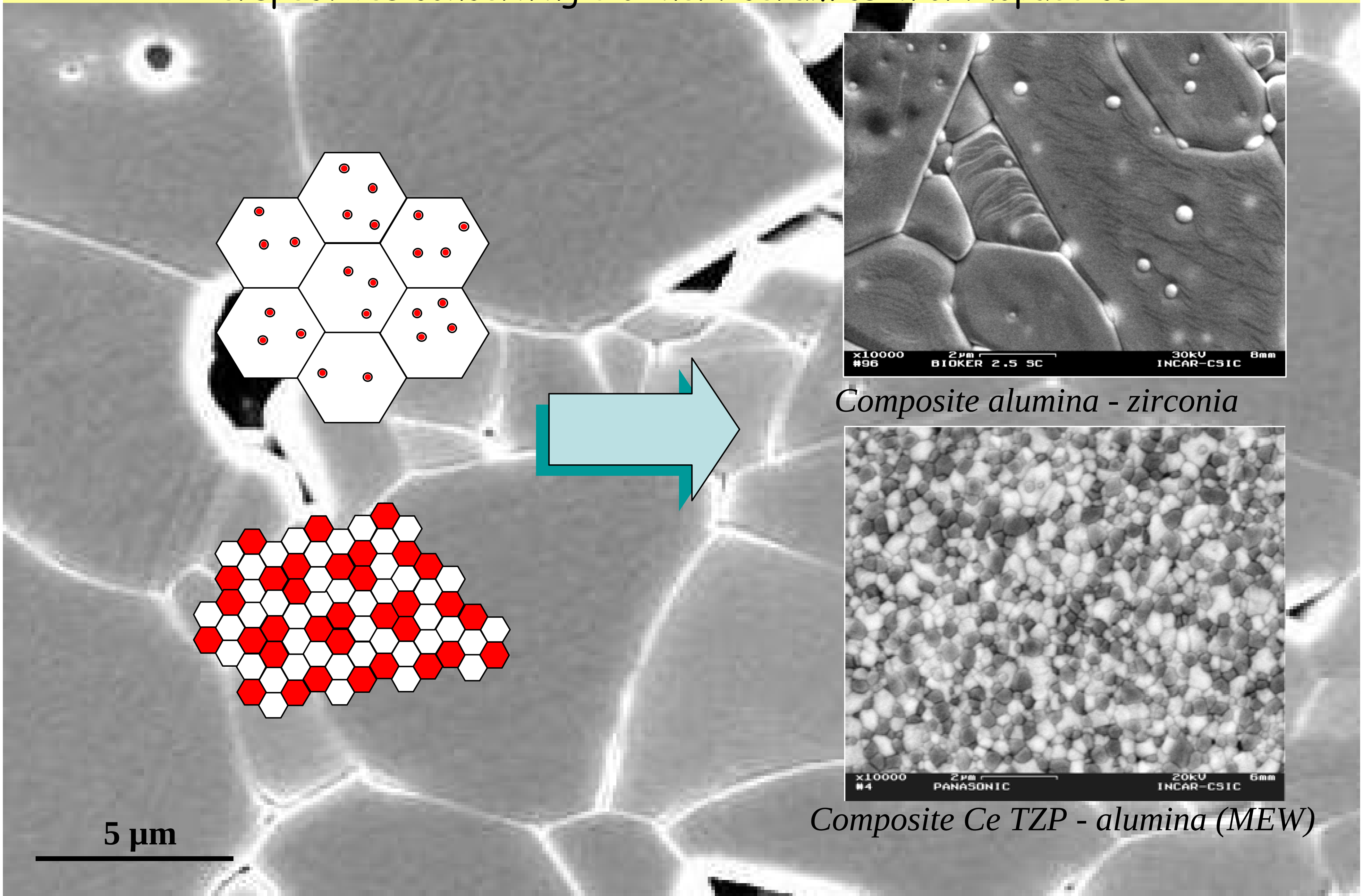






Application of bio-inert ceramics for orthopaedics / Perspectives

Perspectives concerning bio-inert ceramics in orthopaedics :

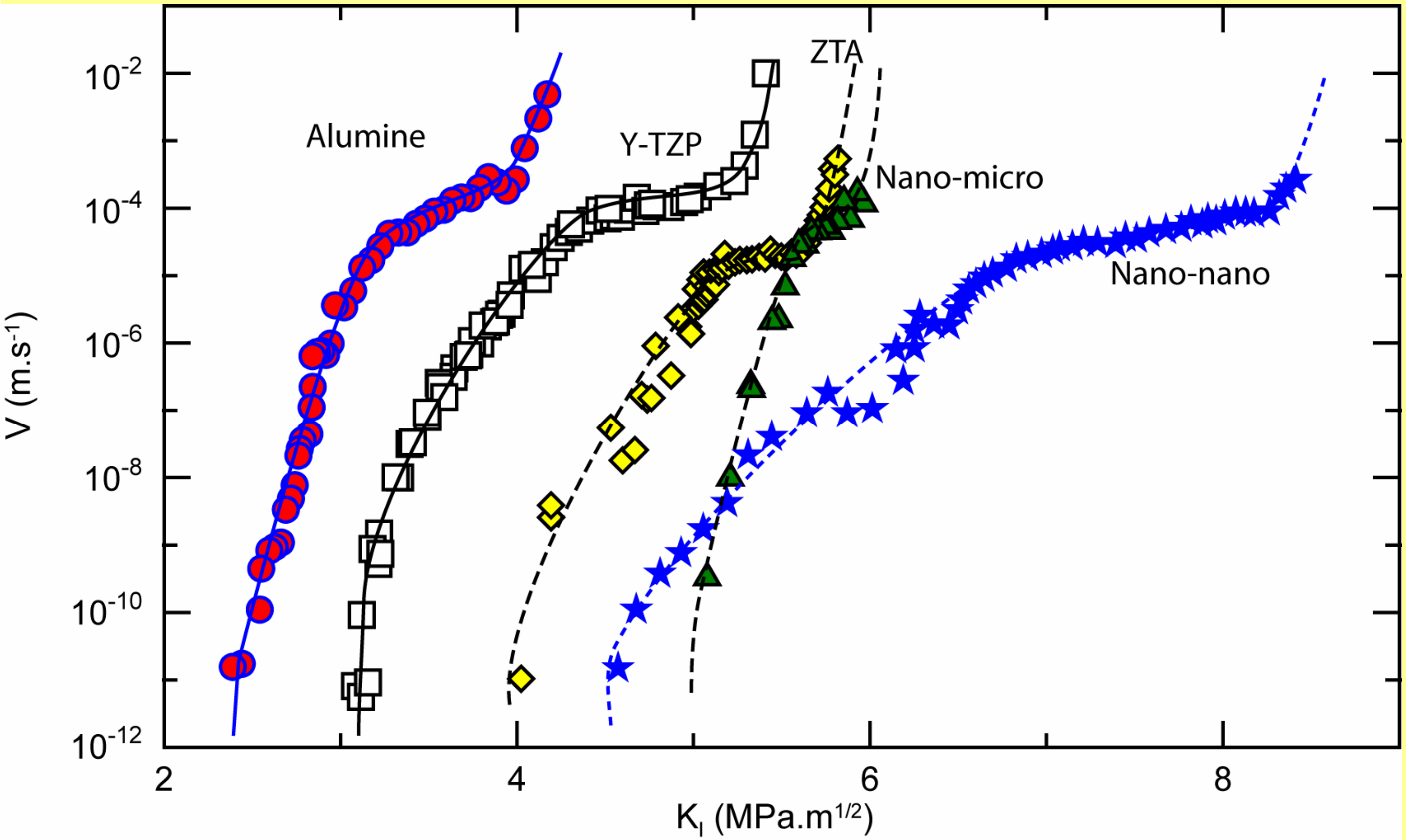


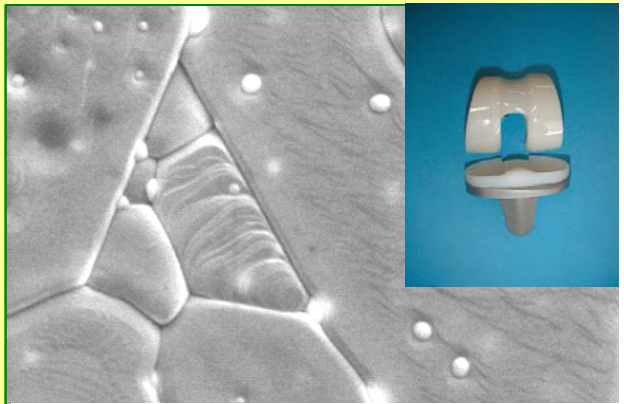
Composite alumina - zirconia

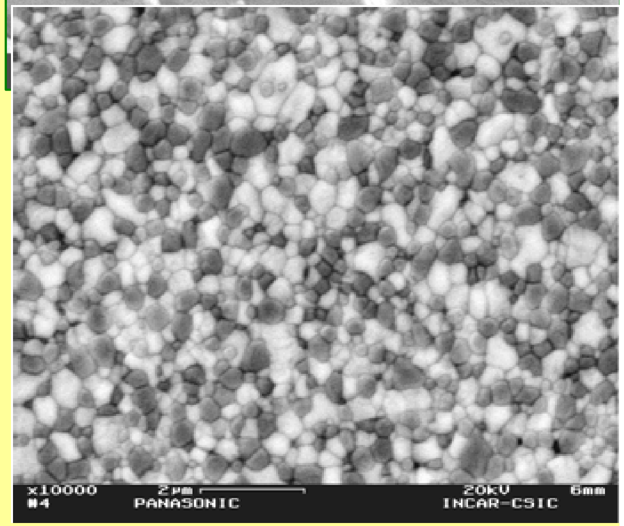
Composite Ce TZP - alumina (MEW)

Perspectives concerning bio-inert ceramics in orthopedics :

Alumina - zirconia composites and nano-composites with high threshold





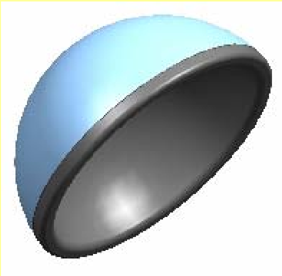


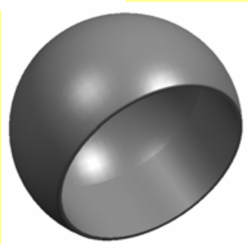
Wider range of designs, hip and knee resurfacing implants (minimally invasive surgery)
First clinical use of a ceramic knee prosthesis

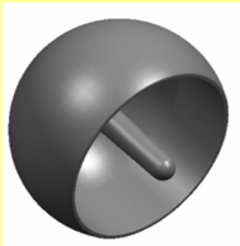
Perspectives concerning bio-inert ceramics in orthopaedics :

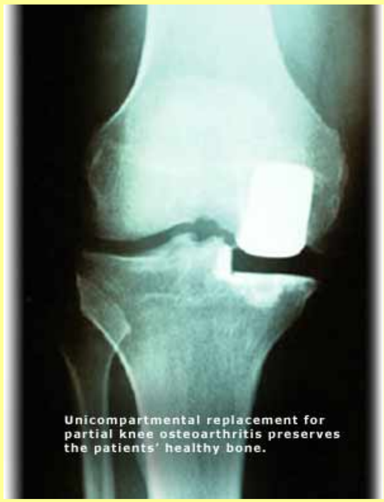
New device concepts

New device concepts: resurfacing systems for MIS









The search for a positive effect on tissue response

Bio-active ceramics : synthetic materials with a composition near or identical to the mineral part of bone.

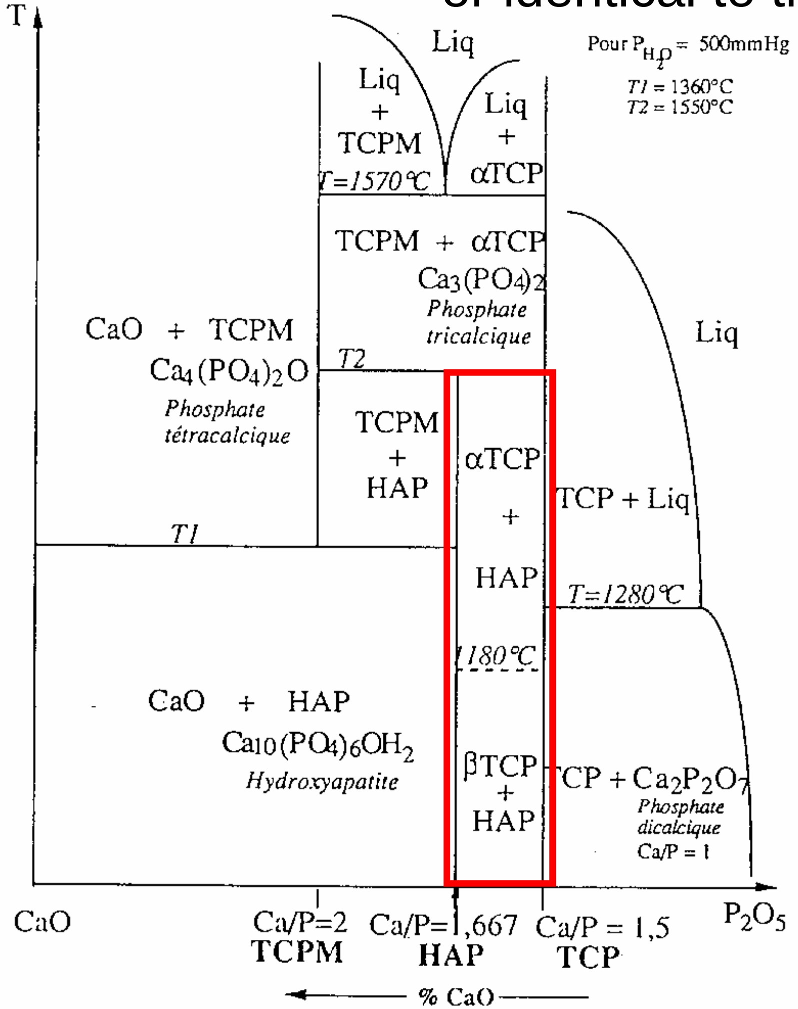


Fig. 4 Diagramme de phases du système CaO-P_2O_5 phases cristallines des différents phosphates calciques présents en fonction de la composition et de la température.

Hydroxyapatite *(no resorption)* : HAP

$Ca_{10}(PO_4)_6OH_2$

Tricalcium phosphate*(resorbable)* : TCP

$Ca_3(PO_4)_2$ α-TCP and β-TCP

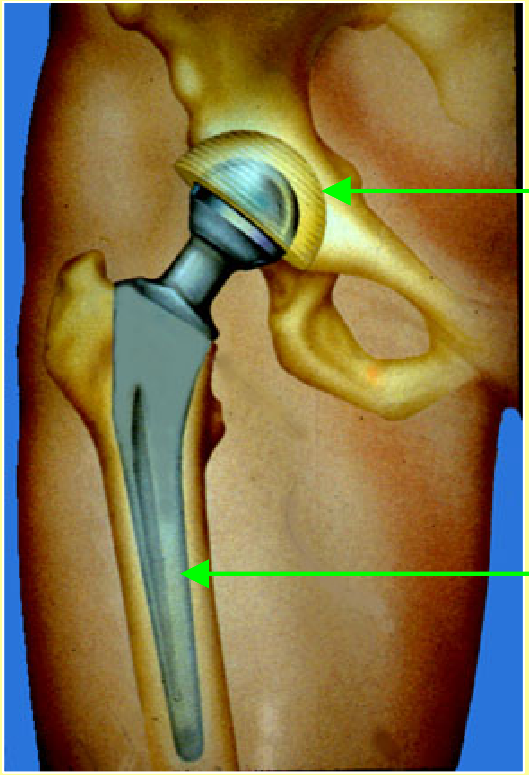
Resorption rates :

HAP < β-TCP < α-TCP

Others : DCP (monetite), TCPM …
Bio-glasses
} *Not yet in orthopedics*

Bio-active ceramics / Coatings

Bio-active coatings on 'non-cemented' prostheses



Before 80's :

Acrylic cement or macro-porous surface

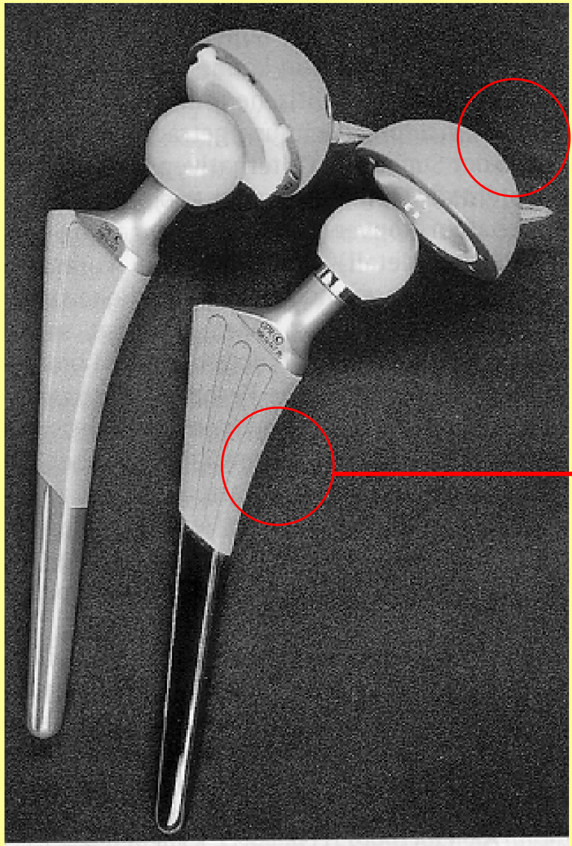
Today's :

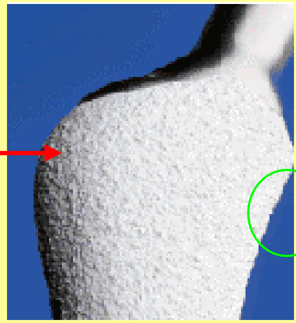
Increasing use of Hydroxyapatite on rough or micro-porous surfaces

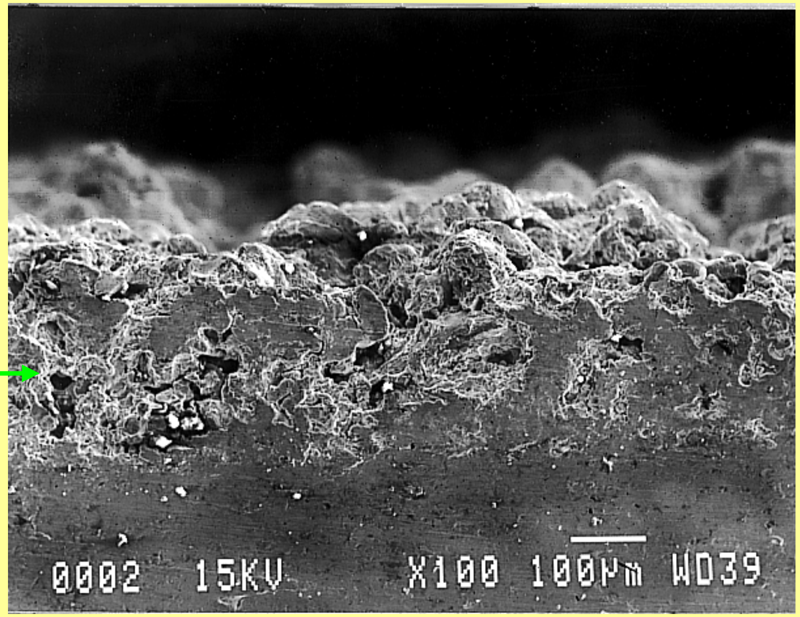
Clinical results after 15 years use :

- excellent for young patients (< 50 years old) : ~ 95 % success after 10 years
- moderate for old patients (needs bone healing prior to walk)

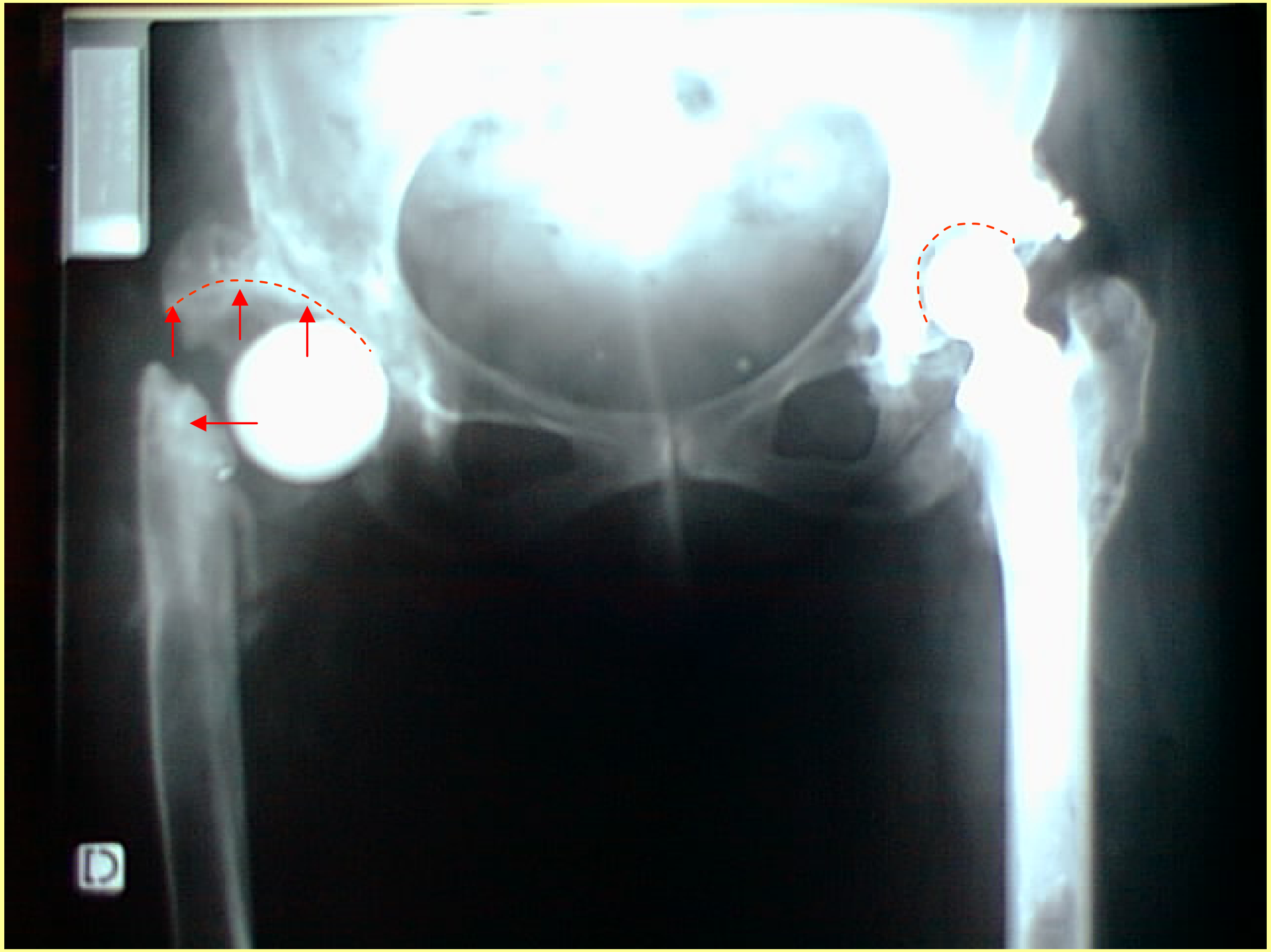
Bio-active coatings on 'non-cemented' prostheses

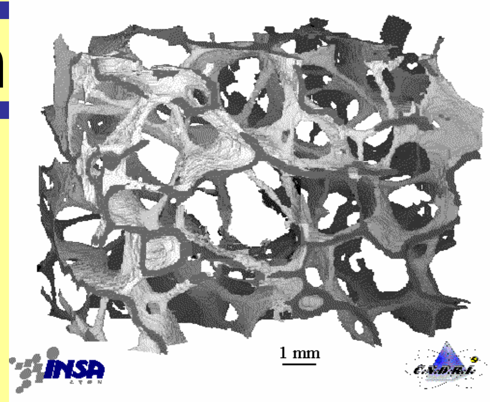






Bone substitutes in revision surgery

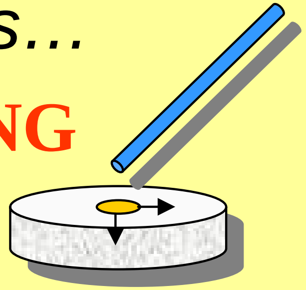


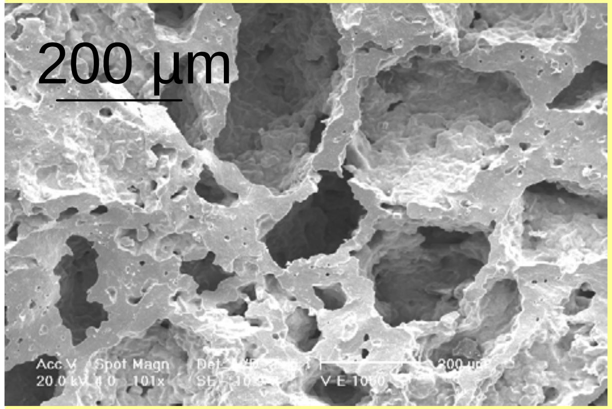


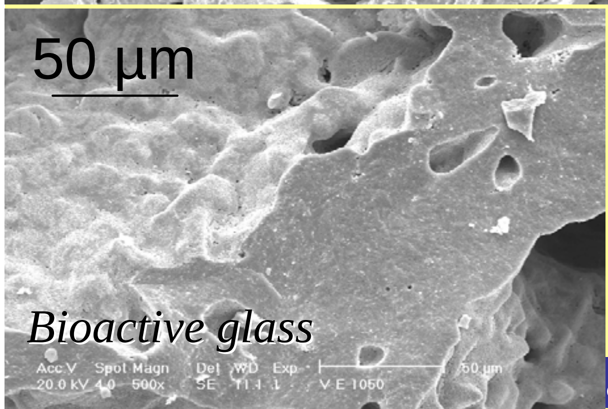
Bio-active ceramics / Bone substitution

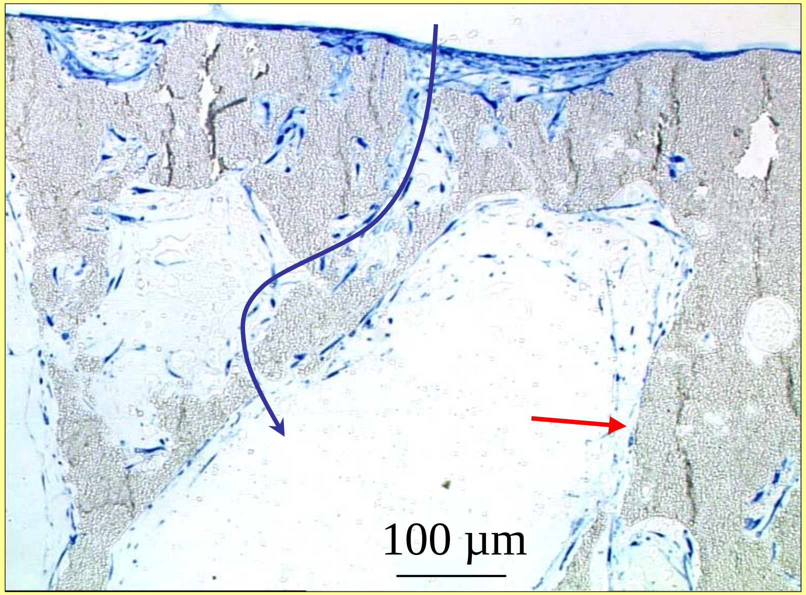
- *Processing of porous bone substitutes mimicking bone architecture (structure and composition)*
- *Cell culture*
- *Incorporation of chemicals and cells…*

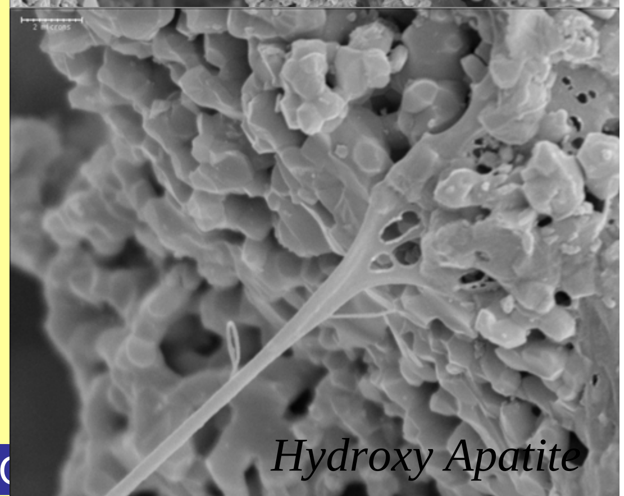
TOWARD TISSUE ENGINEERING





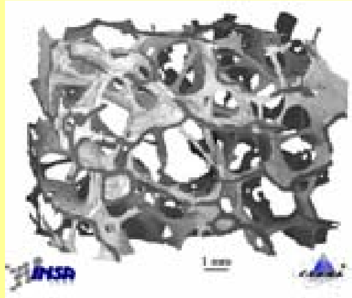






Bio-active ceramics / Bone substitution

Processing of porous bone substitutes
…Trying to mimic the bone architecture...



stirring

HAP Powder → stirring
TCP Powder → stirring
Dispersing agent → stirring
water → stirring

↓

Strengthening agent

↓

Porogen particles - or foam

↓

casting

↓ *(drying - 40°C)*

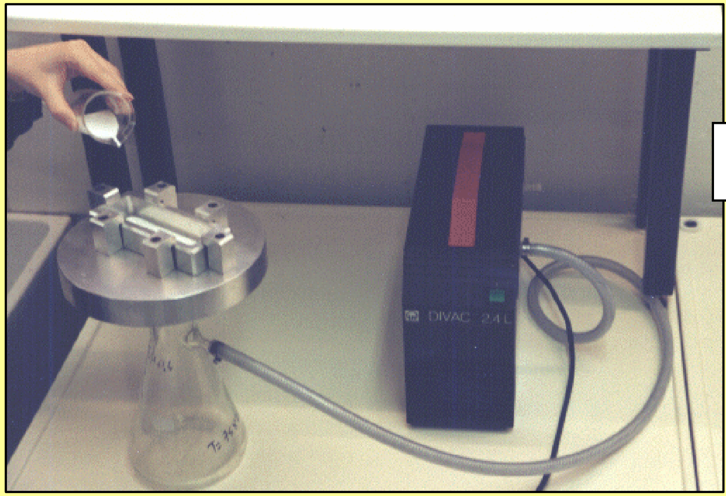
Debinding

↓ *(600°C)*

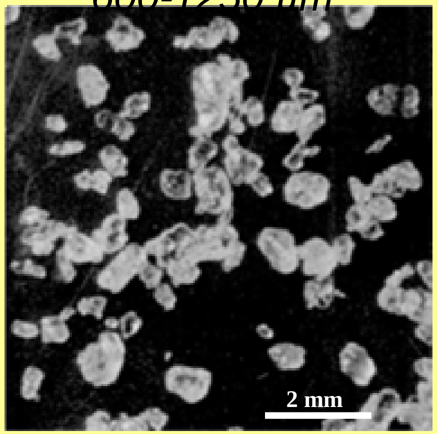
Sintering

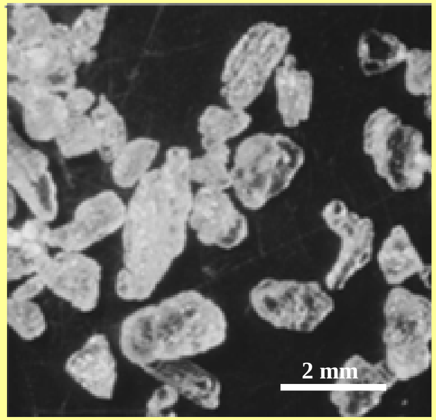
↓ *(1200°C)*

Machining

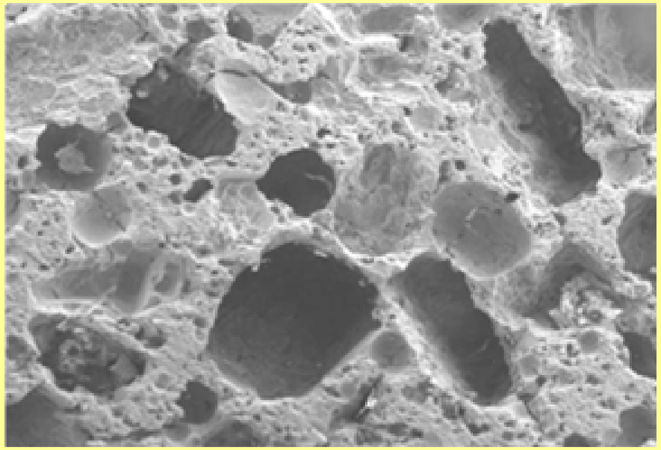


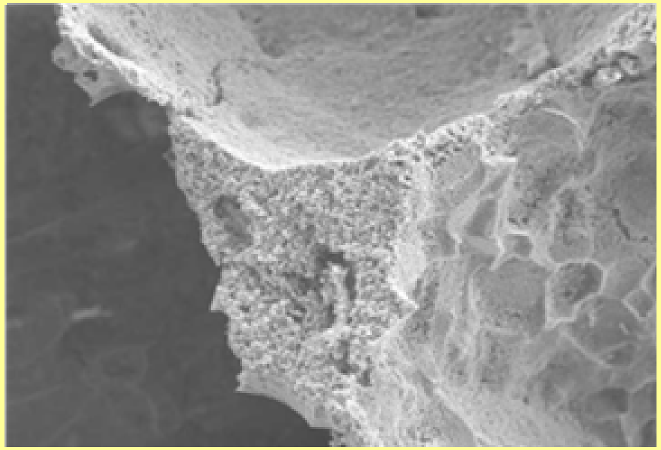
granulometries :
300-600 µm
600-1250 µm

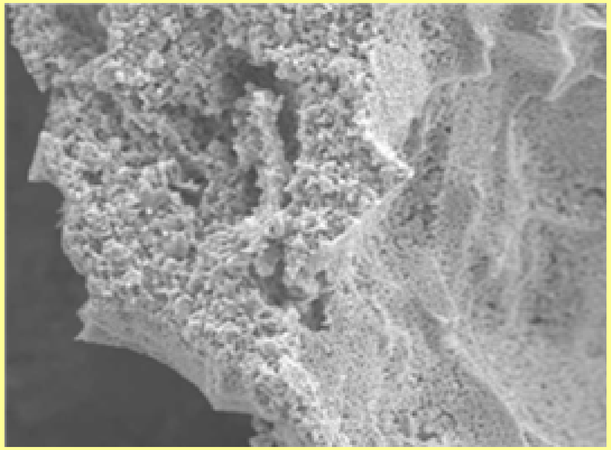




Influence of processing on properties

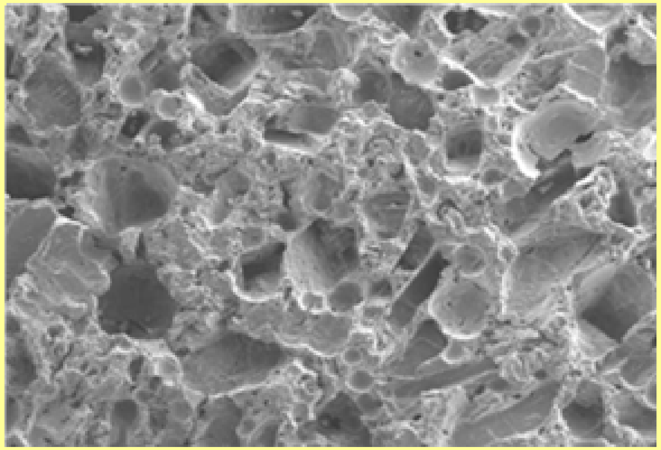


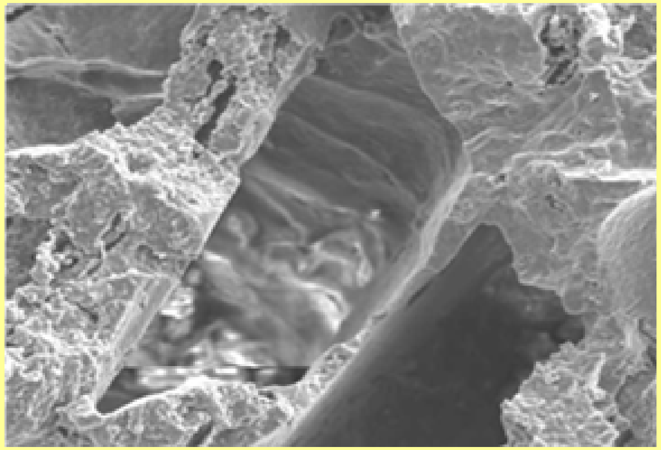


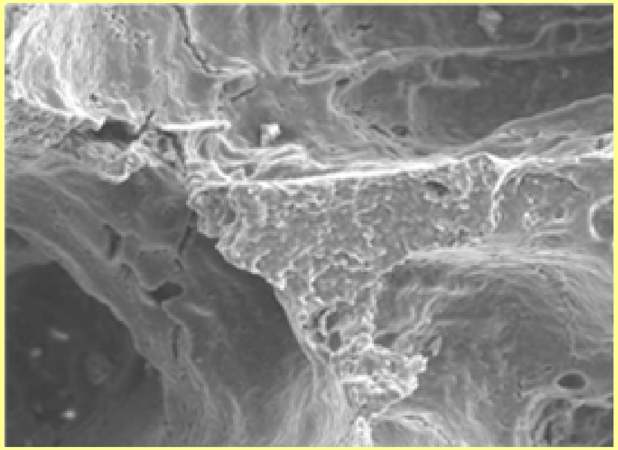


Large macro-pores

Low sintering temperature





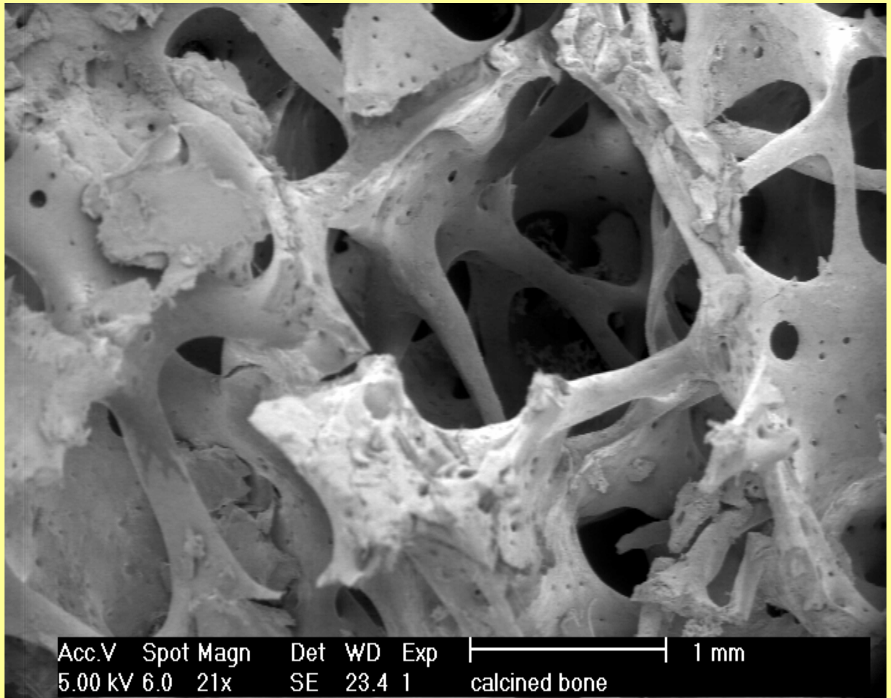


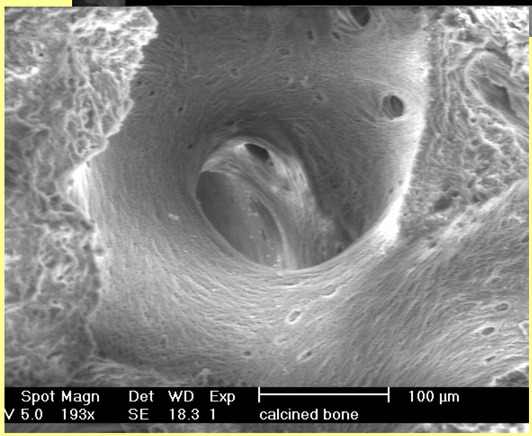
Small macro-pores

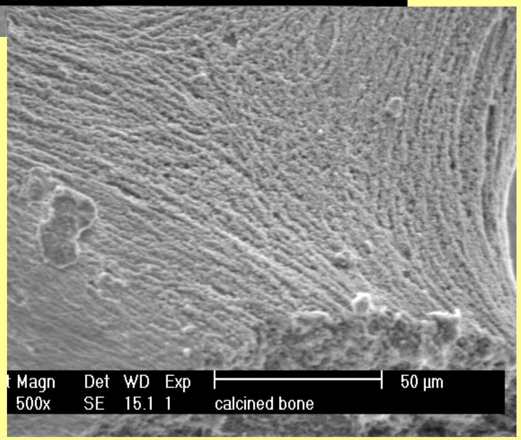
High sintering temperature

Bio-active ceramics / Bone substitution

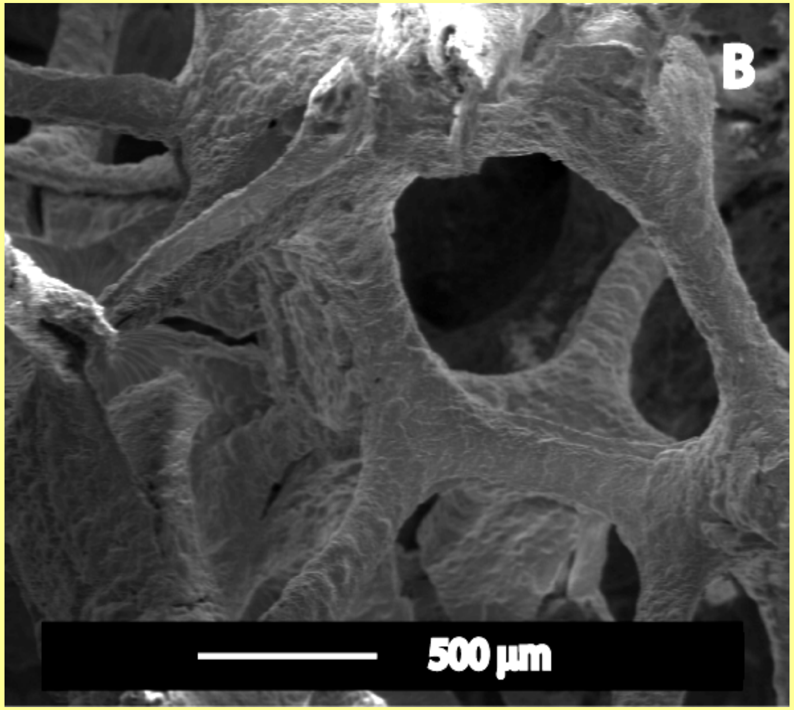
Natural ceramic : duck bone (HAP)





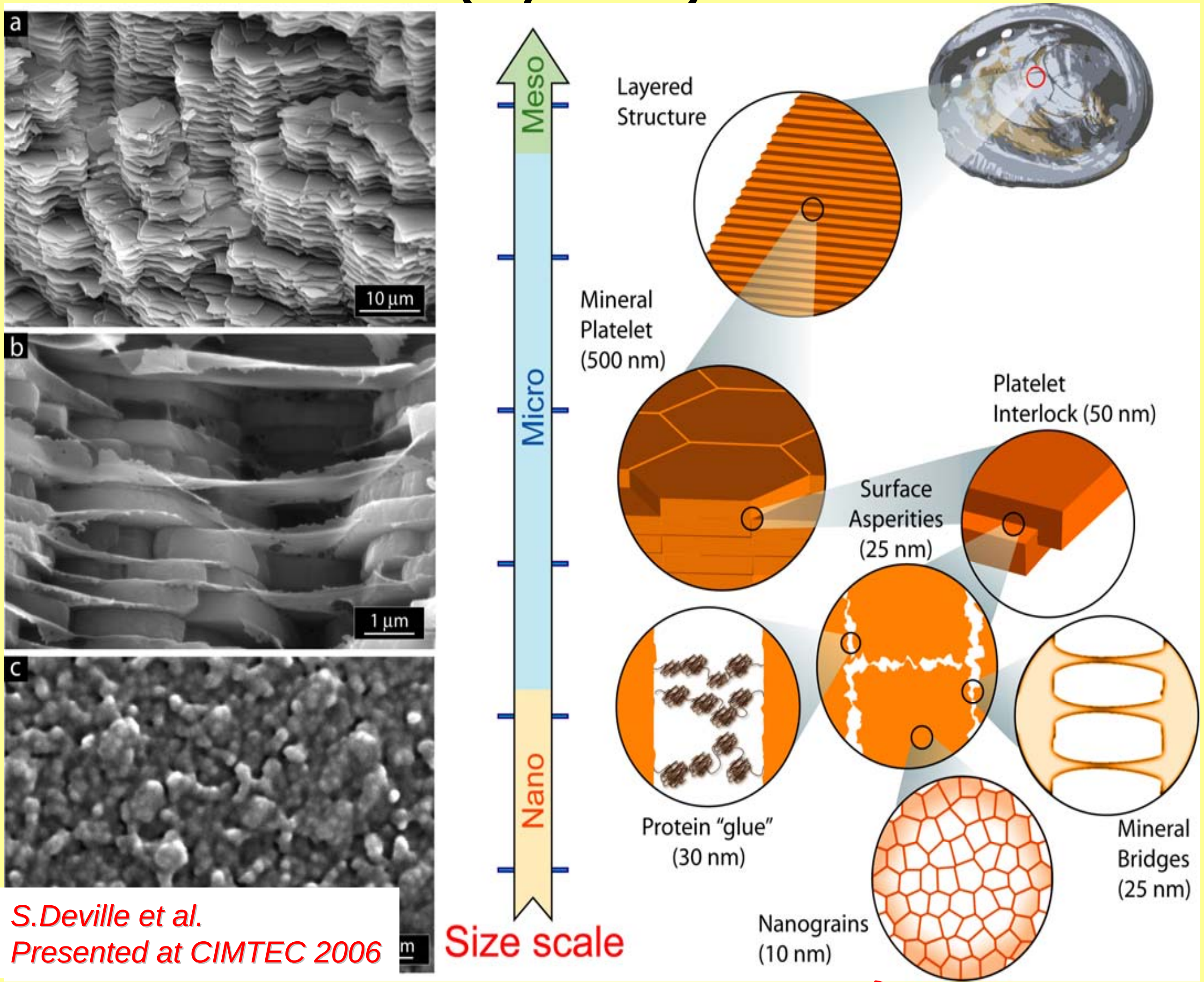


Synthetic ceramic by polymer foam replication



Bio-active ceramics / Bone substitution

Natural ceramic
Abalone (oyster) shell



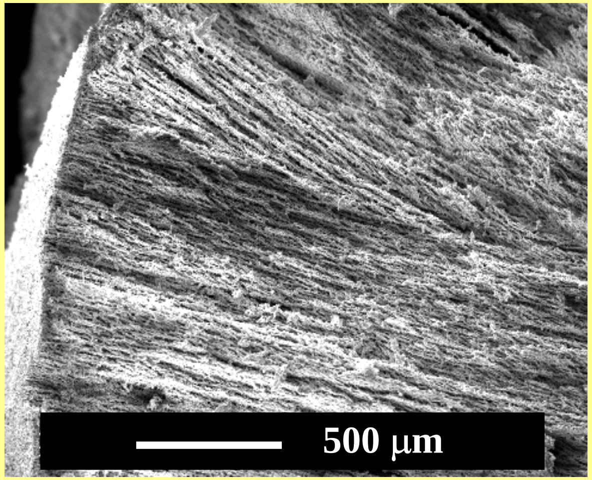
S.Deville et al.
Presented at CIMTEC 2006

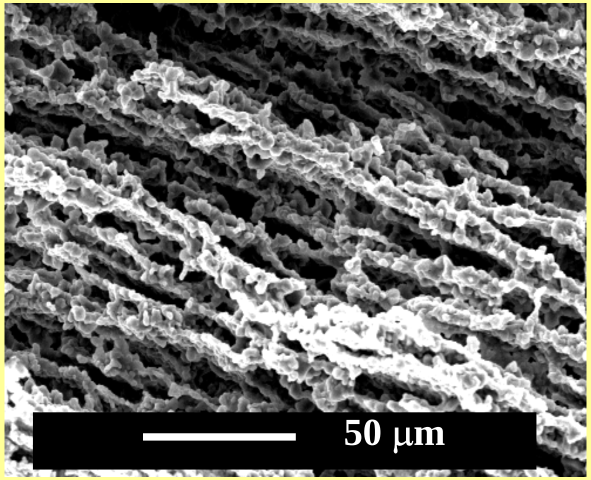
Mineral part (>95%): $CaCO_3$

Organic part (<5%): proteins and polysaccharides

$$K_{IC} \sim 8 MPa\sqrt{m}$$

Synthetic ceramic by freeze-casting



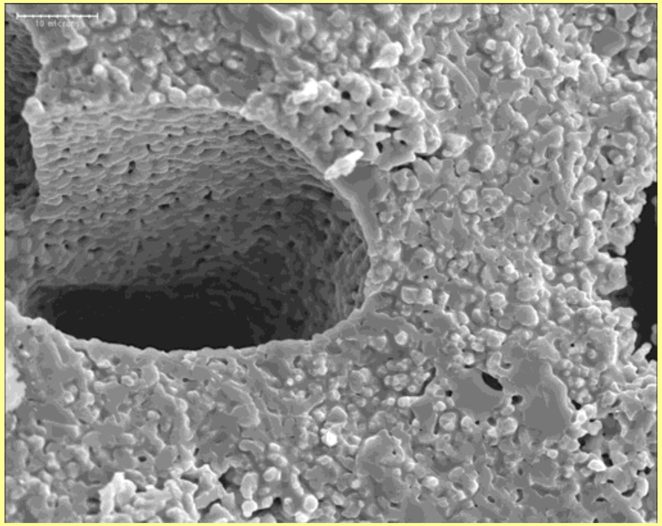


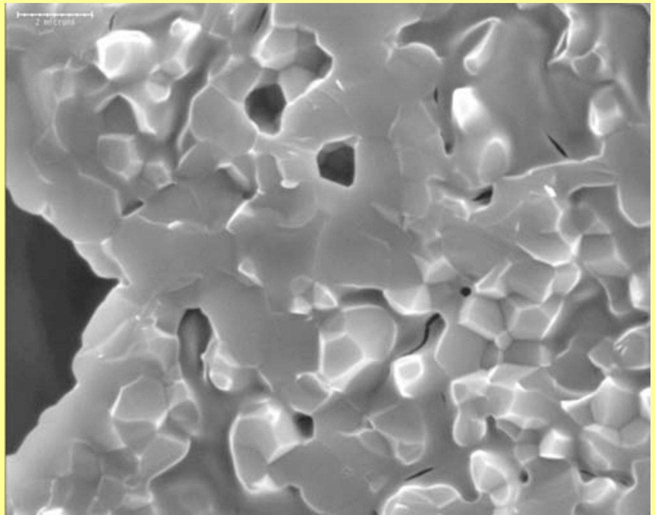
Perspectives concerning bio-active ceramics

Drug release

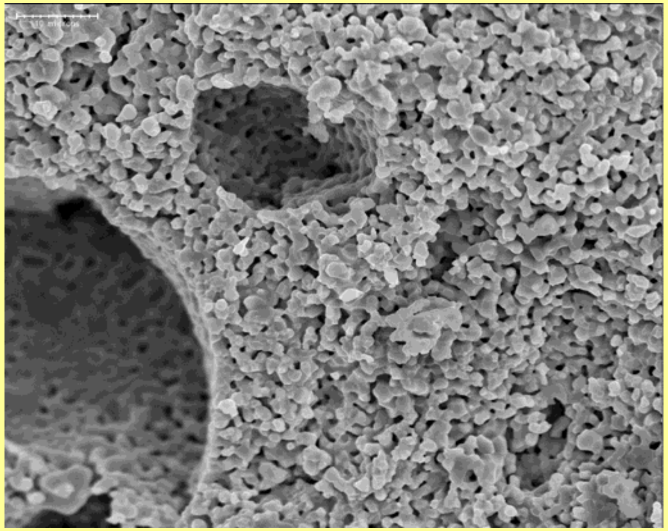
Incorporation of antibiotics in bone fillers - *release rate in vitro*

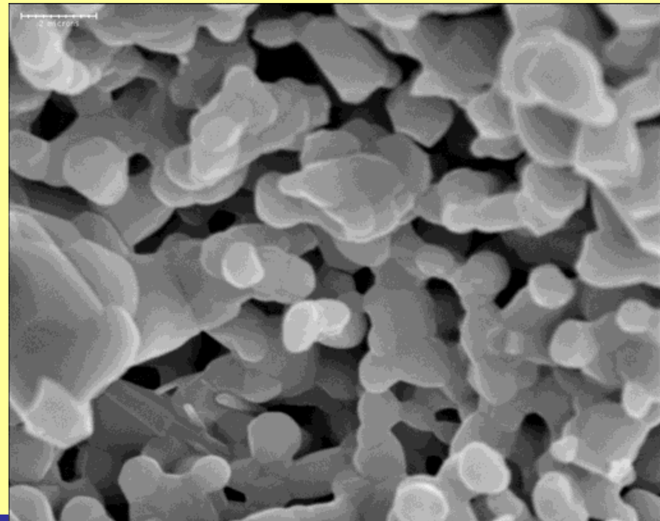
Incorporation (gentamicine)





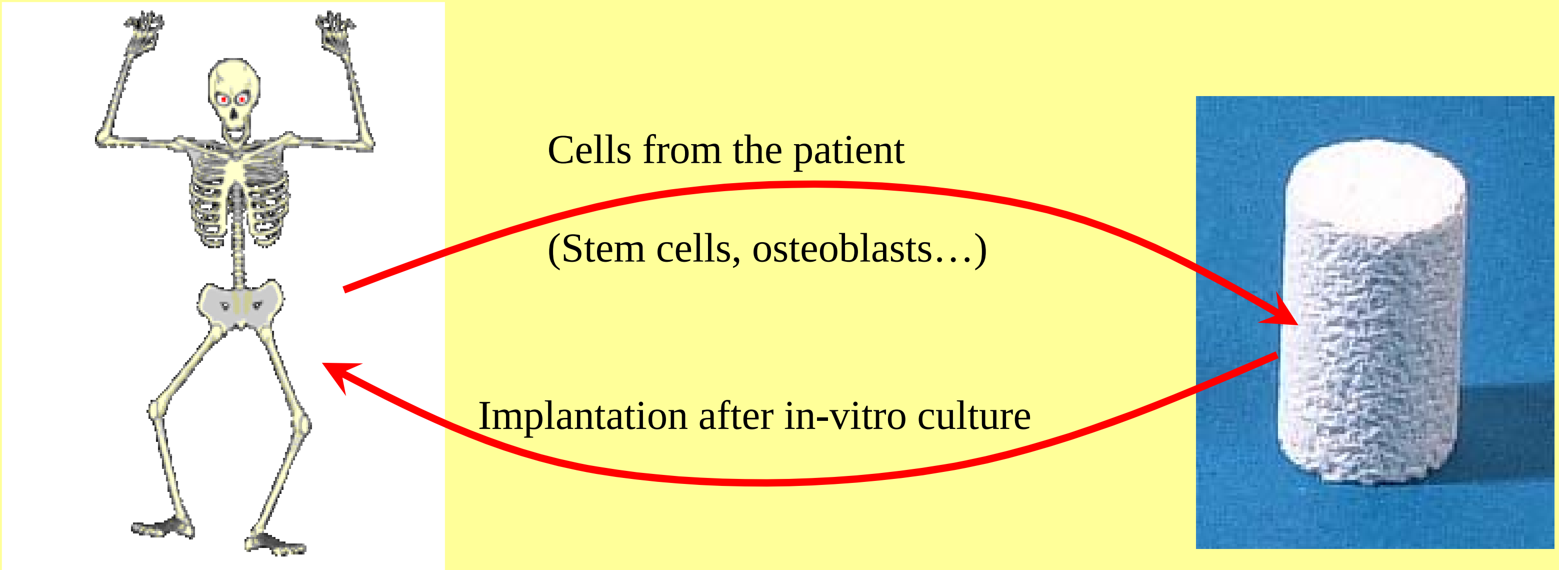
48 h release





Perspectives concerning bio-active ceramics

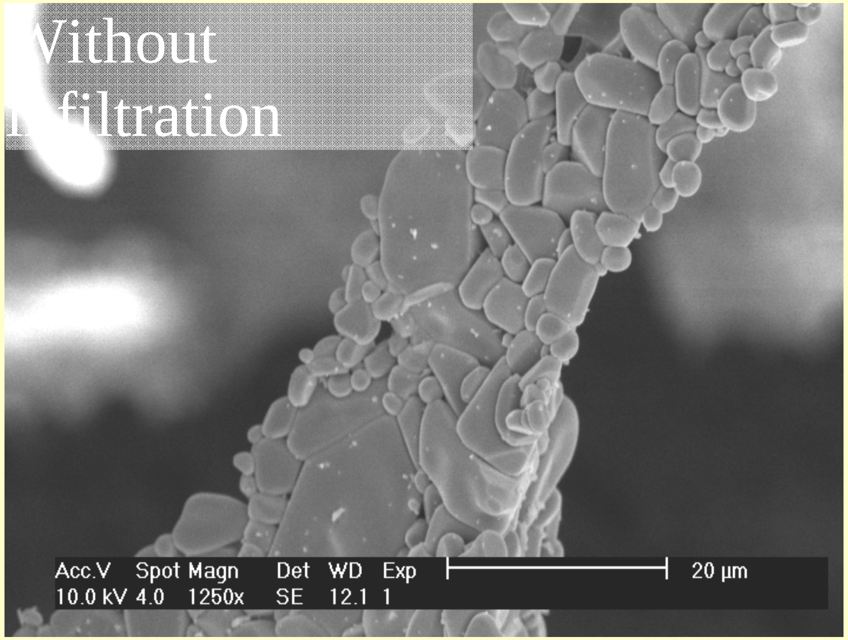
- Insights from tissue Engineering

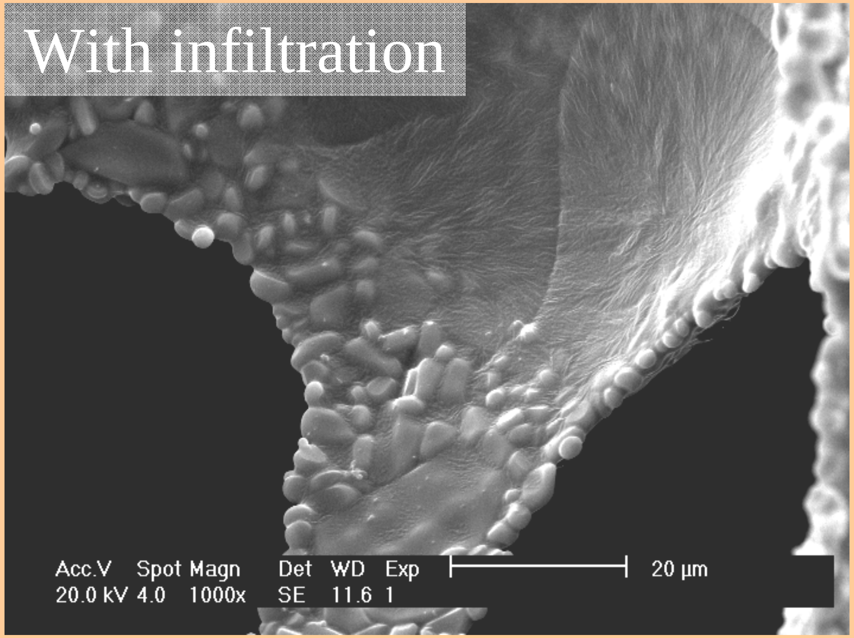


- => Incorporation of antibiotics, growth and differentiation factors… in the bone substitute, to promote in-vivo tissue growth.

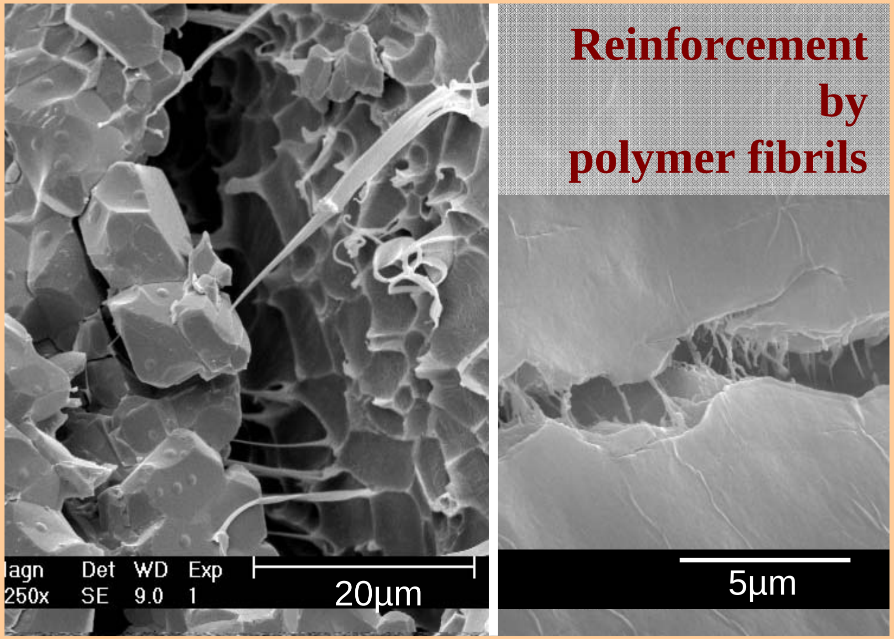
Bio-active ceramics / Perspectives

Ceramic – polymer composites





Nalla et al.
Nature Materials, vol 2, March 2003



Bio-active ceramics / Perspectives

Ceramic – polymer composites:
Mechanical properties