Structure and mechanical properties of teeth

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Outline

- Basic structure and components of teeth
- Mechanical properties

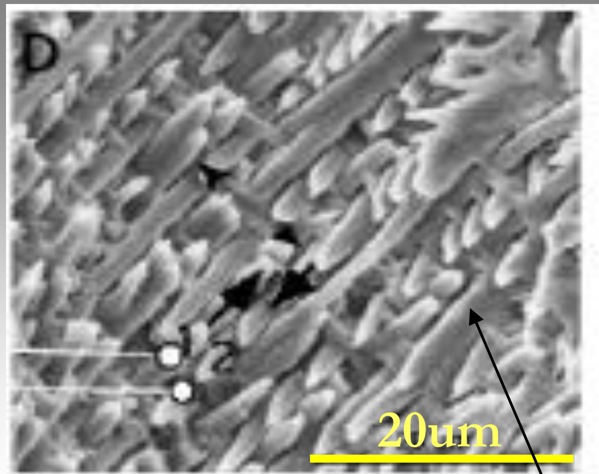
  1. tubule orientation

  2. tubule density

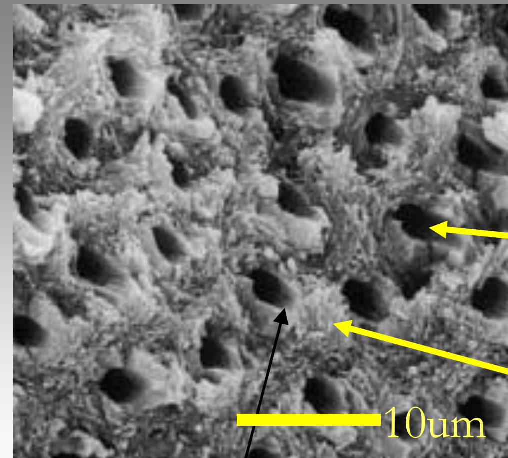
  3. age of the human dentin
- Animal teeth and preliminary results
- Conclusions

Structure and components of teeth

- Teeth are composed of an internal region called dentin which is tougher and external layer called enamel which is harder.
- Enamel has high degree of mineralization and no collagen.
- Dentin is a hydrated composite material composed of 30vol%type-I collagen fibrils, 25vol% fluid and 45vol% nanocrystalline carbonated apatite mineral.

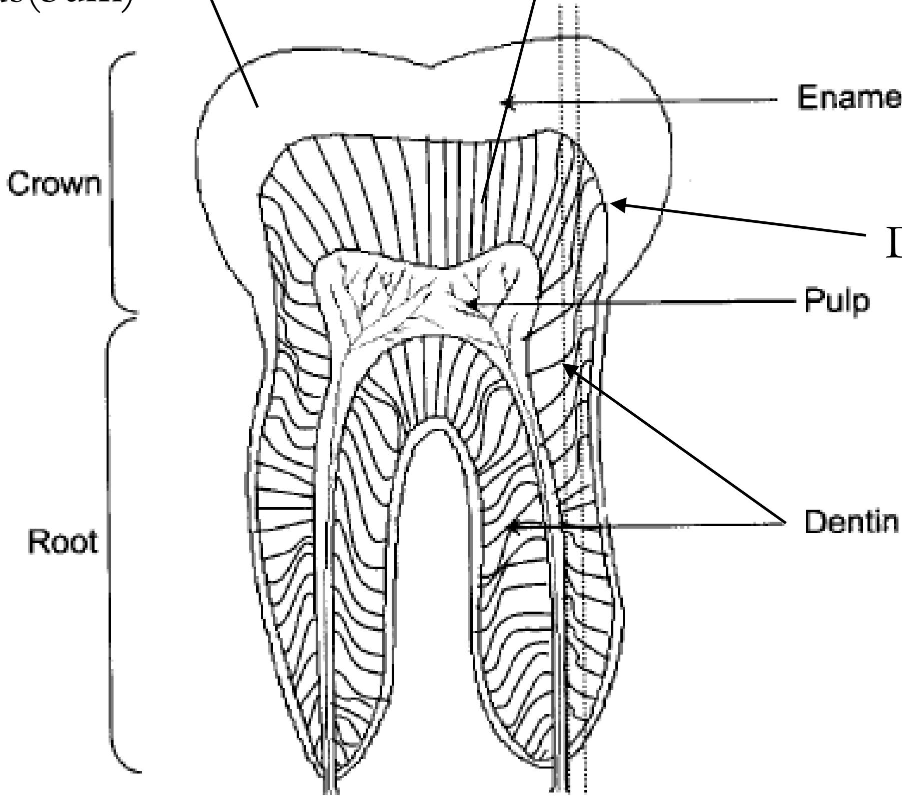


Hydroxylapatite rods(5um)

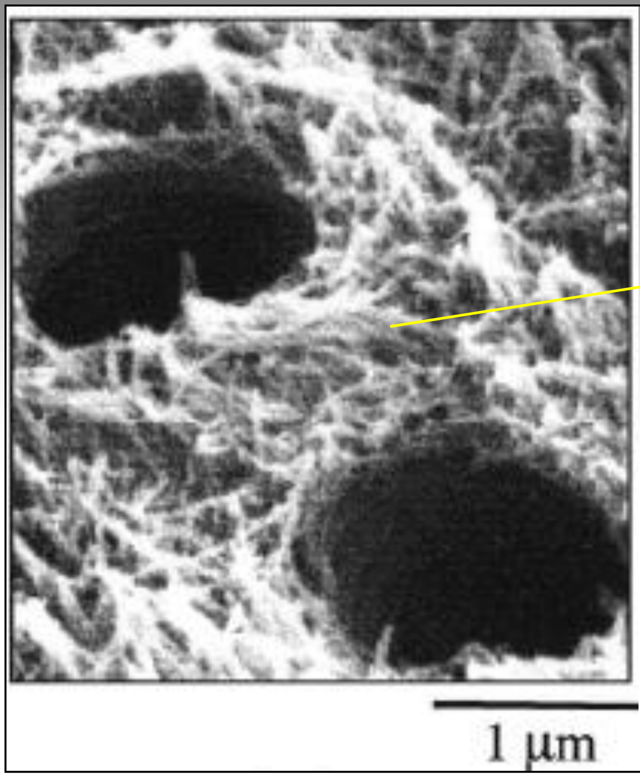


Tubules (1um)

Hydroxylapatite crystals(0.5-1um)

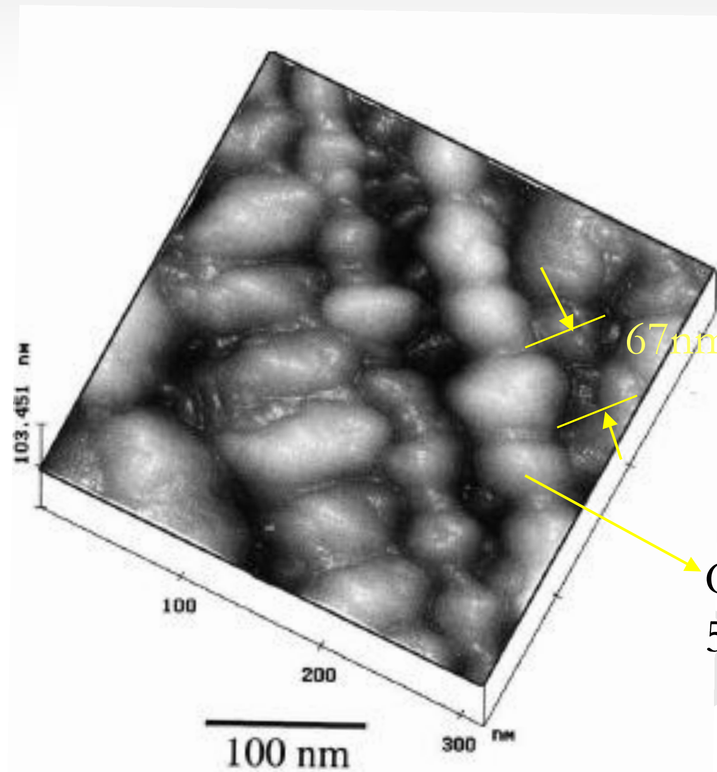


Imbeni V, et al.Biomed Mater Res A 2003:66:1-9 & Snead ML, et al. Mater Sci Eng C 2006:26:1296-30



Collagen fibril

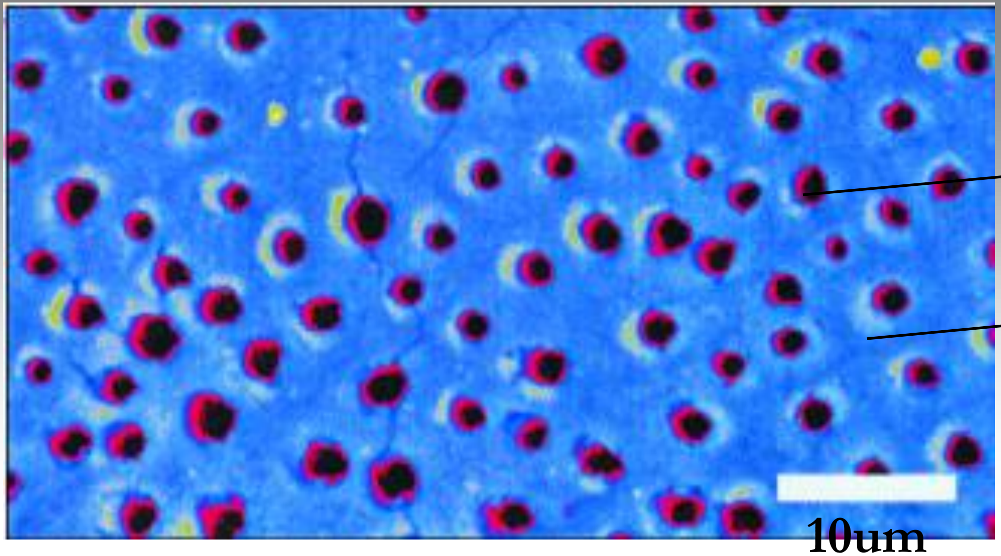
SEM of demineralized dentin



Collagen fibril
50-100nm in diameter

AFM of collagen fibril

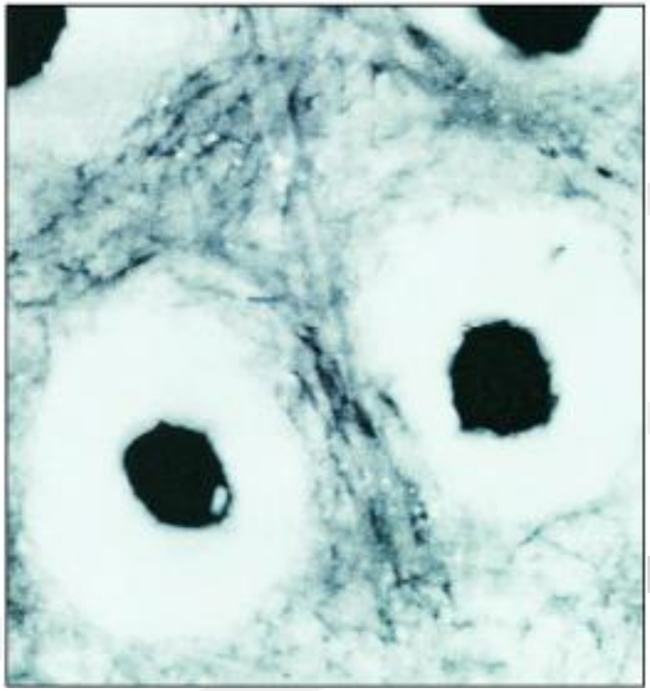
J.H.Kinney,S.J.Marshall,et al.Crit Rev Oral BiolMed 2003;14:13-29



Peritubular dentin

Intertubular dentin matrix

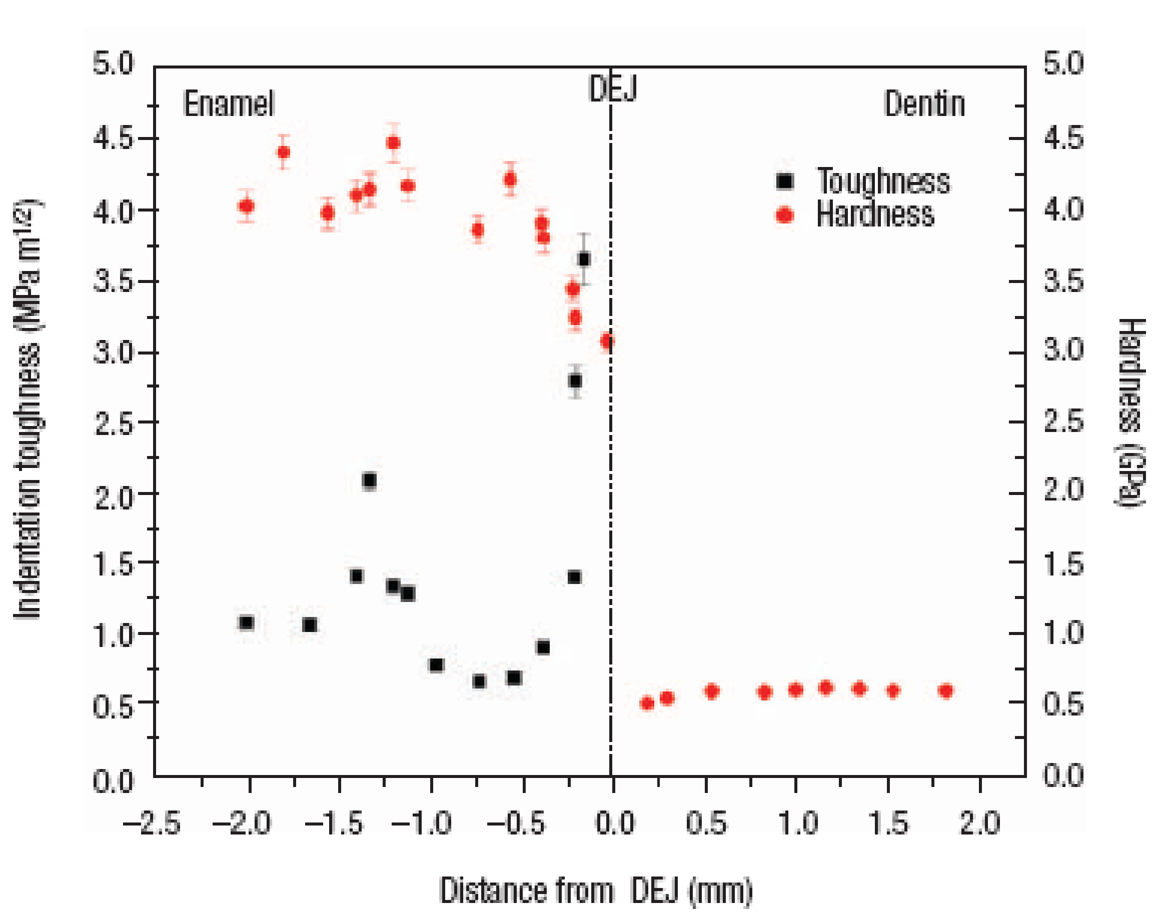
SEM of fully mineralized dentin



AFM of fully mineralized dentin

J.H.Kinney,S.J.Marshall,et al.Crit Rev Oral BiolMed 2003;14:13-29

Dentin Enamel junction



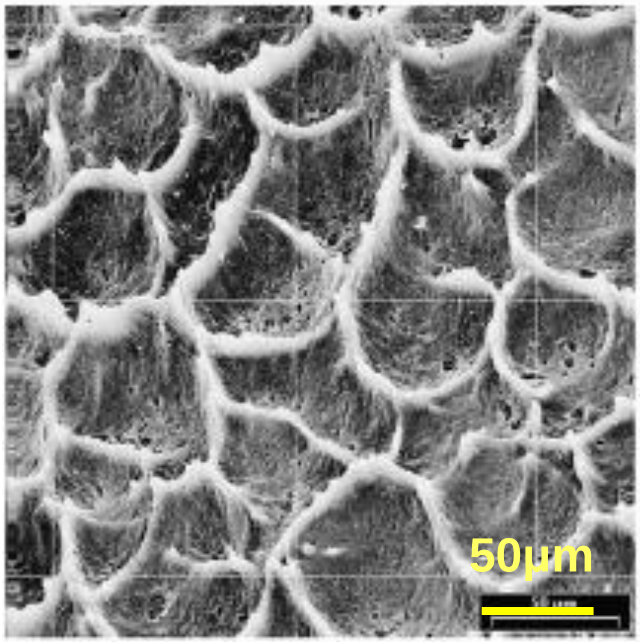
Typical profiles of Vickers hardness and the indentation toughness

- The load range is between 3 and 5N
- There is no toughness measurement due to the inelasticity in dentin suppresses the formation of indent cracks

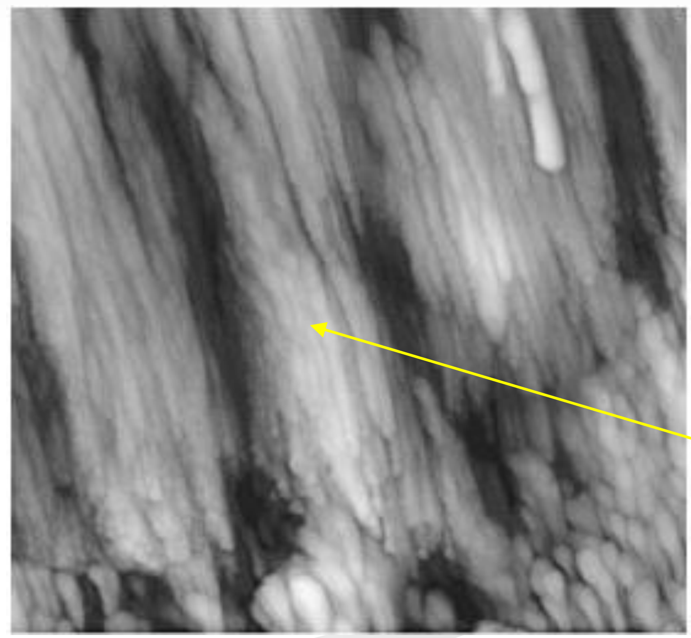
Imbeni V,et al Nature Material 2005;4:229-32

SEM and AFM images of DEJ

- The DEJ scallops
- AFM image of DEJ shows apatite crystal structure



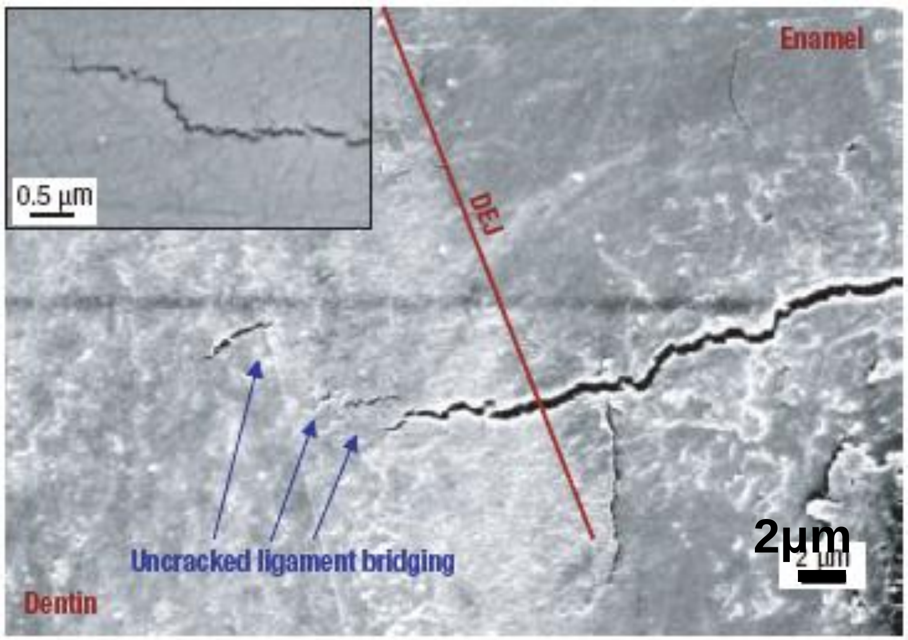
SEM image of DEJ

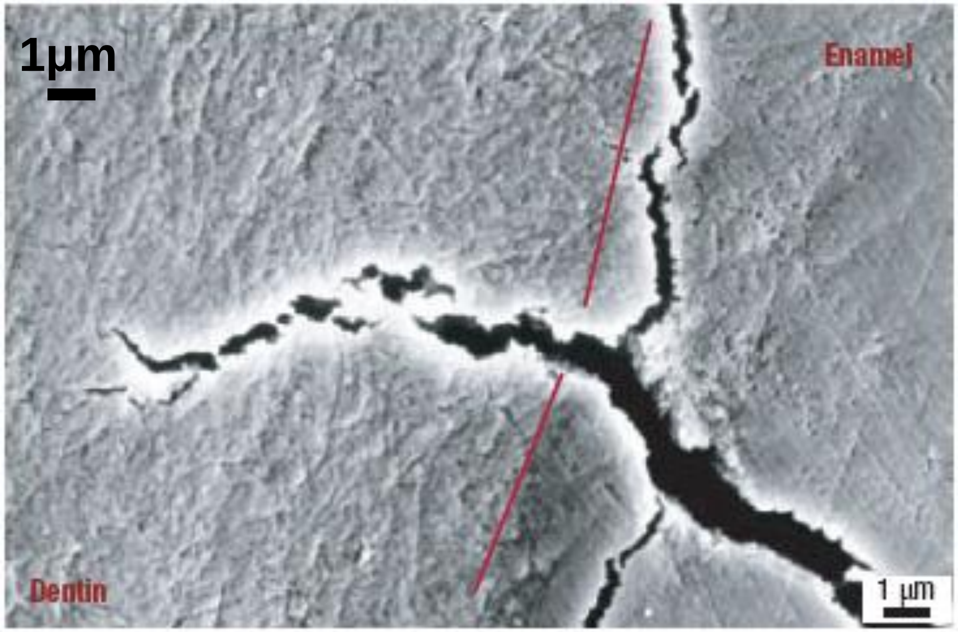


AFM image of DEJ

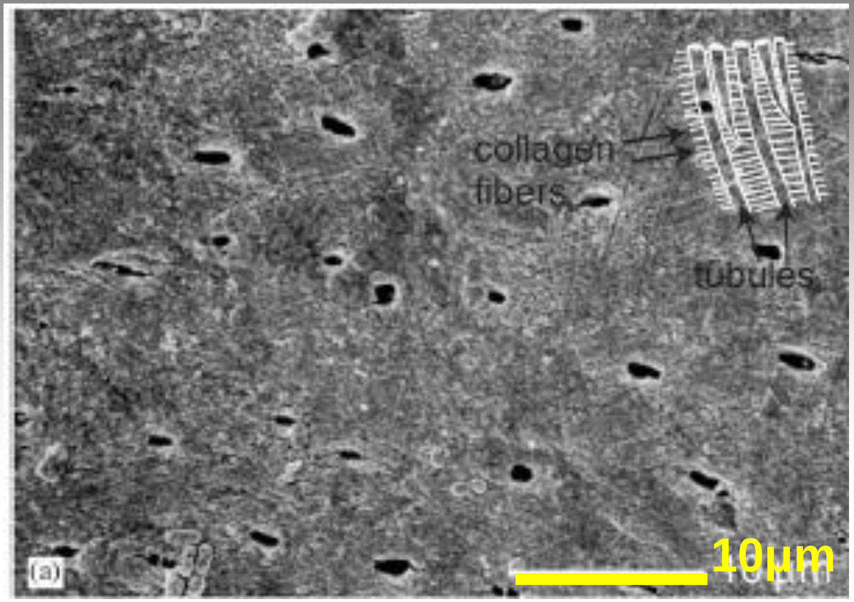
Sally J.Marshall,et al J. of the European Ceramic Society 23 2003 2897-2904

SEM of arrested crack

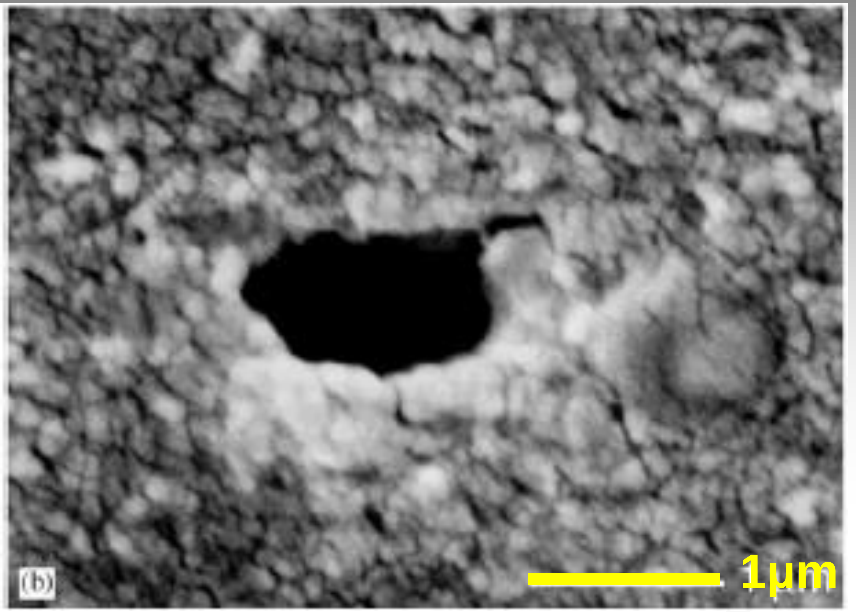




Imbeni V,et al Nature Material 2005;4:229-32



SEM of elephant tusk dentin



SEM of tubule

- The tubules of elephant tusk are more elliptic in shape.
- The mineralized peritubular dentin cuff is very small or nonexistent compared with human dentin

Nalla RK ,et al Biomaterials 24(2003)3955-3968

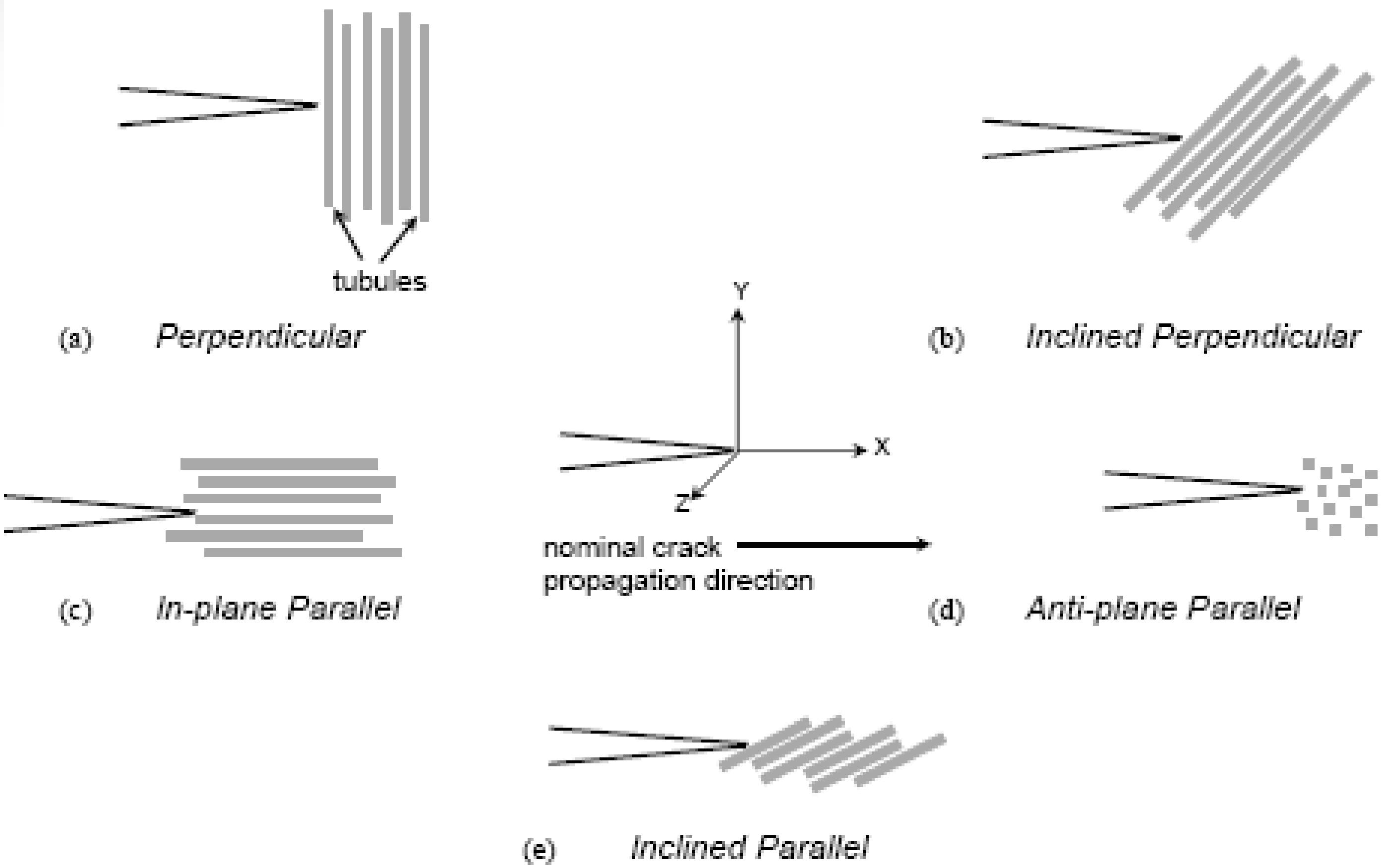
Factors which affect the mechanical properties of dentin

- 1. Tubule orientation

  Collagen fibril
- 2. Tubule density
- 3. Age of the human dentin

1. Effect of tubule orientation

- Effect of orientation on fracture toughness of dentin
- Work of fracture is defined as the work per unit area to generate a new crack (Rasmussen et al)



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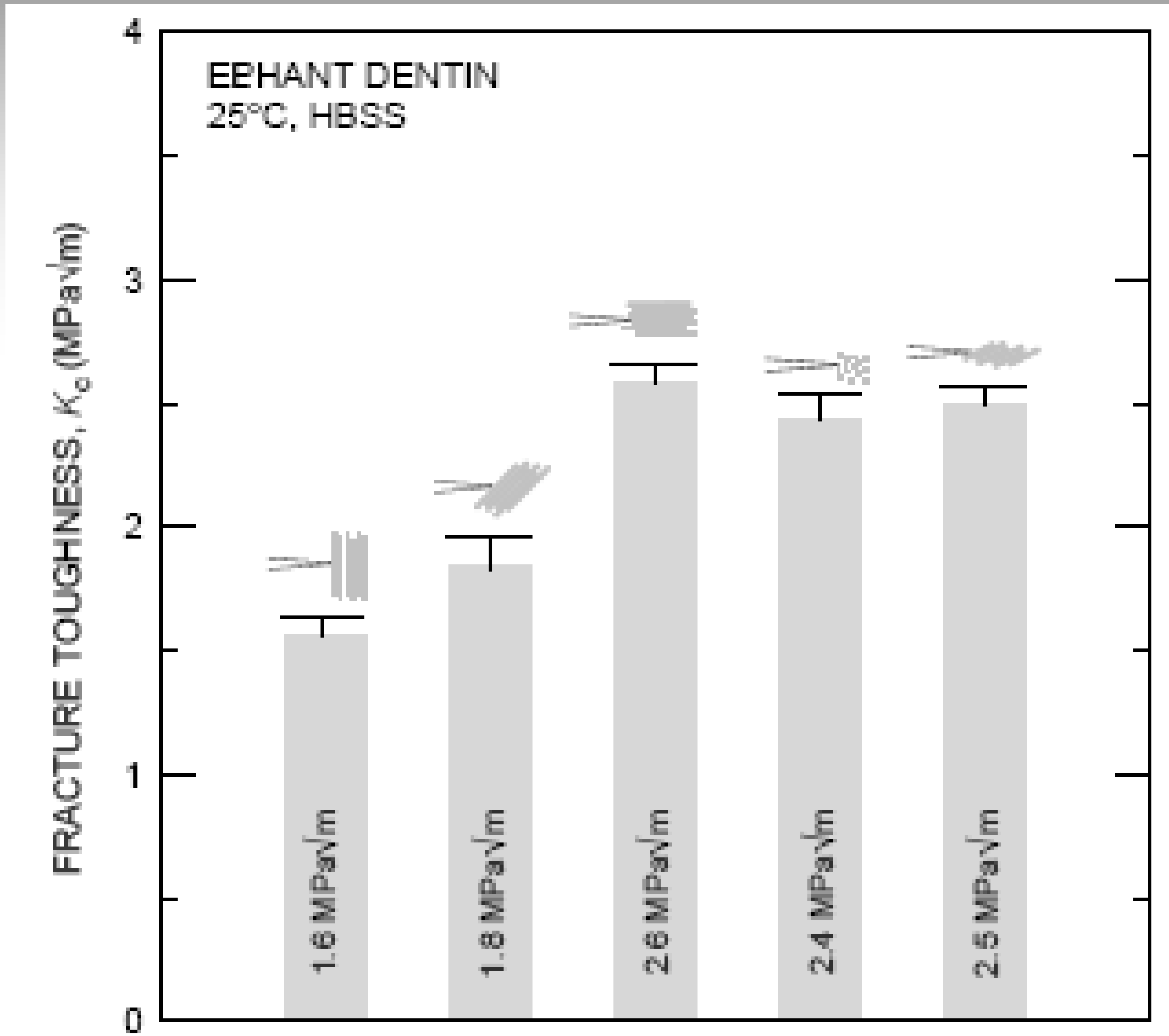
Fracture toughness results



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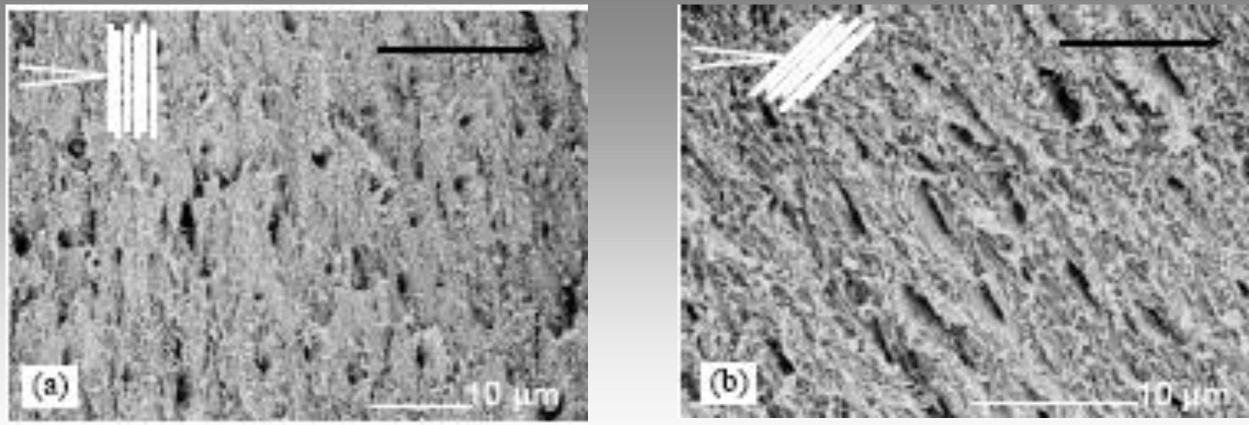
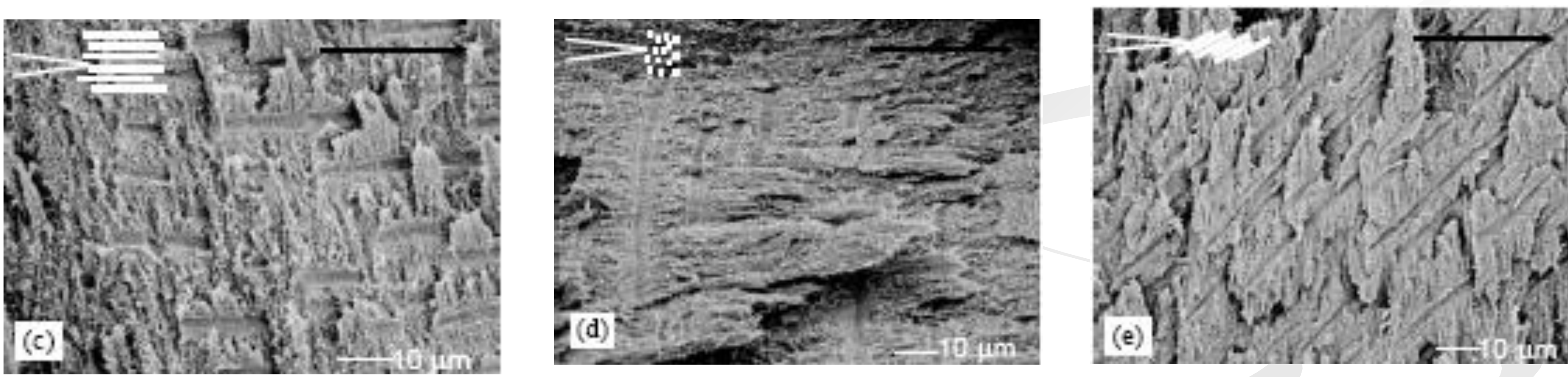


SEM of fracture surface for perpendicular orientation

- **Tubules appear as voids for the perpendicular orientation**



SEM of fracture surface for parallel orientation

- **Tubules appear as "tire" tracks for the parallel orientation**

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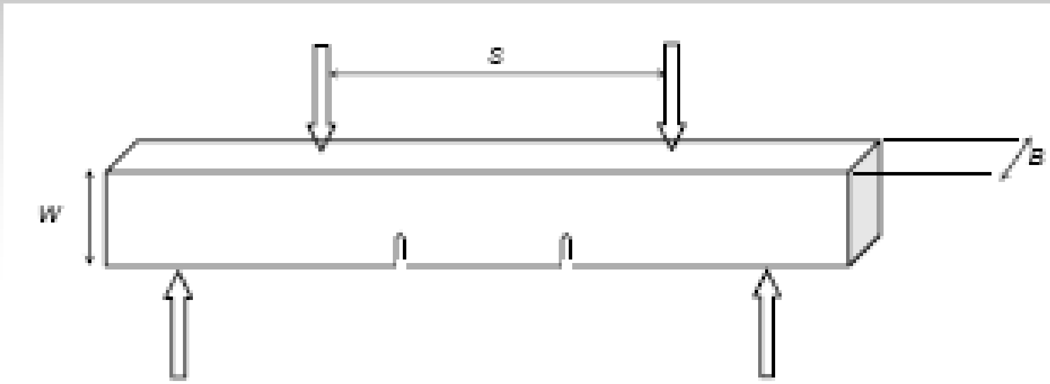
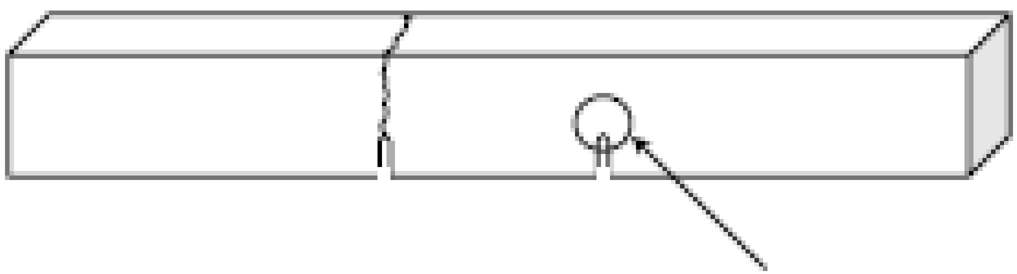
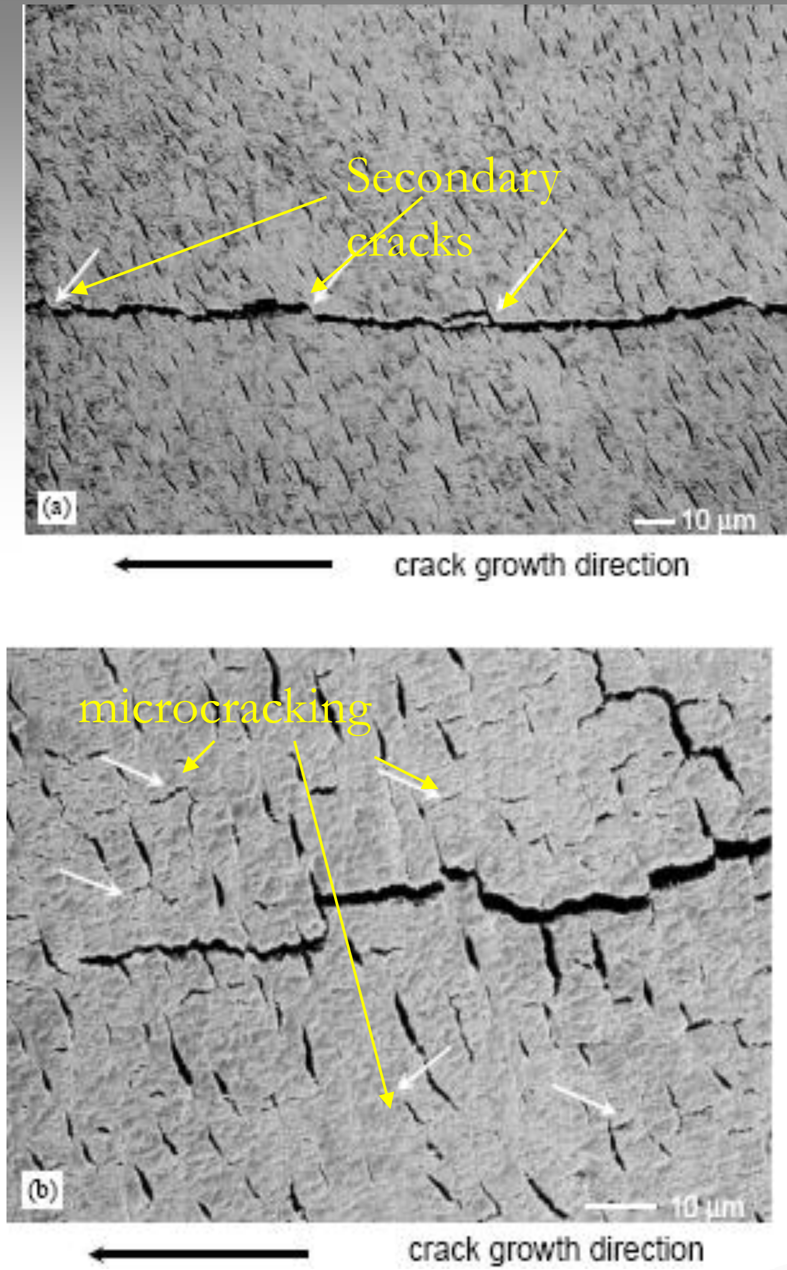
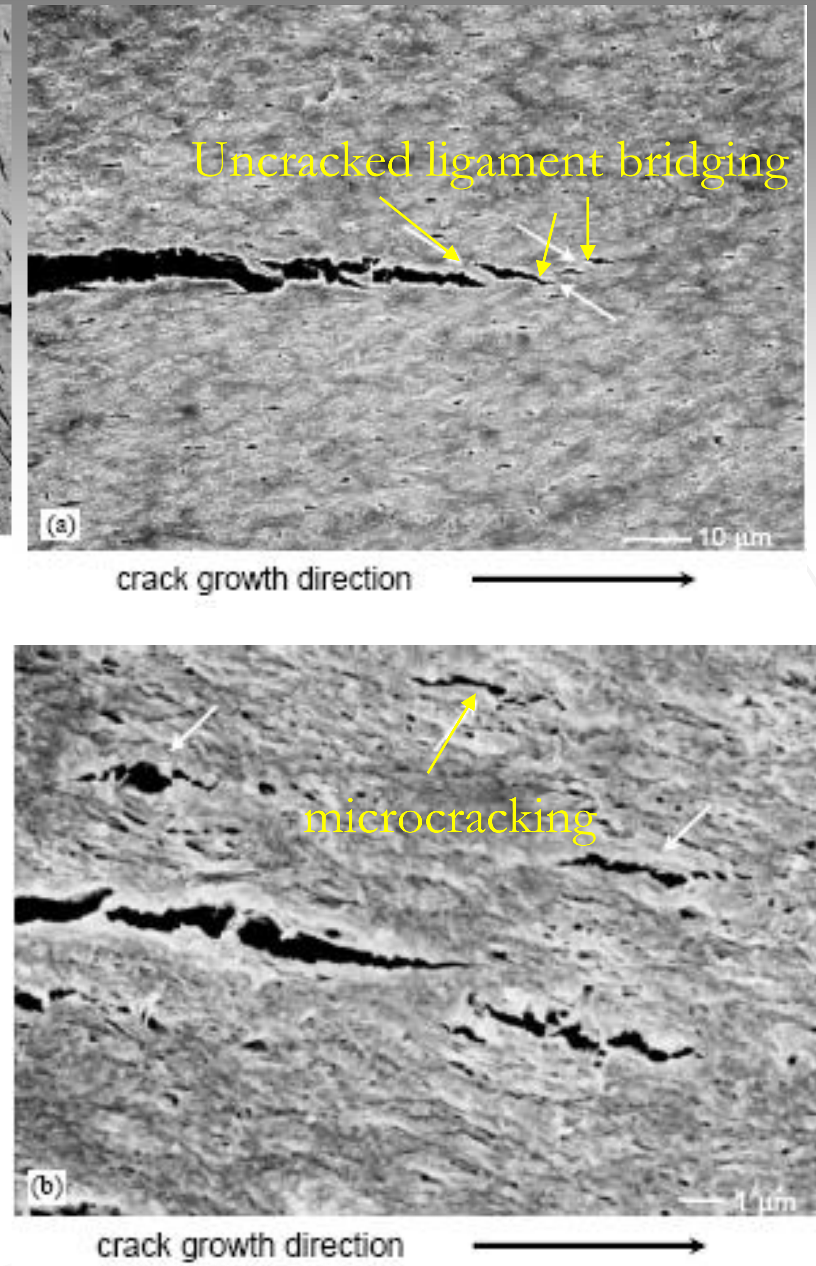
Crack path observation







Perpendicular orientation



Anti-Parallel orientation

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How the crack interacts with microstructure influences the toughness

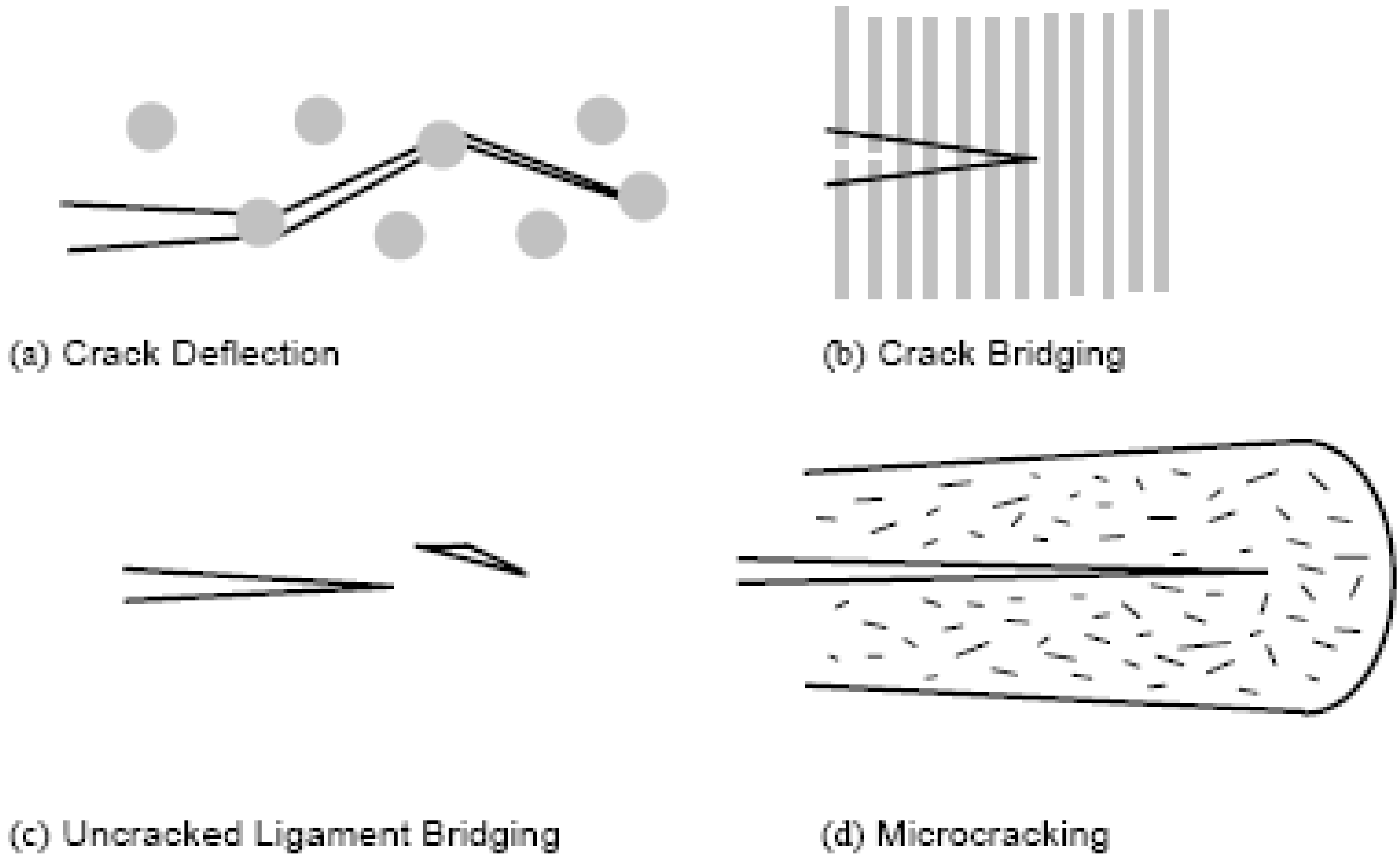
- Intrinsic toughening

Microstructure affect the inherent resistance to microstructural damage and fracture ahead of the crack tip

- Extrinsic toughening

Microstructure promote crack-tip shielding which is to reduce the stress intensity experienced at or behind the crack tip

Some principal toughening mechanisms



Schematic illustration of four principle toughening mechanisms in dentin

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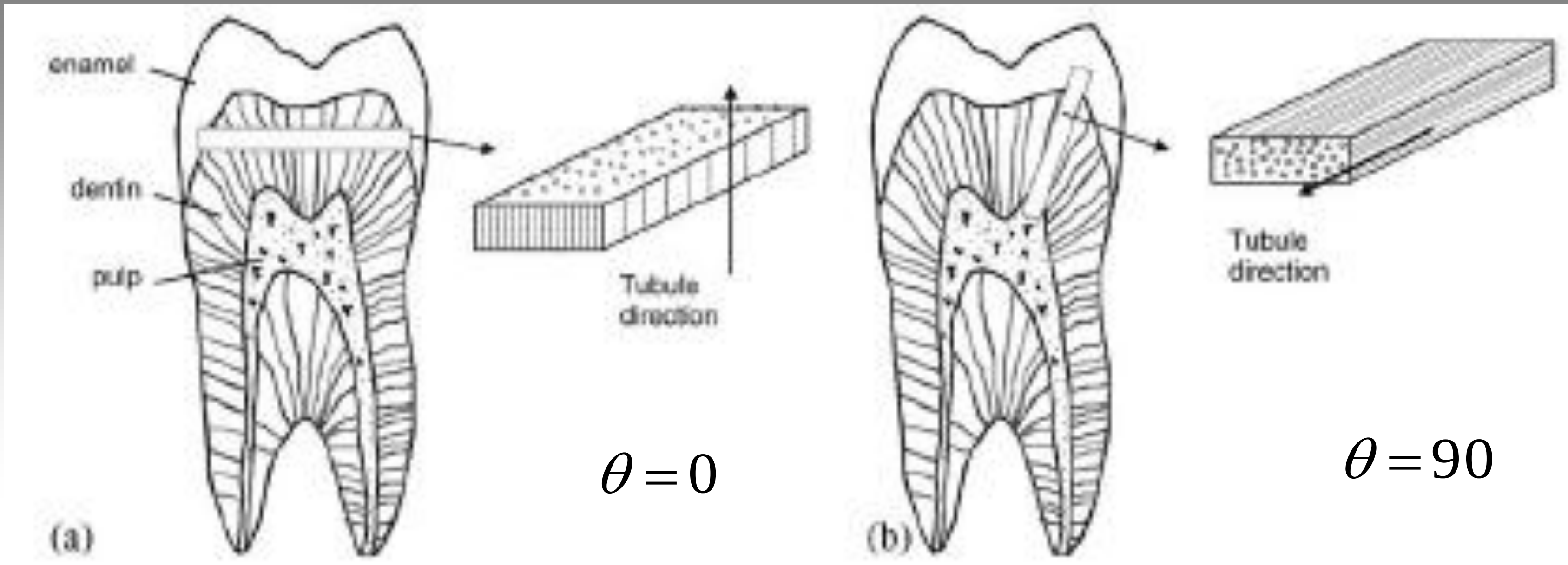

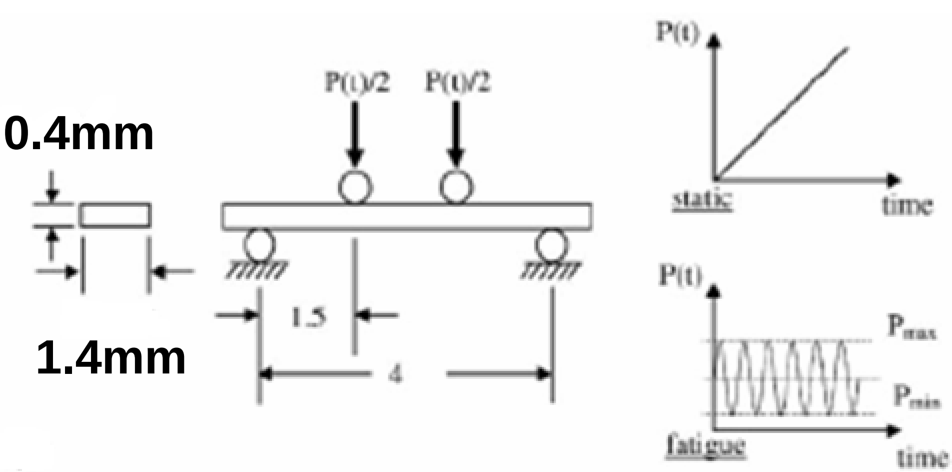

- quasi-static loading is applied at crosshead rate of 0.001mm/s
- Flexural fatigue load cycle frequency is 5Hz and stress ratio is 0.1

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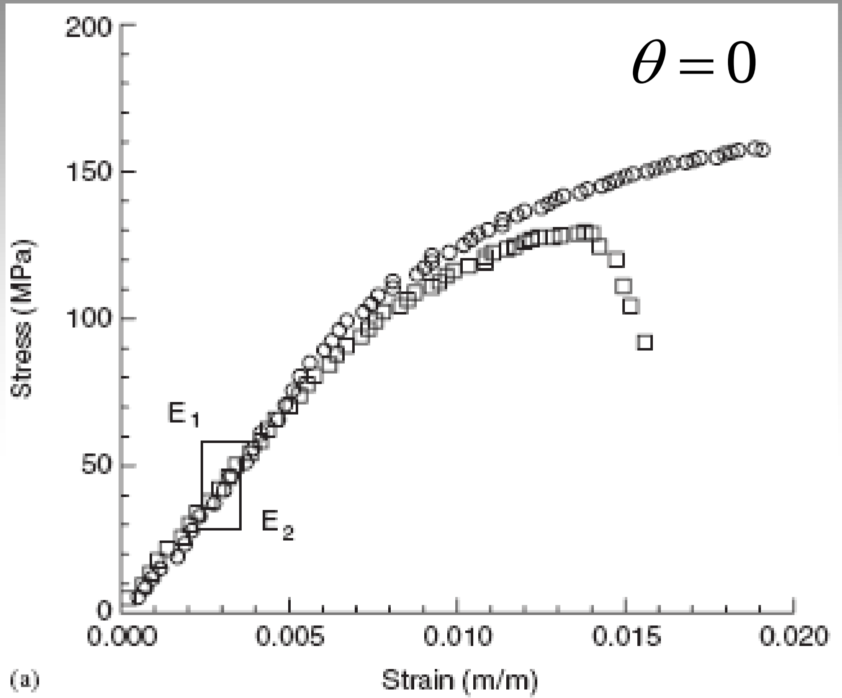
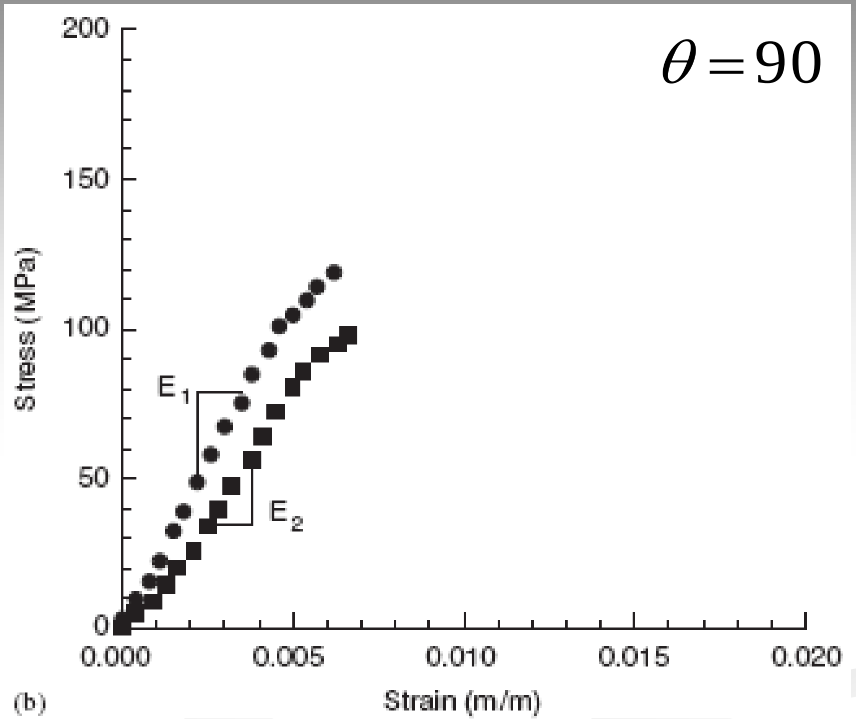
Quasi-static four point flexure result





	θ=0	θ=90
Flexural Strength(MPa)	160	109
Energy to fracture(MPa)	1.9	0.5
Age	24±3	23±3
#of specimen	26	21

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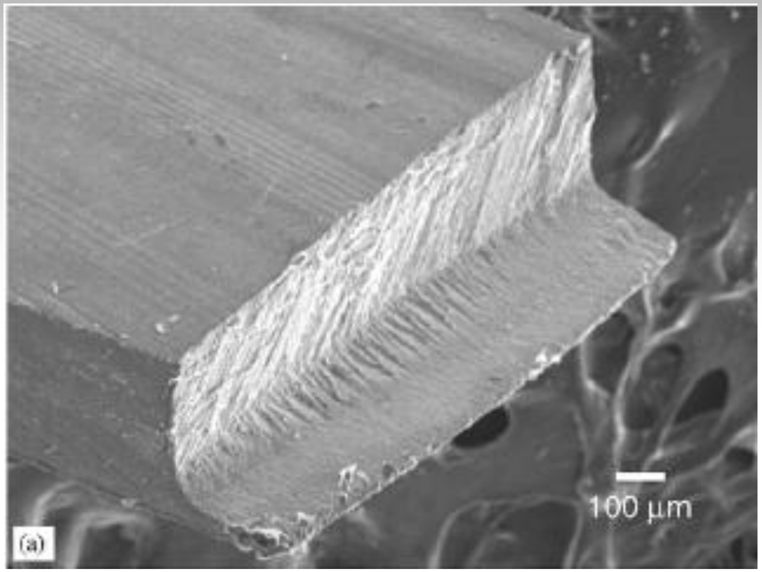
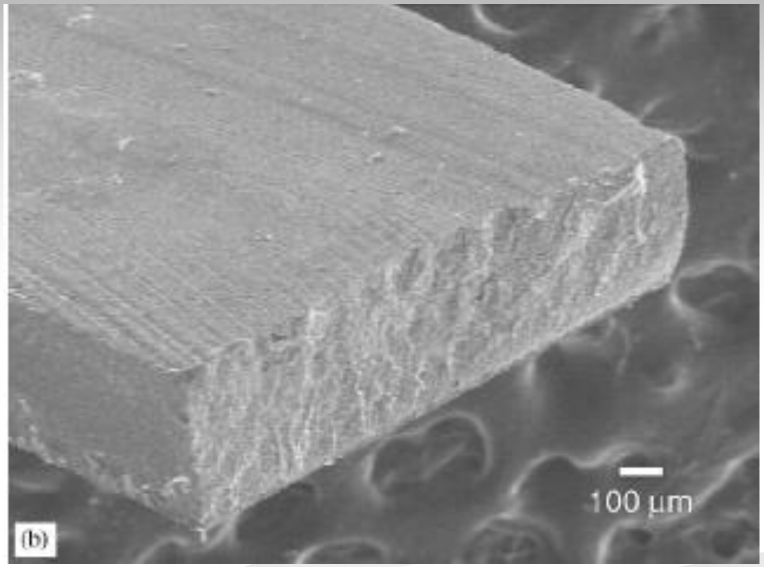
SEM images of fracture surface



$\theta = 0$



$\theta = 90$

- Specimen with θ=0 display an overlap shear lip on the compressive side of the neutral axis
- Fracture surface of the θ=90 appears rougher than that of θ=0

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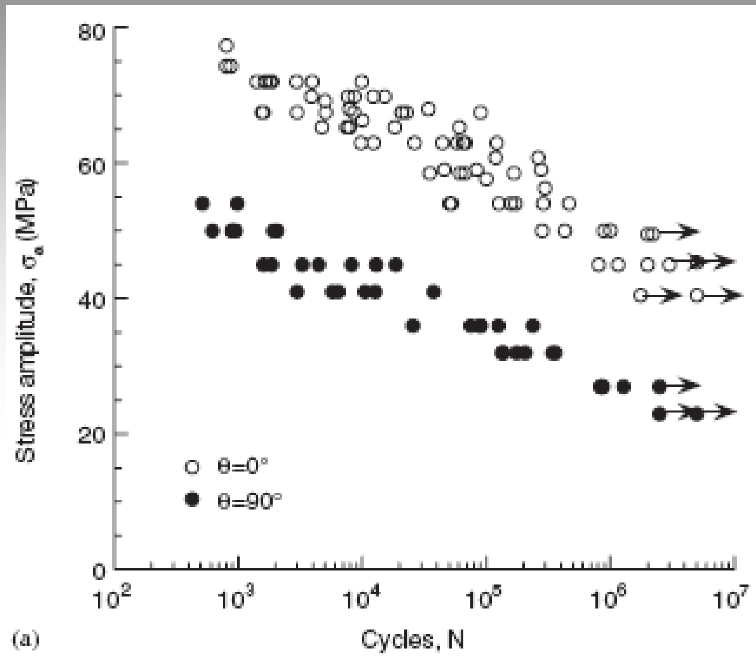
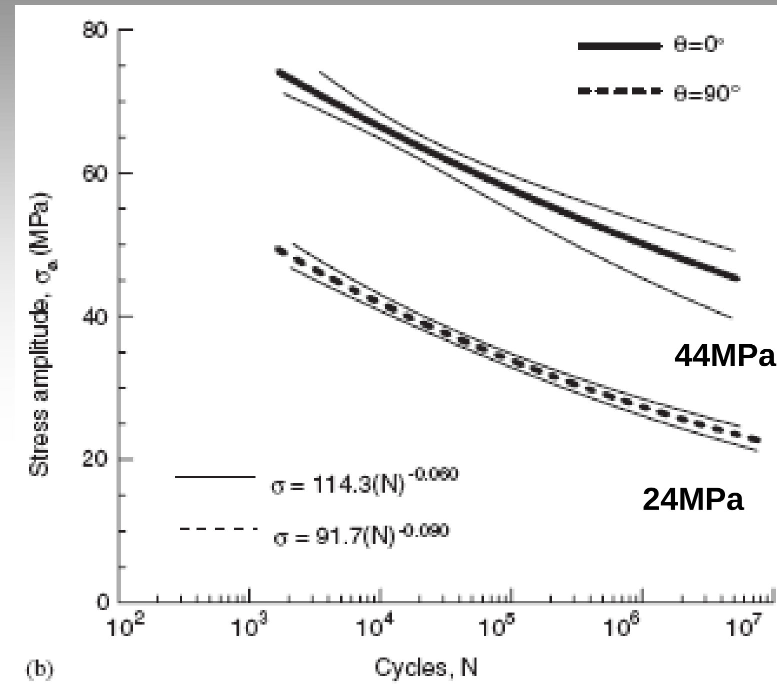
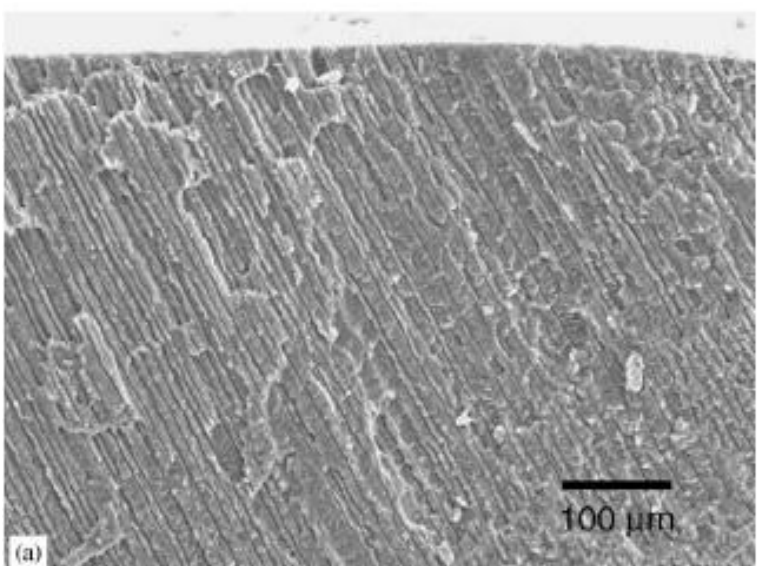
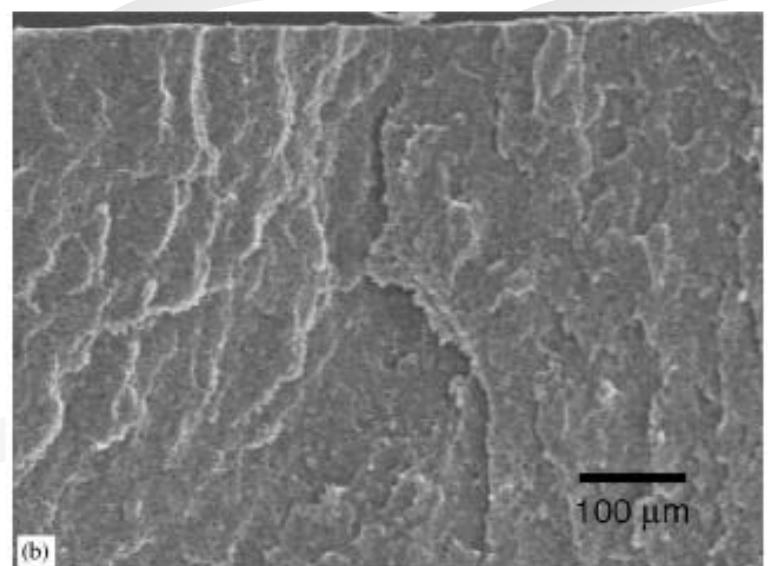
Fracture fatigue results







θ=0°



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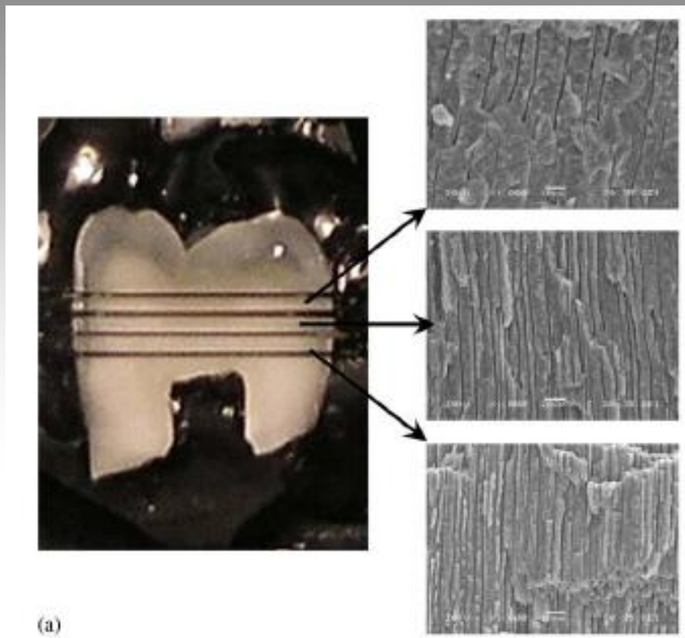
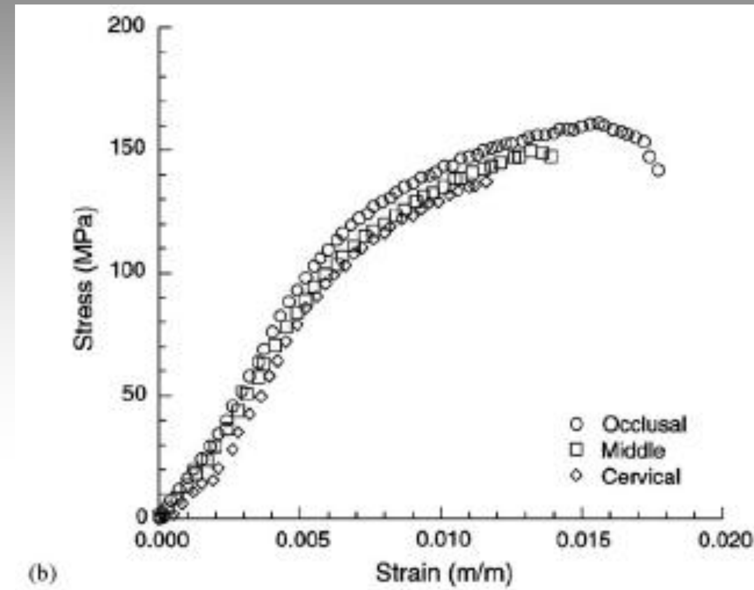
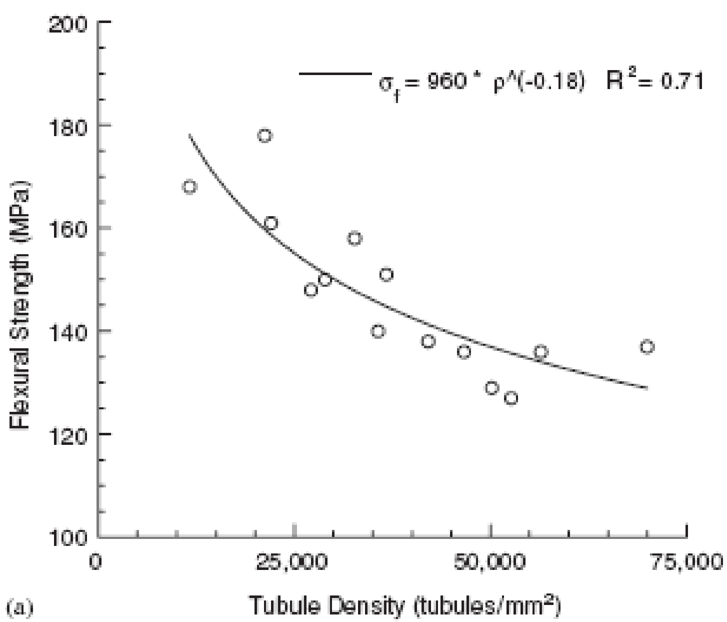
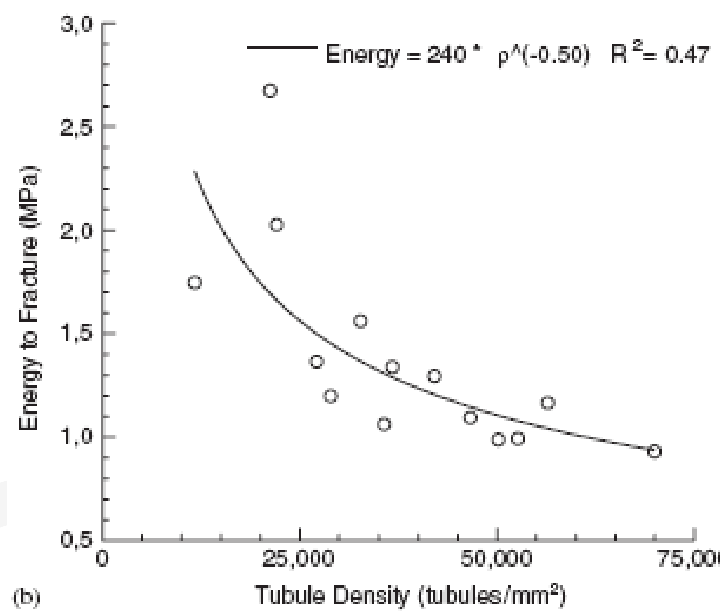
2. Effect of tubule density









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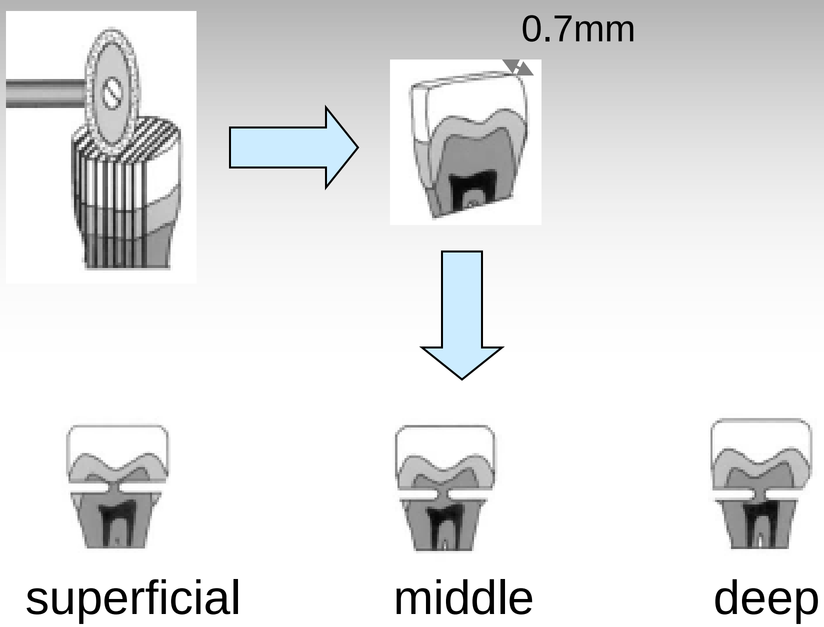
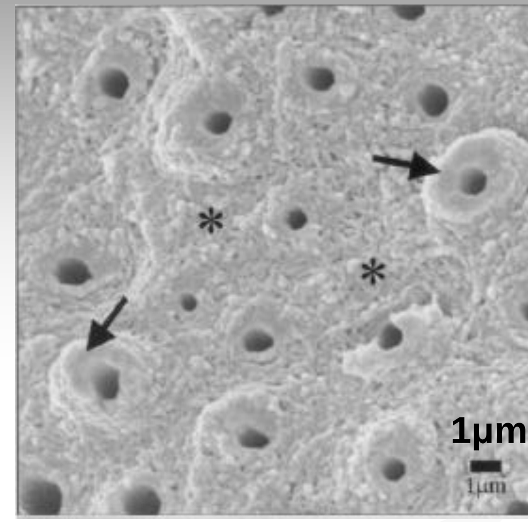
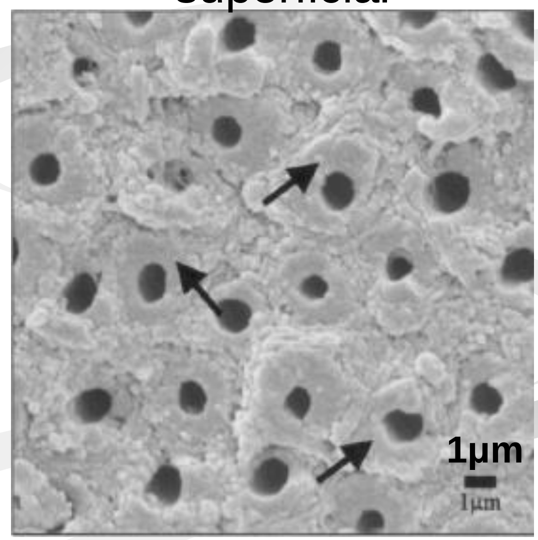
Ultimate tensile strength of dentin with different depth



Tooth structure	Mean UTS (MPa)
Superficial dentin	60.6
Middle dentin	48.7
Deep dentin	33.9



superficial

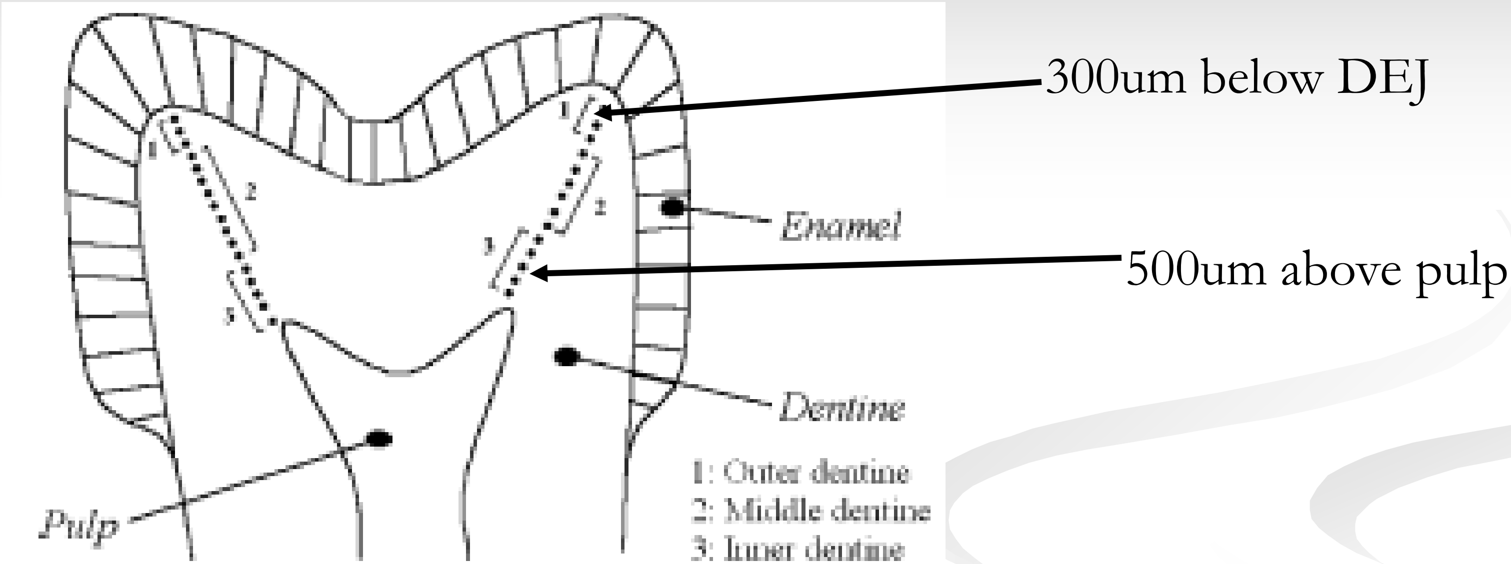


deep

Narcelo Giannini,etc. Dental materials 20(2004)322-329

Microindentation on molar primary dentine

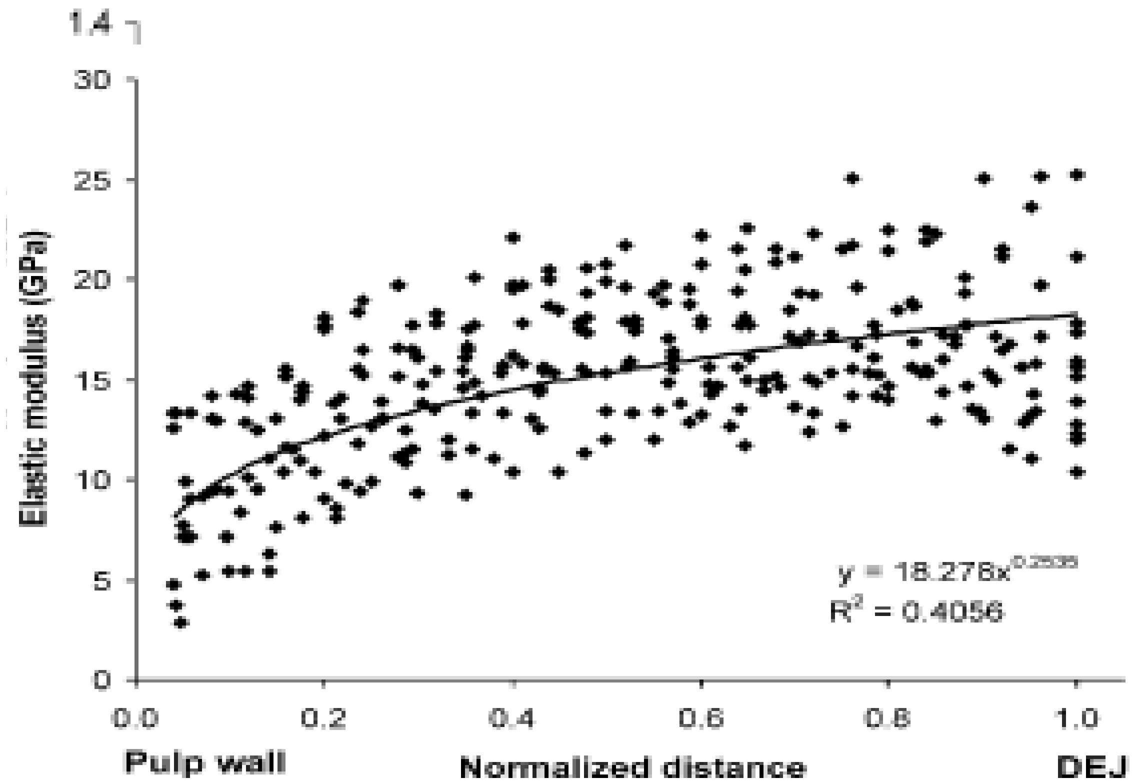
- The test divided into three groups depends on different distance from DEJ



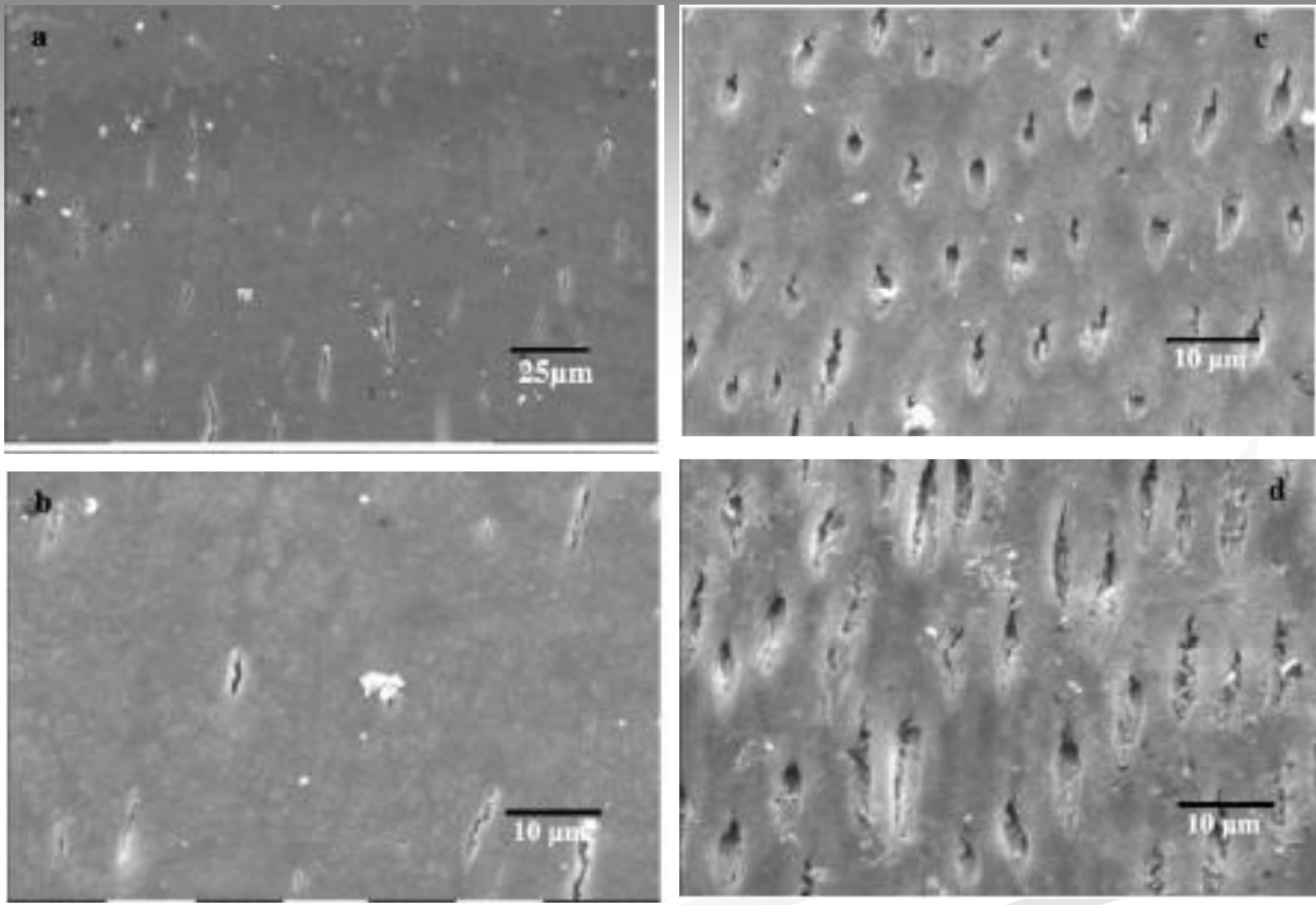
- The molar dentine were placed in a solution of hydrogen peroxide 1% for 24 hr after extraction
- The force applied is 25mN with 25 incremental loading steps

Linny Angker,et al Journal of Dentistry,(2003) 31, 261-267

Dentin region	Elastic modulus(GPa)	Elastic modulus ranges (GPa)
300μm to DEJ	16.91±3.85	10.36-25.22
Middle dentin	17.06±3.09	9.25-25.08
500μm to pulp	11.59±3.95	2.88-19.68



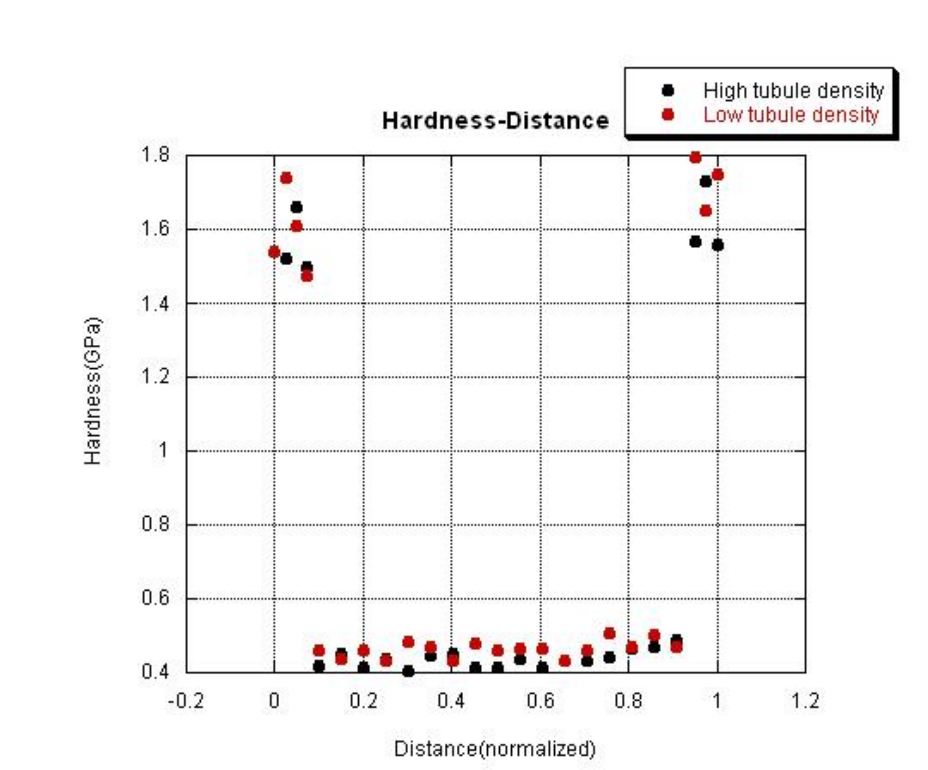
Linny Angker,et al Journal of Dentistry,(2003) 31, 261-267

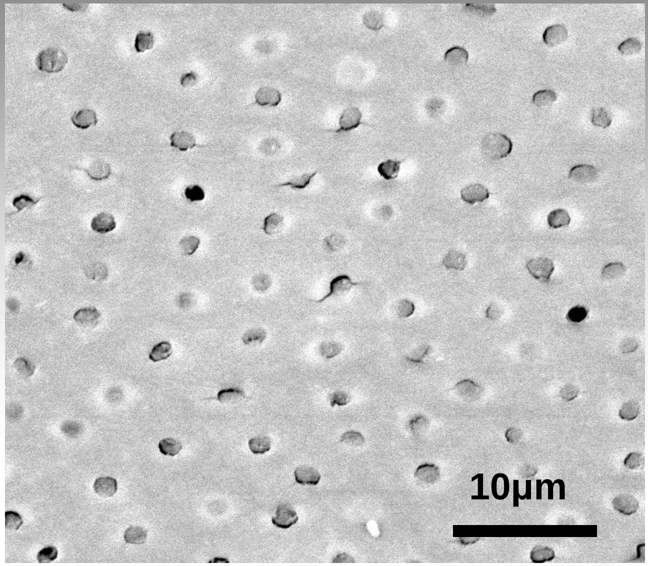


SEM images of dentine in three regions

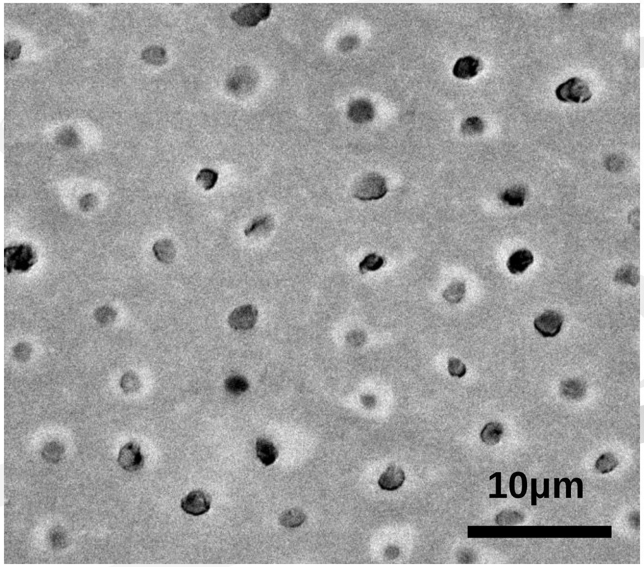
Linny Angker, et al ,Journal of Dentistry,(2003) 31, 261

Different hardness related to different tubule density





inner part(high density)

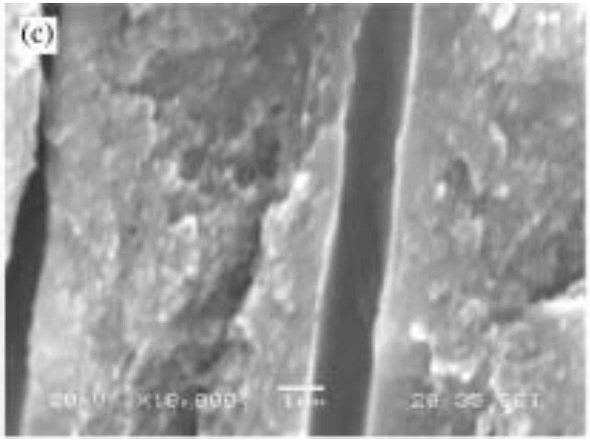


outer part(low density)

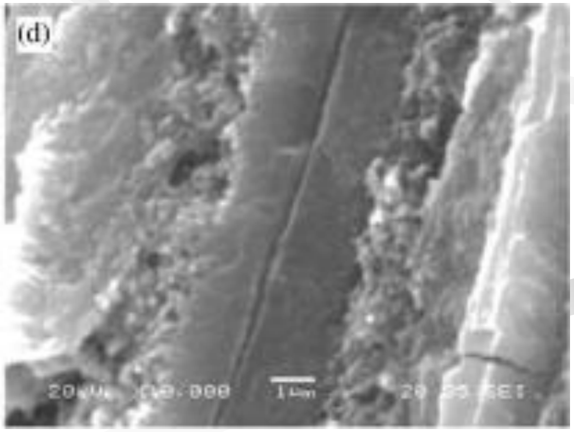
3. Effect of aging

- Aging can affect mechanical properties such as the crack-growth resistance, ductility and toughness of teeth.
- The deterioration of the mechanical properties are due to the filling of the dentin tubules with carbonated apatite.
- The way how the crack interacts with the microstructure in dentin is important which is observed by SEM.

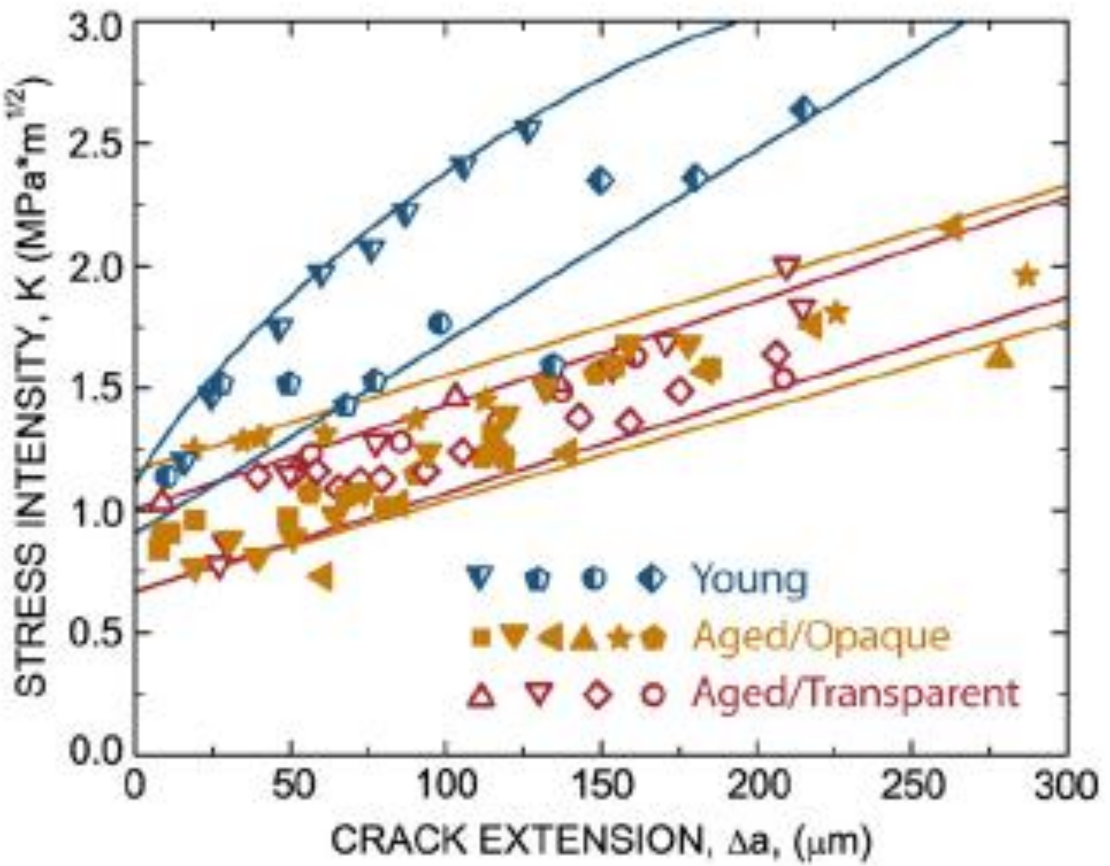
age20

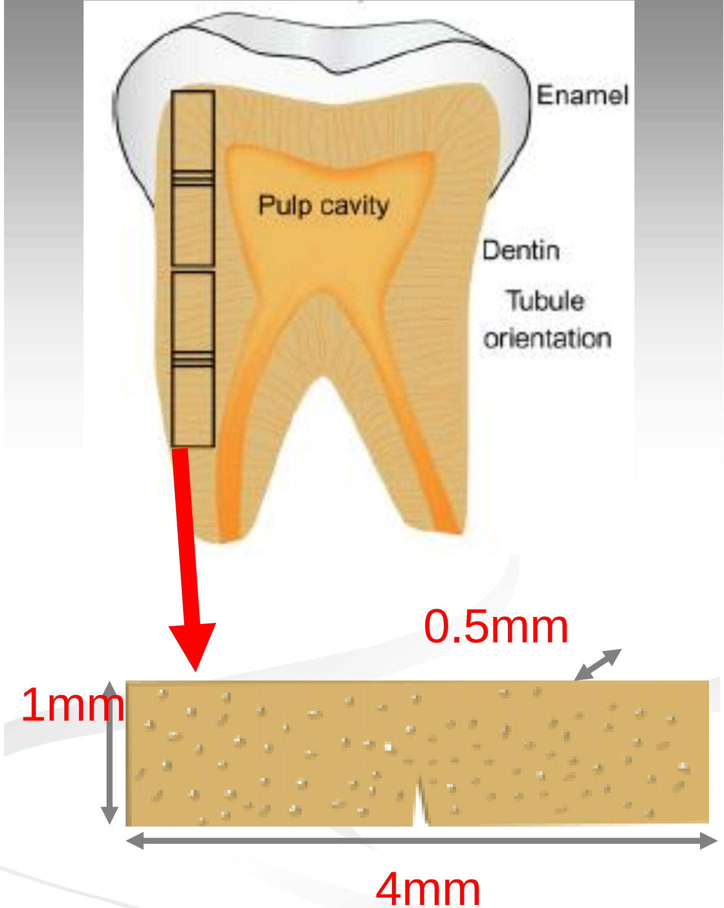


age67



D.Arola,et al ,Biomaterials, 2005;26:4051-40

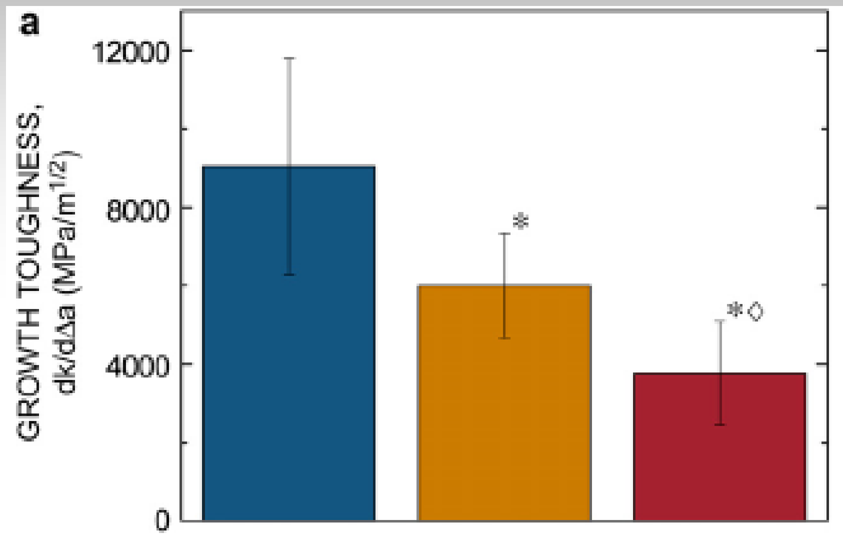


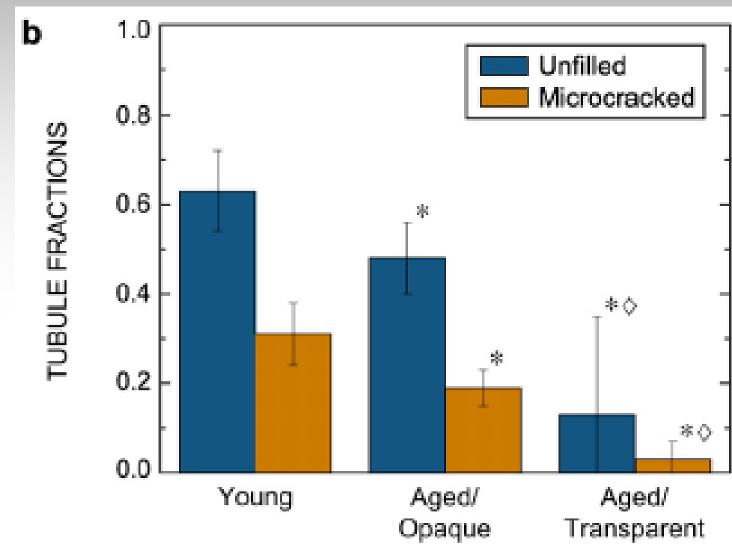


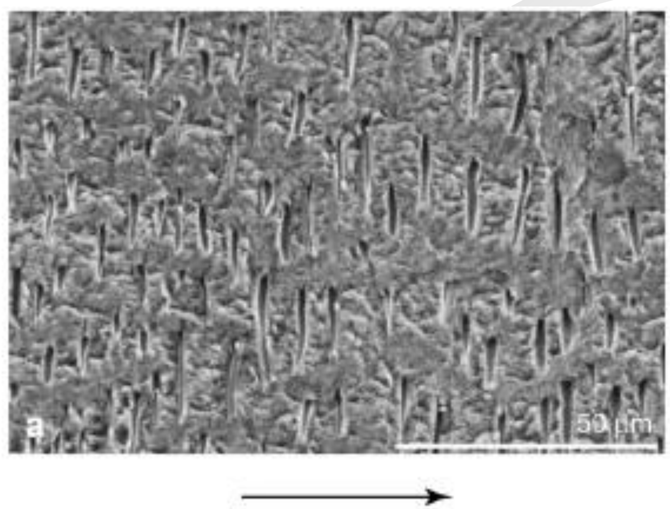
	Tubules/10000μm	Filled tubule fraction
Young	129±60	0.04±0.03
Aged/opaque	106±29	0.20±0.08
Aged/transparent	128±48	0.87±0.19

K.J.Koester, et al Biomaterials 2008;29:1318-1328

- Crack-growth toughness: the slope of the resistance curve.



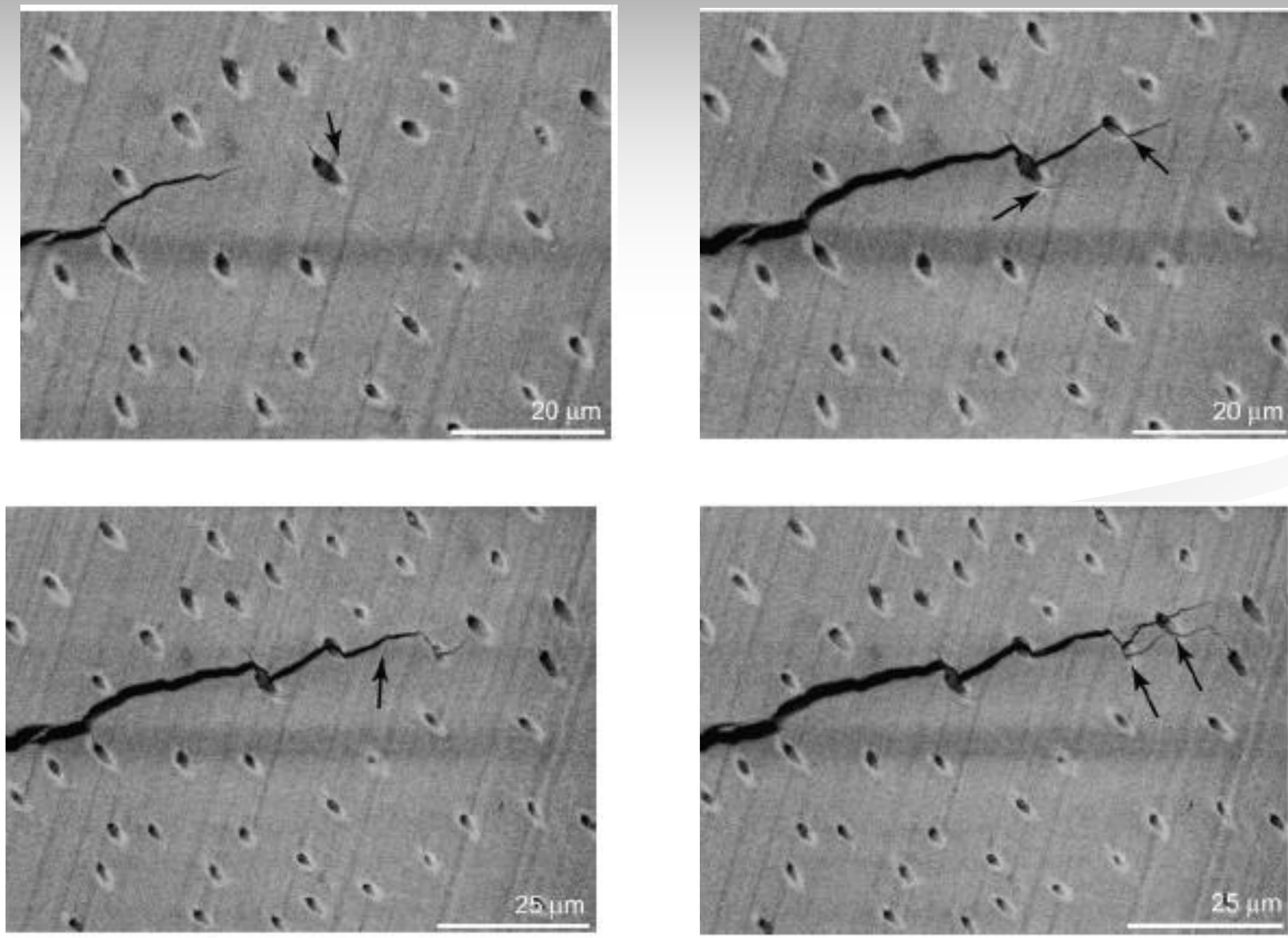




Crack Propagation

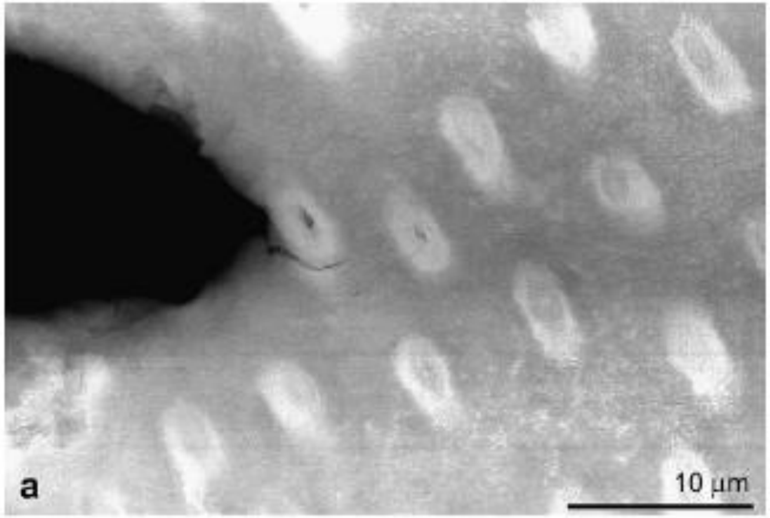
K.J.Koester, et al Biomaterials 2008;29:1318-1328

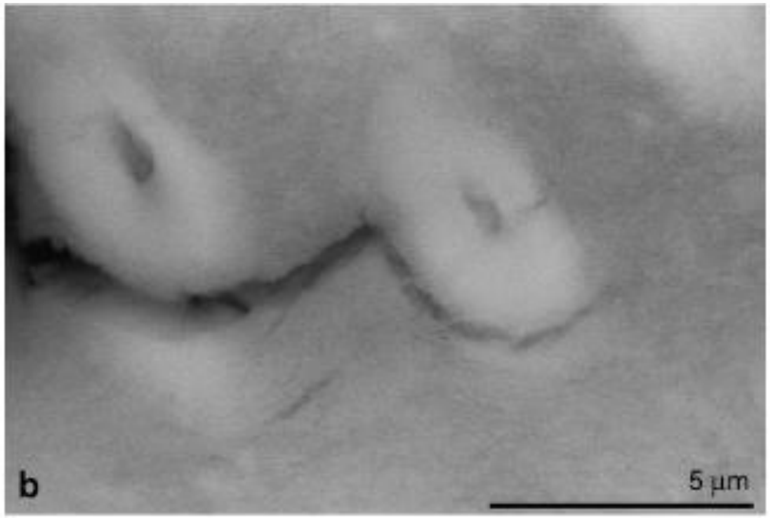
ESEM images of crack propagate in young dentin



K.J.Koester, et al Biomaterials 2008;29:1318-1328

- When the crack interact with the filled tubule, it will propagate around the interface with the matrix instead of penetrating the filled tubule.

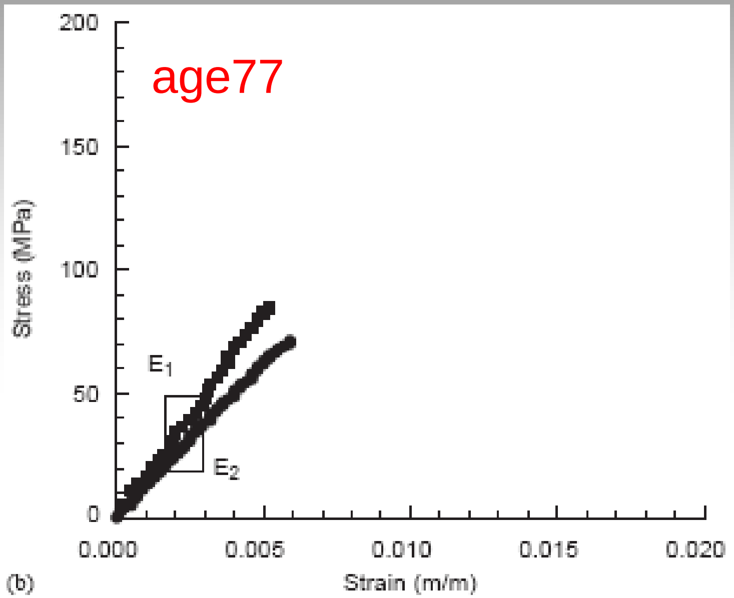


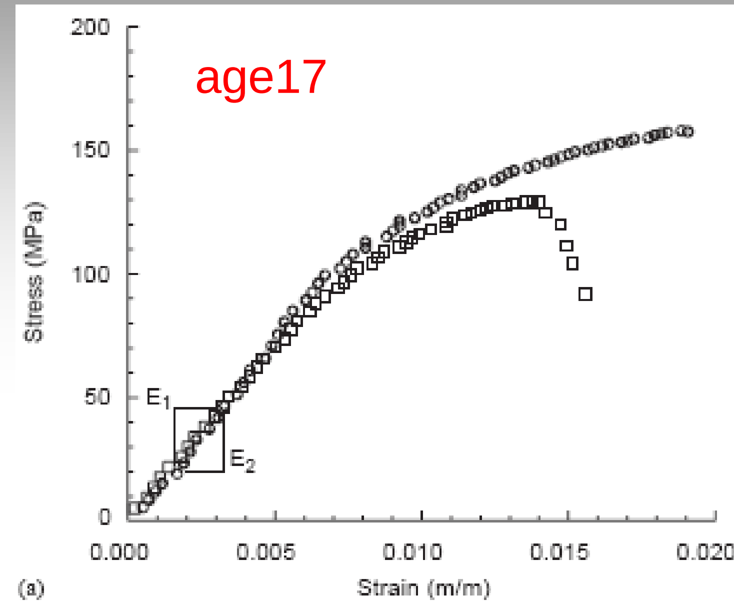


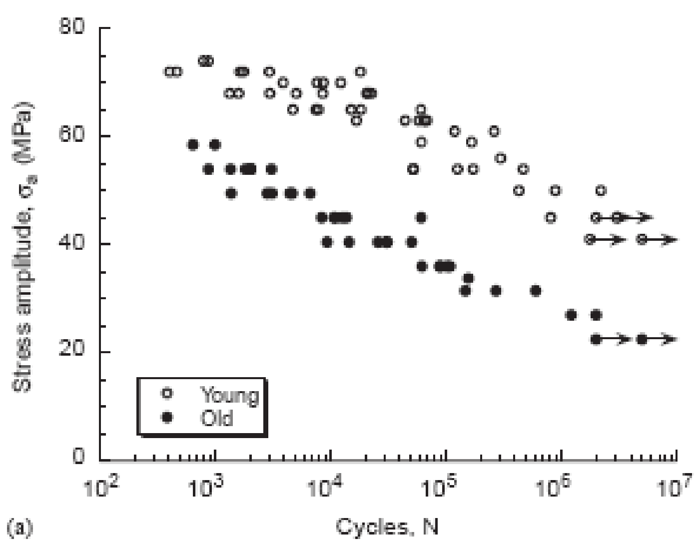
K.J.Koester, et al Biomaterials 2008;29:1318-1328

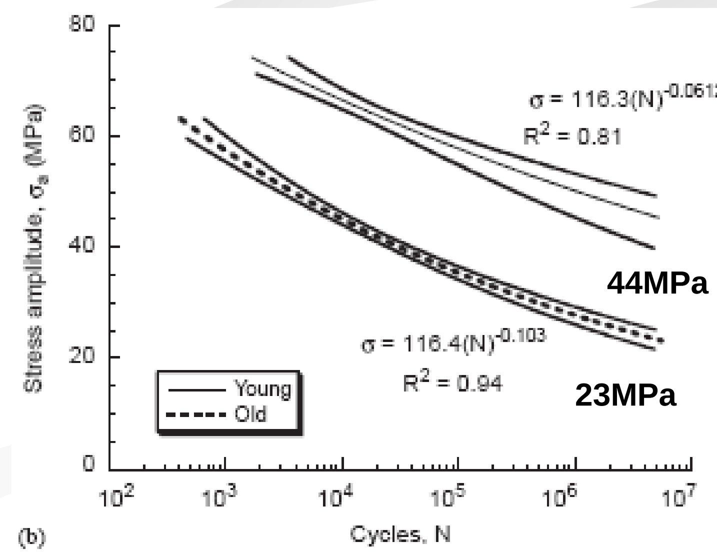
Young dentin(19-30)	Aged dentin(40-70)
Unfilled tubule	Filled tubule
More microcrack and microbranching tubules	Fewer microcrack and microbranching tubules due to fewer unfilled tubule
Straighter crack deflection	Less straighter crack path
Crack bridge forms between tubules	Crack bridge is formed by filled tubule itself

Effect of aging on flexural and fatigue test









D.Arola, R.K. et al Reprogel, Biomaterial 2005;26:4051-4061

Shark teeth

1 Puncture teeth

- There is no serrations on the puncture teeth which is to reduce the resistance to puncture the prey.
- The recurvature of the teeth is to hold the prey and the reversal at the tooth tip is to ensure initial puncture

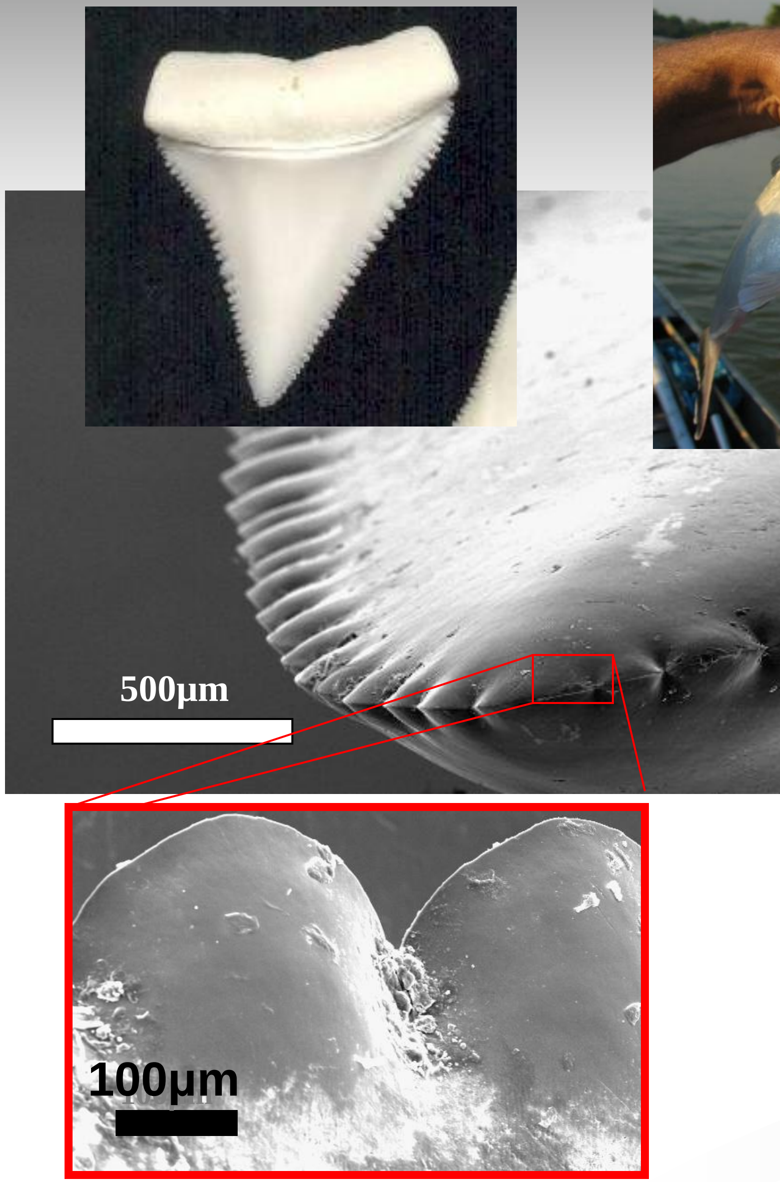
2 Silicing teeth

- Slicing teeth usually possess serration to enhance draw cutting
- The serrations usually appear on upper teeth

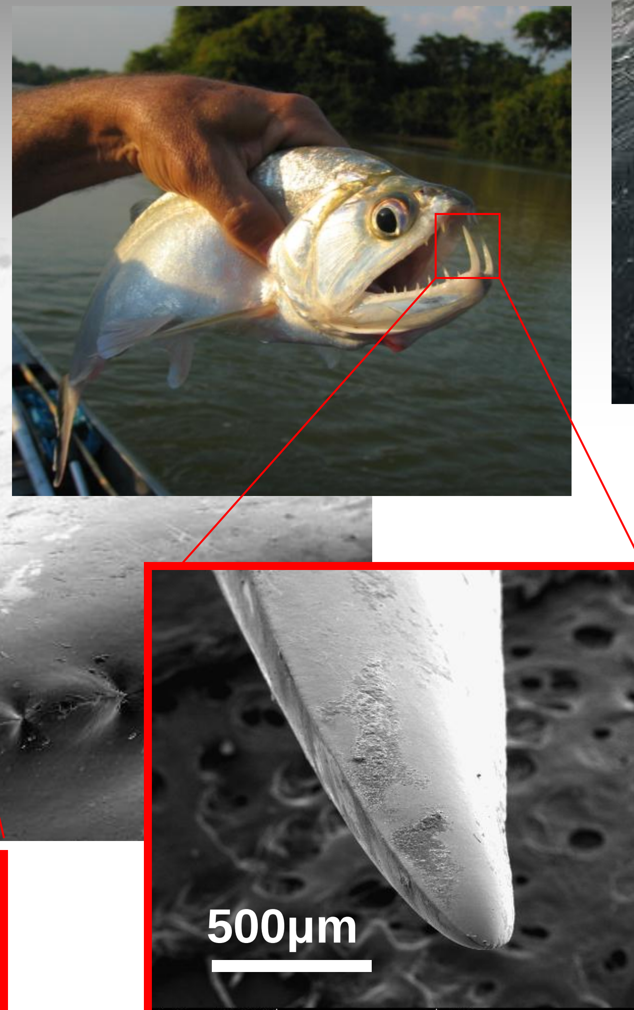
Anterior upper and lower teeth of the lamniform sand tiger shark

Great white shark tooth

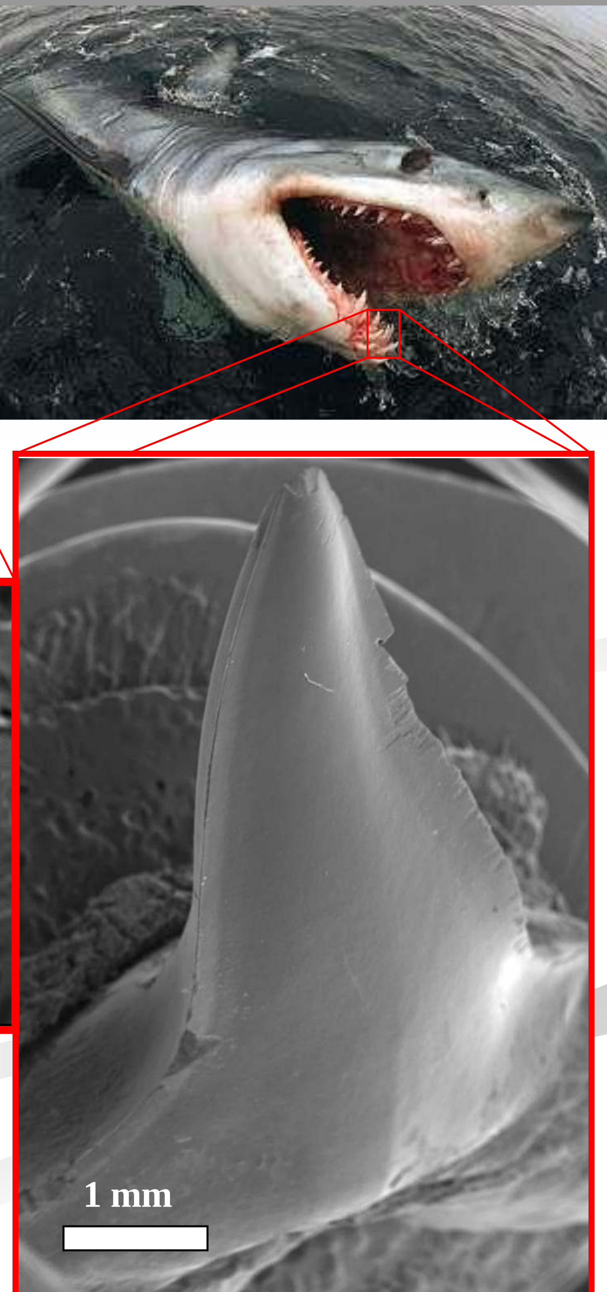
Great white shark tooth



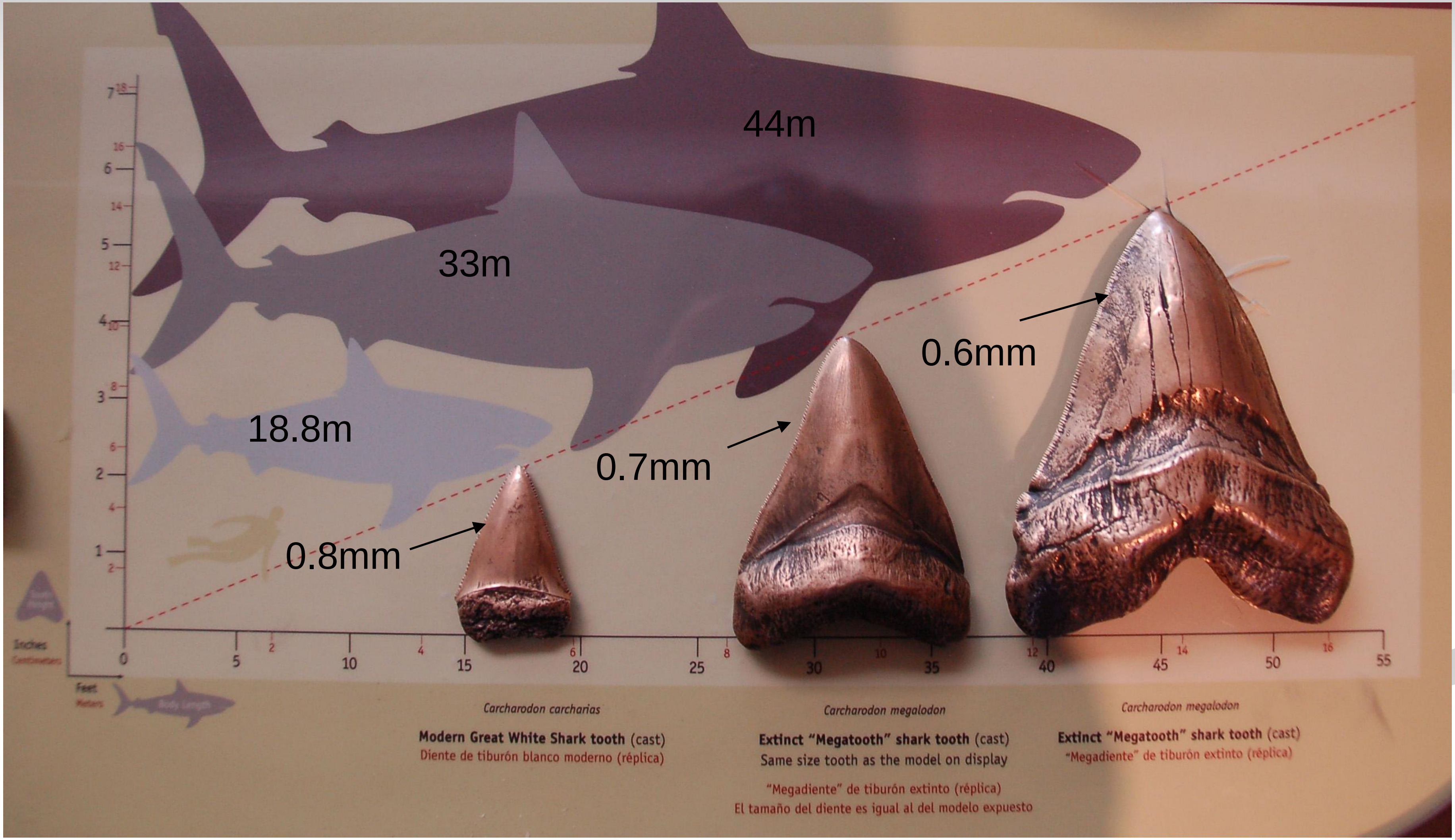
Dogfish tooth



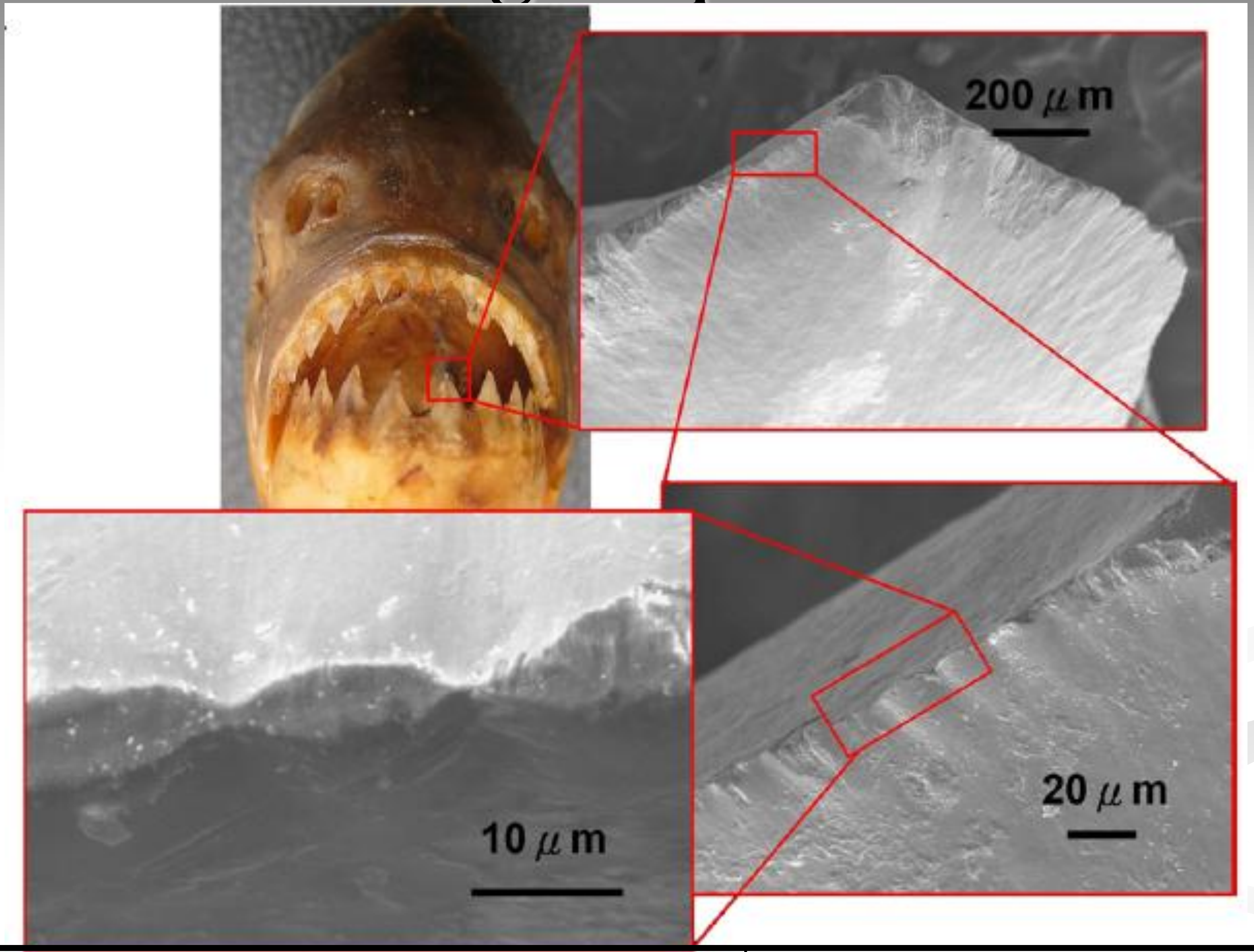
Mako shark tooth



Megalodon and great white shark teeth



Serrated edge of piranha teeth

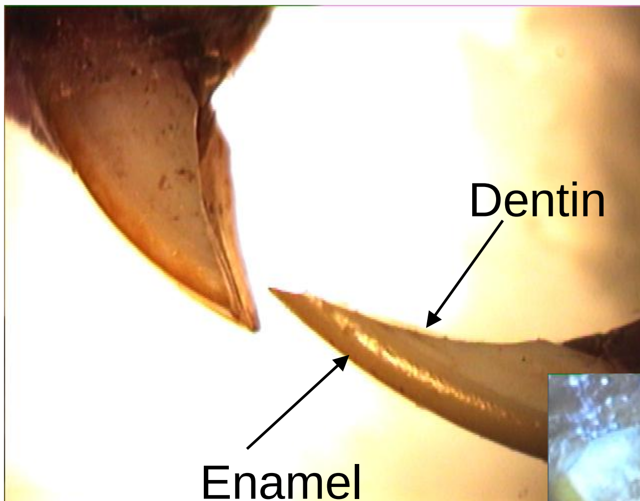


	Serration size(μm)
Tyrannosauroid dinosaurs	312
Great white shark	300
Piranha	15

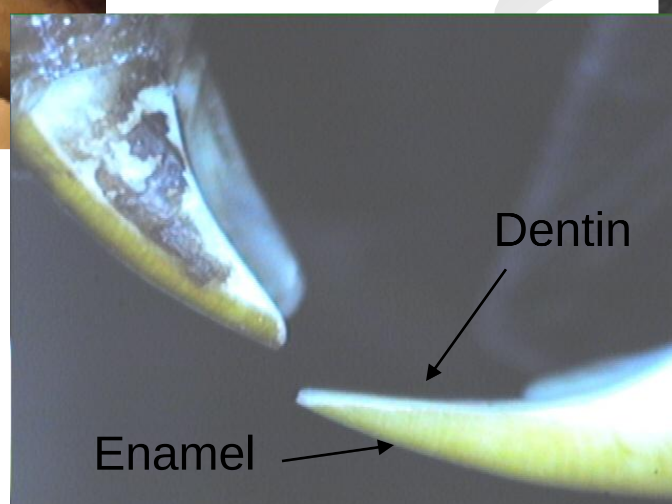
Rodent tooth

- Self-sharpening

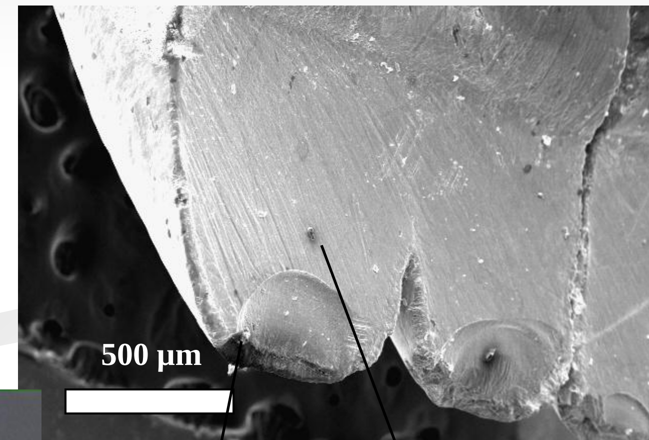
Rodent's tooth has hard enamel covered along outside surface but soft dentin inside. The wear progresses more rapidly on the soft dentine and keep the sharpness of the teeth.



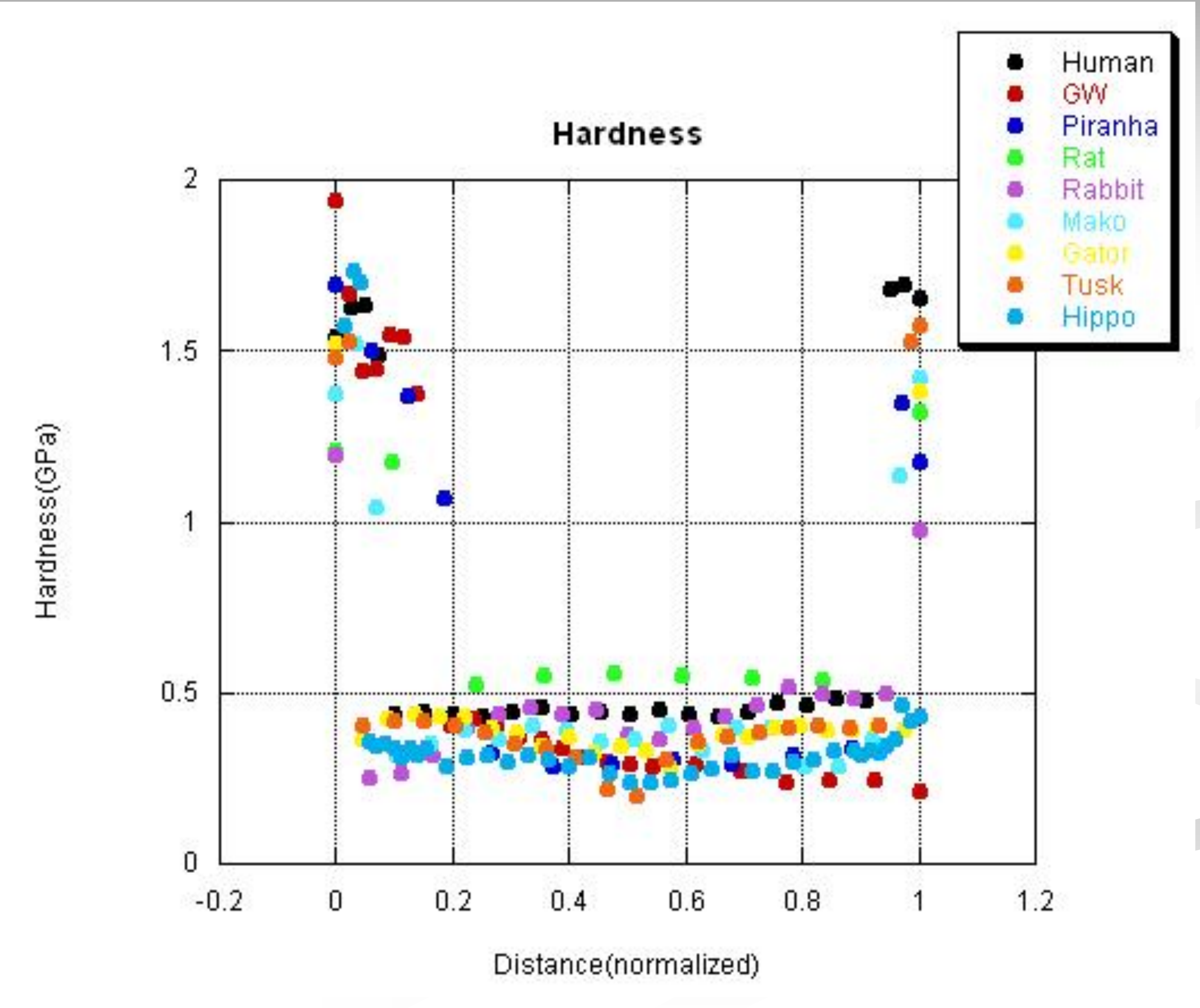
Rat



Squirrel



Hardness of several animal teeth



Conclusions

- The dentin with tubule orientation parallel to the loading direction exhibits higher mechanical properties than those with tubule orientation perpendicular to the loading direction.
- The dentin close to DEJ has higher hardness and elastic modulus than that close to pulp due to the lower density and diameter of tubule.
- Aged dentin displays lower crack growth toughness due to the large fraction of tubule filled with carbonated apatite.
- For all scale of sharks, their serration size are in the same order.
- Hardness tests display that all kinds of animals have similar hardness value in dentin and enamel.