Quantitative Texture Analysis of shells, Palm Canyon mylonites, natural ice, metamorphic amphibolites and SCT-microquartz

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Outline

- Textures of mollusc shells
  - Generalities
  - **a**- and **c**-axes patterns of aragonitic layers, twinning
  - Complex growth of layers: microstructure versus texture
  - global versus local probes
  - QTA and Mollusc's Phylogeny
  - QTA and calcitic fossils
  - QTA and Mollusc's prothaetics
- Polyphased Mylonite (Palm Canyon, California)
- Natural ice from the Greenland GRIP core
- Metamorphic Amphibolites from Alps
- Siliceous Crust-Type microquartz

Textures of Mollusc Shells

In collaboration with

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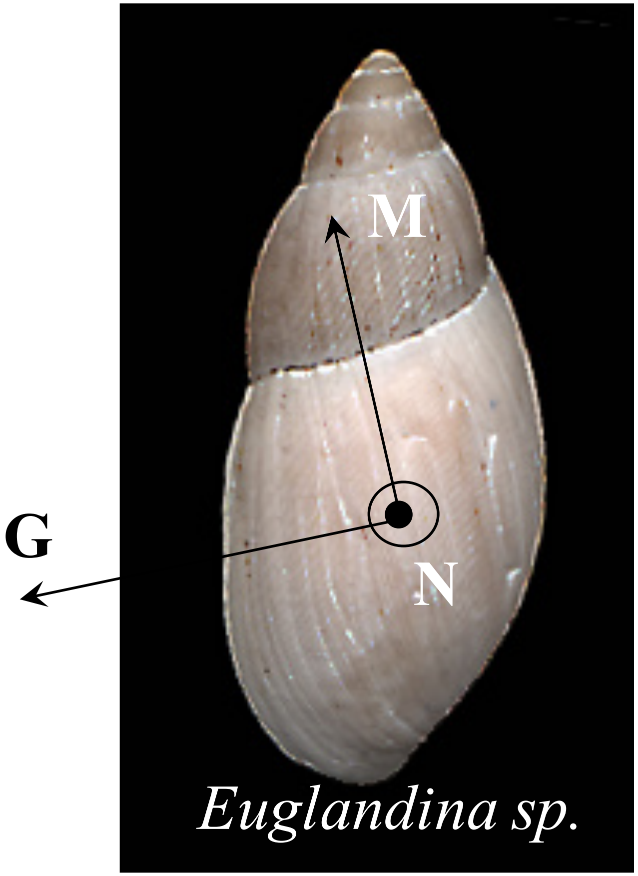
H.-R. Wenk *(DEPS Berkeley, USA*)
L. Harper *(DES Cambridge, UK)*
M. Morales *(SIFCOM Caen, France)*

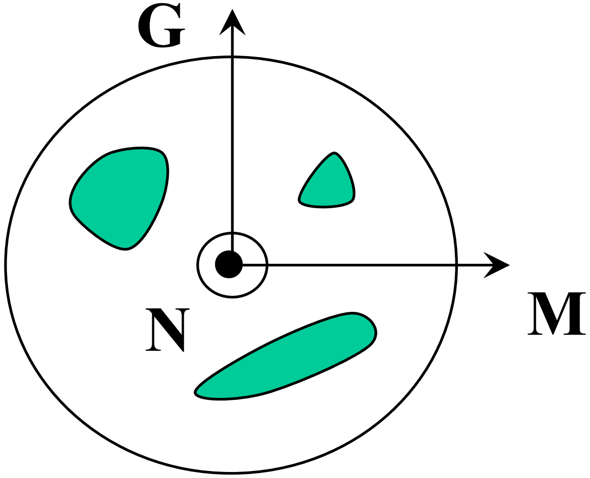
Generalities

Reference frame in mollusc shells



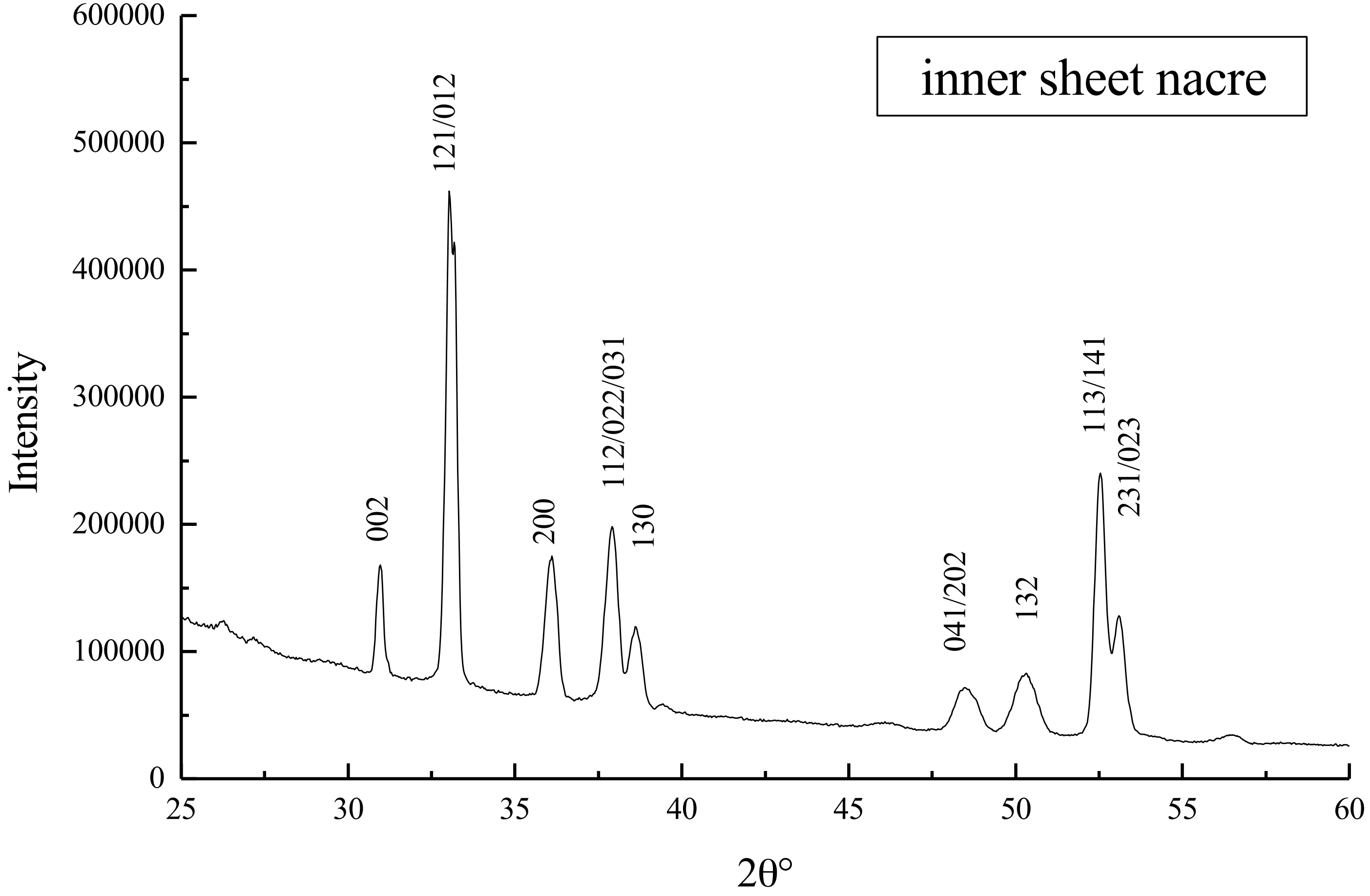
Euglandina sp.

- Crystal: $CaCO_3$, aragonite (Pmcn) or calcite ($R\bar{3}c$), for thousands of crystallites:

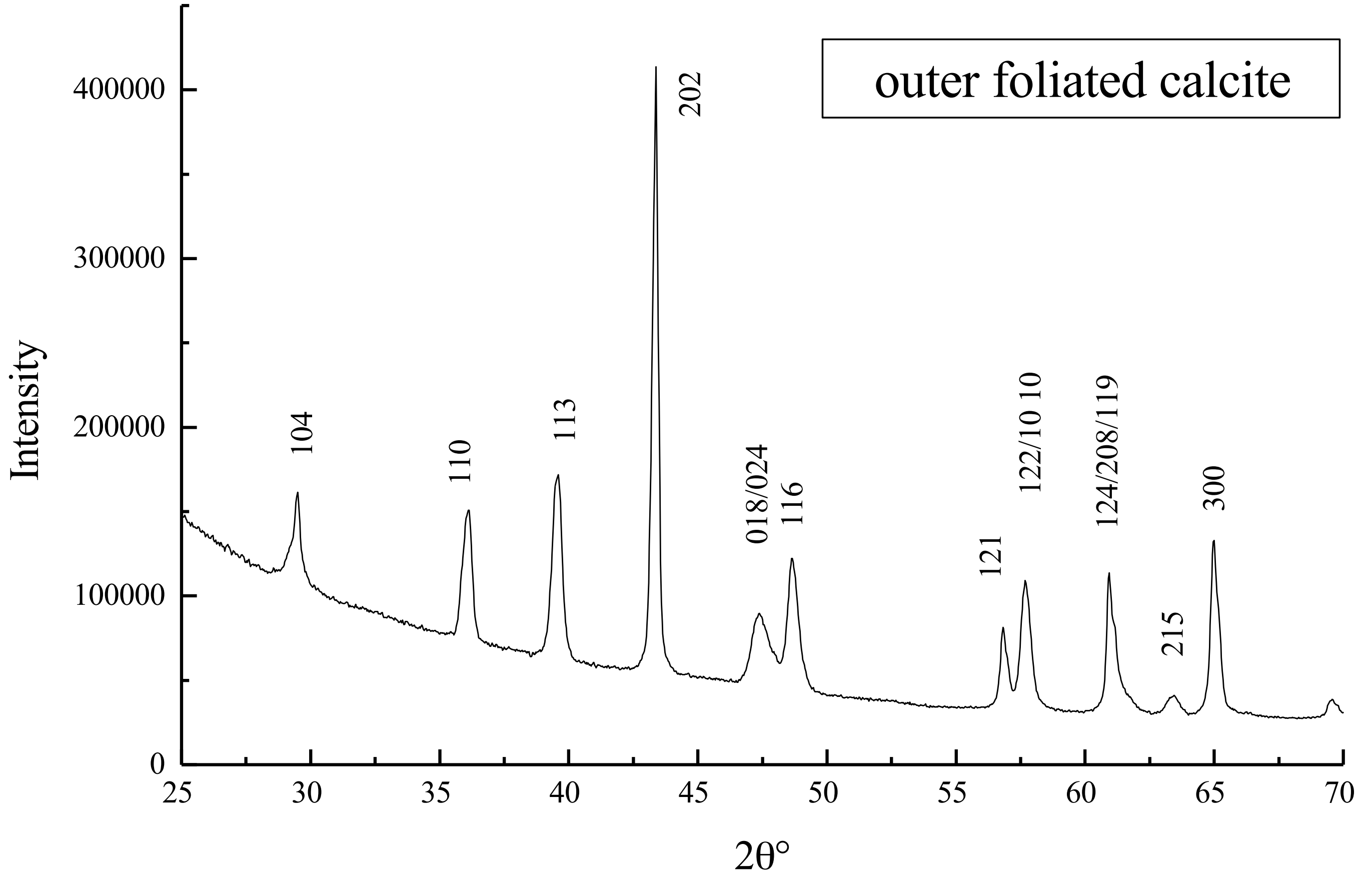


Typical x-ray diffraction pattern

Mytilus edulis (common mussel)

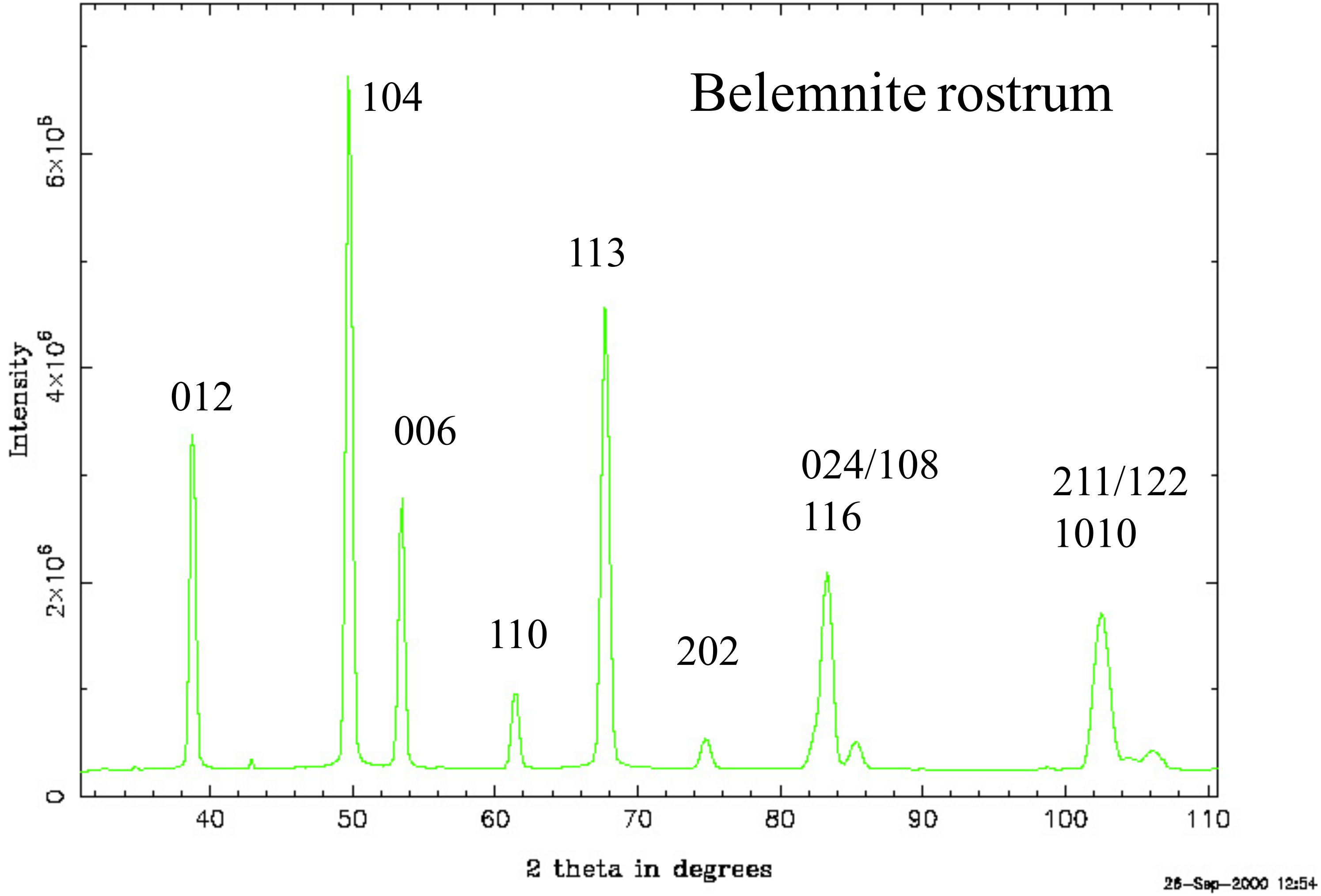


Crassostrea gigas (common oyster)

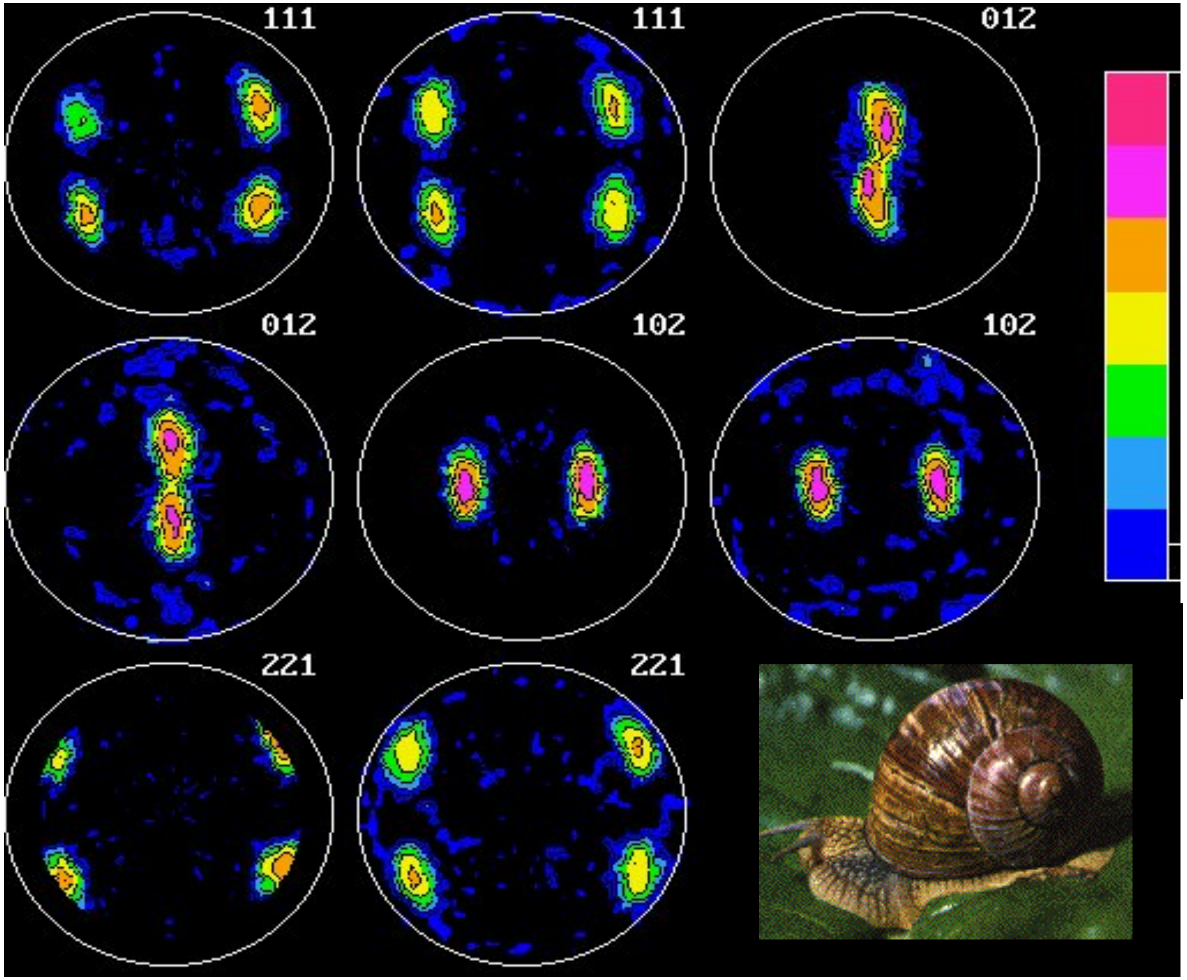


Measured for around 1000 sample orientations, using x-rays, neutrons
With electrons, around 3000 crystallites probed, provided flat surface

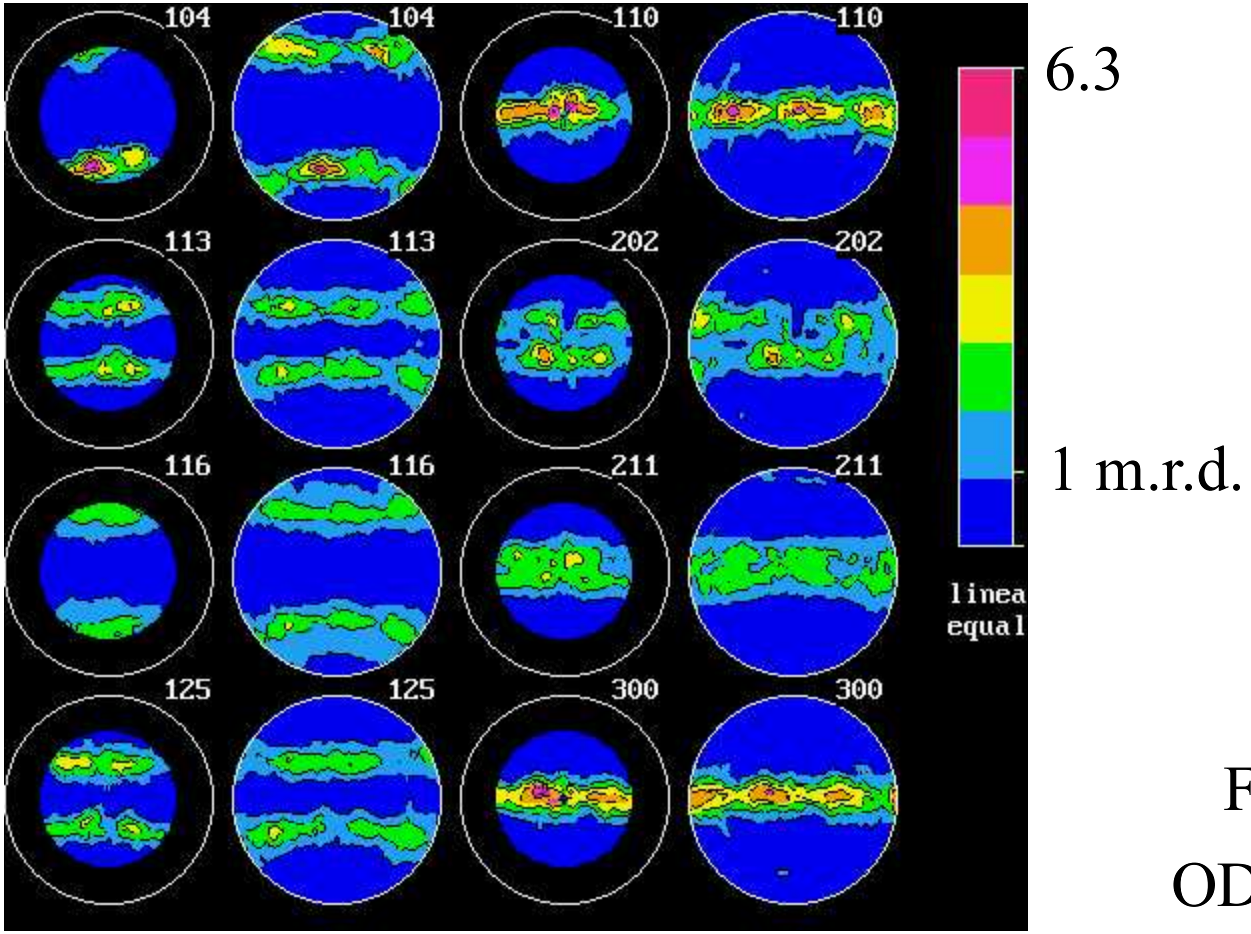
Typical neutron diffraction pattern



ODF-reliability (x-rays: point detector): *Helix pomatia* (Burgundy land snail: Outer com. crossed lamellar)



OD-reliability (x-rays: PSD): *Bathymodiolus thermophilus* (deep ocean mussel: Outer Prismatic layer)



$RP_{0.05} = 25\%$

$RP_1 = 17\%$

$S = -1.9$

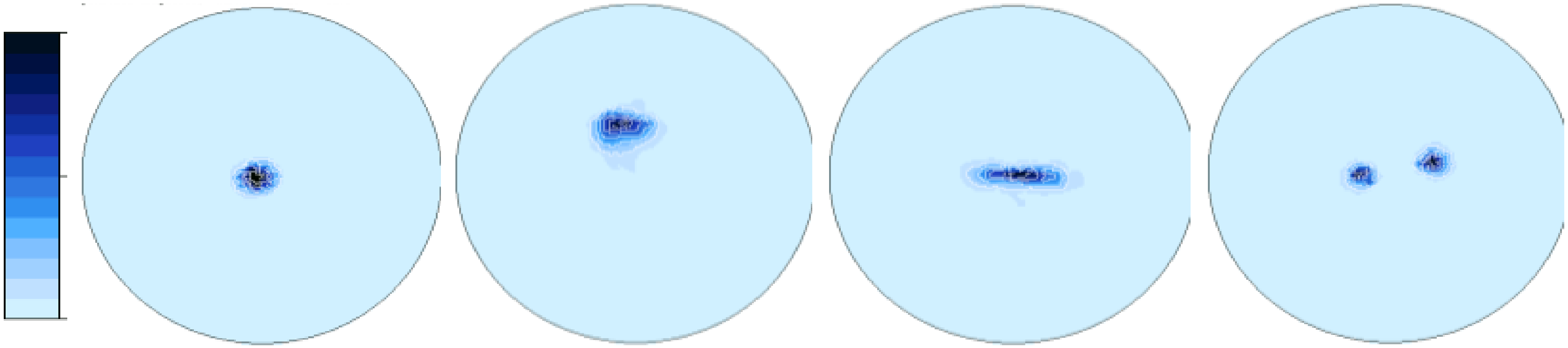
$F^2 = 13$ m.r.d.^{2}

$OD_{max} = 63$ m.r.d.

a- and **c**-axes patterns of aragonitic layers, twinning

c-axes texture patterns

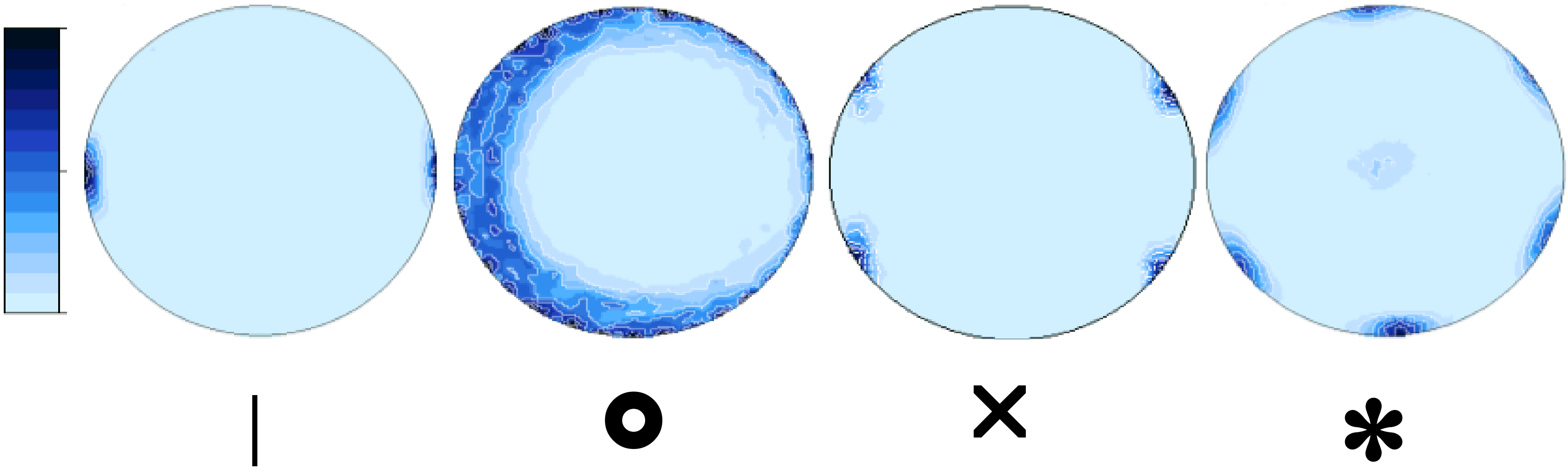
Pinctada maxima	*Nerita polita*	*Fragum fragum*	*Cypraea testudinaria*
ISN	ICCL	ICCL	ICCL
“gold pearl oyster”	“polished nerite”	“cockle”	“turtle cowry”



⊥	∠	∀	∨

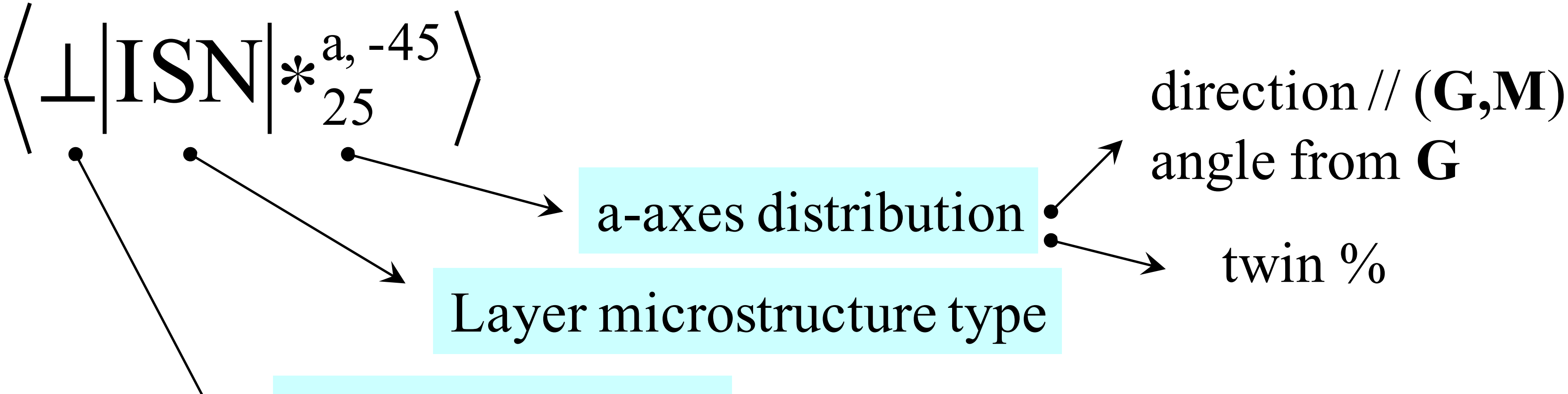
a-axes texture patterns

Helix pomatia	*Tectus niloticus*	*Conus leopardus*	*Nautilus pompilius*
OCCL	ICN	ICCL	ICN
“burgundy land snail”	“commercial top shell”	“leopard cone”	“new caledonia nautilus”



Chateigner, Hedegaard, Wenk, J. Struct. Geol. **22** *(2000) 1723-1735*

Proposal for a nomenclature for texture and microstructure types



$$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,-45}_{25} \right\rangle$$

a-axes distribution

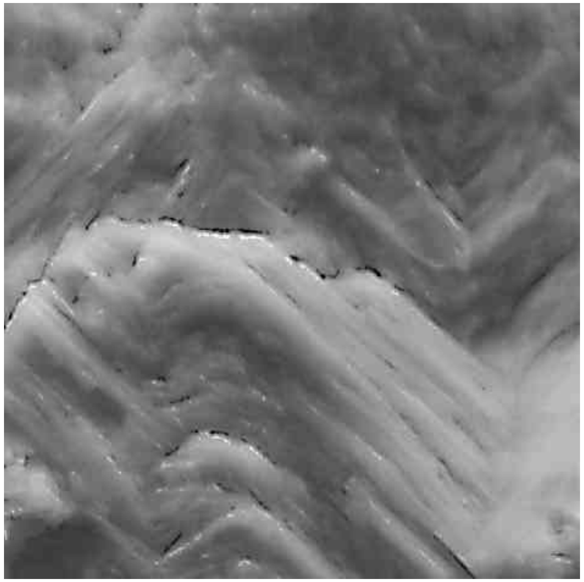
direction // **(G,M)**
angle from **G**

twin %

Layer microstructure type

c-axes distribution

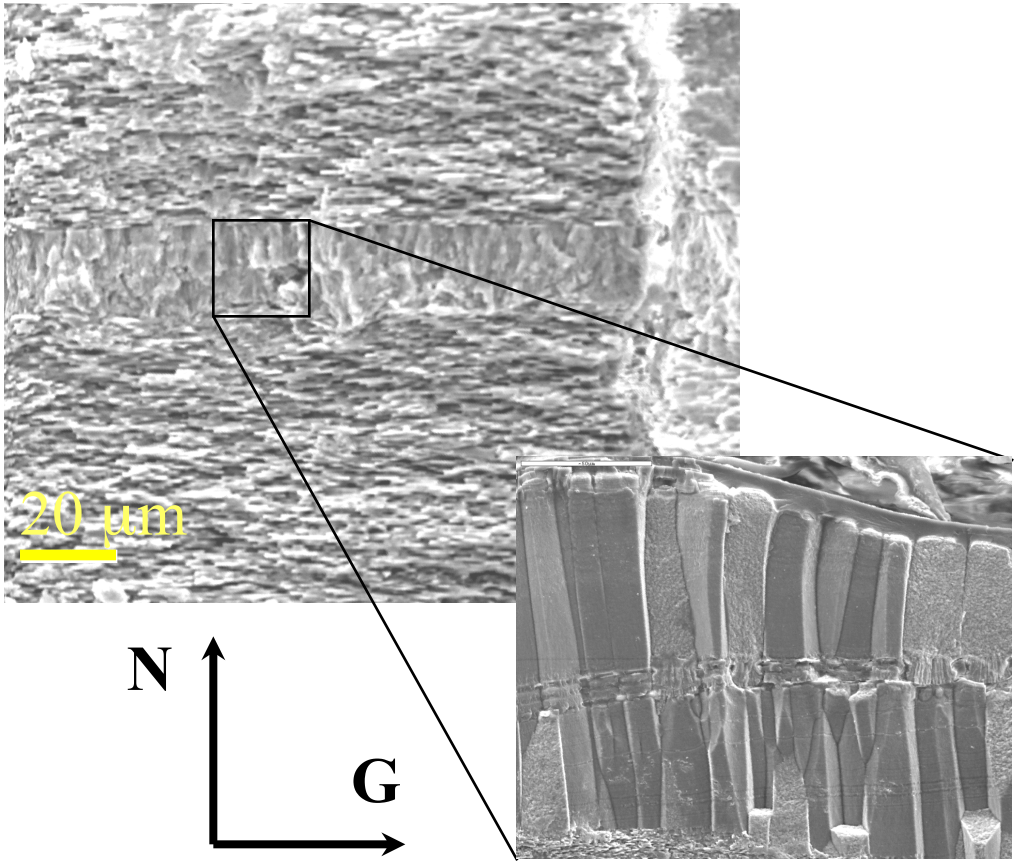
ISN: Inner Sheet Nacre
ICCL: Inner Comarginal Crossed Lamellar
ORCL: Outer Radial Crossed Lamellar
ICN: Inner Columnar Nacre
IPC: Inner Prismatic Calcite …

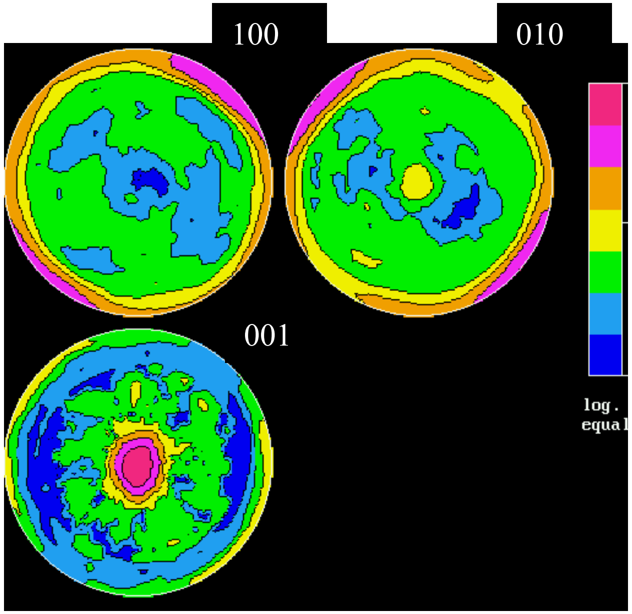


Microstructure versus Texture

Inner sheet nacre of *Anodonta cygnea* (river mussel):

no intra-mineral epitaxy

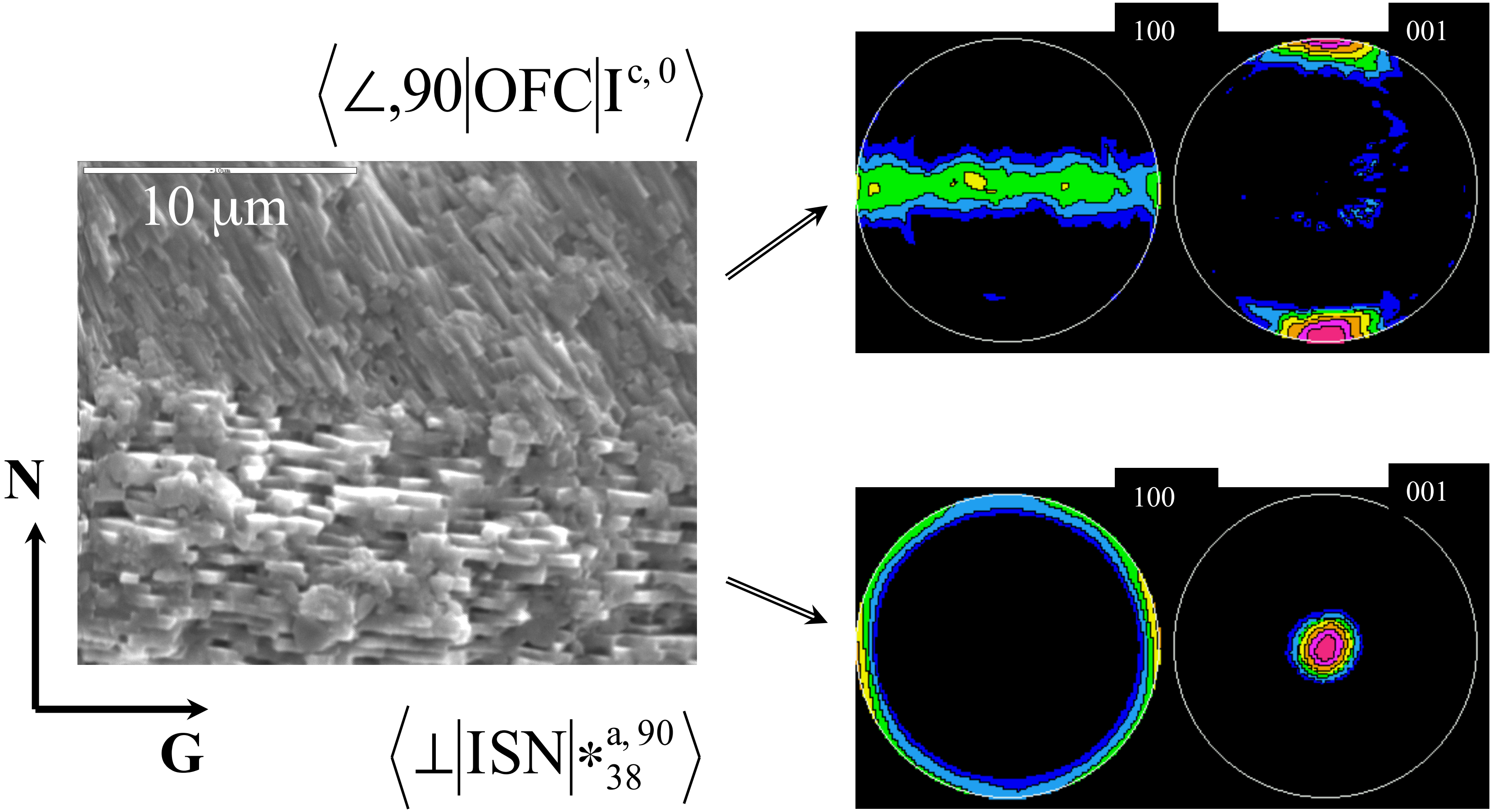




$$\left\langle \perp \left| \mathrm{ISN} \right| *^{a,\,-45}_{25} \right\rangle$$

Bathymodiolus thermophilus (-2400m deep mussel):

no inter-mineral epitaxy

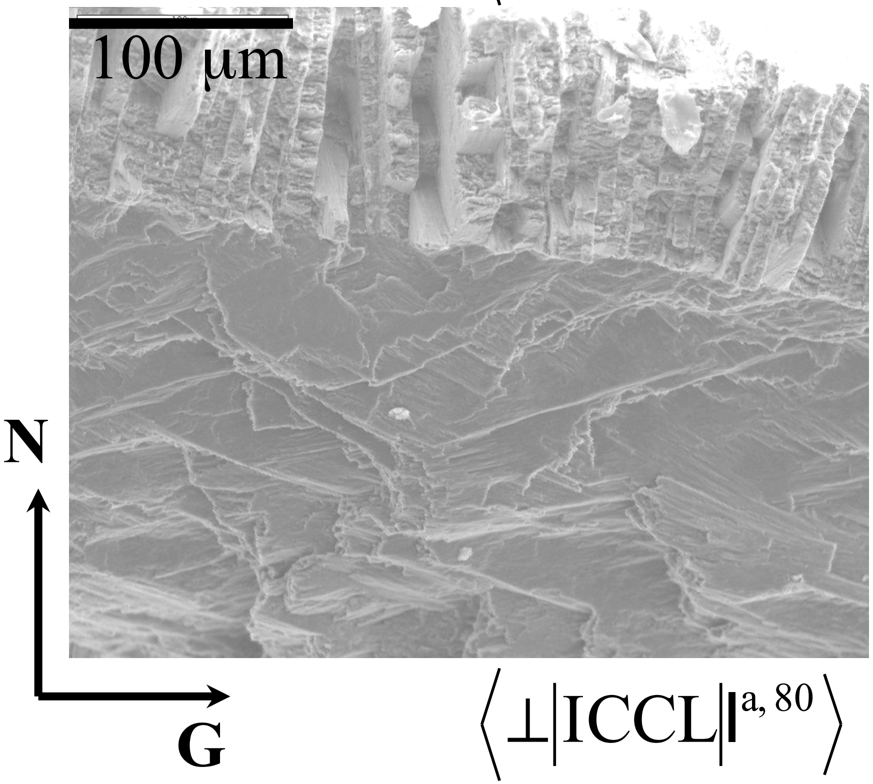


$$\left\langle \angle,90 \middle| \mathrm{OFC} \middle| \mathrm{I}^{c,\,0} \right\rangle$$

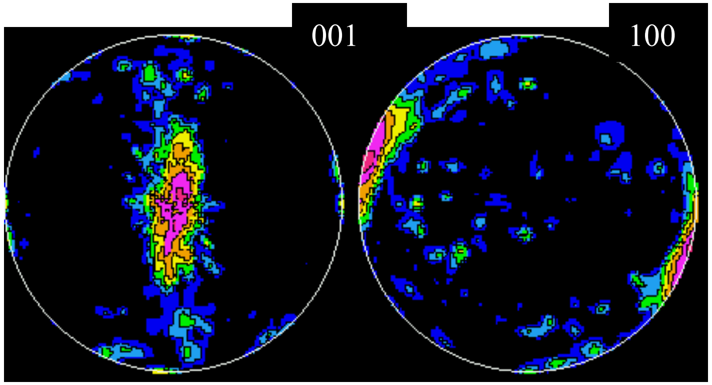
$$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,90}_{38} \right\rangle$$

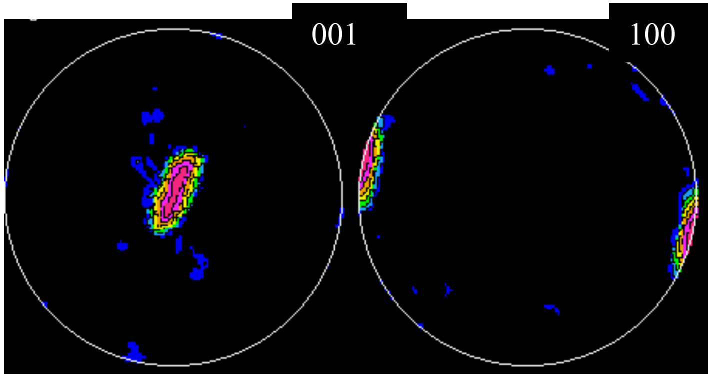
Euglandina sp.: different crystallite shapes, close orientations !

$\left\langle \perp|\mathrm{ORCL}|\mathbf{l}^{a,\,75} \right\rangle$

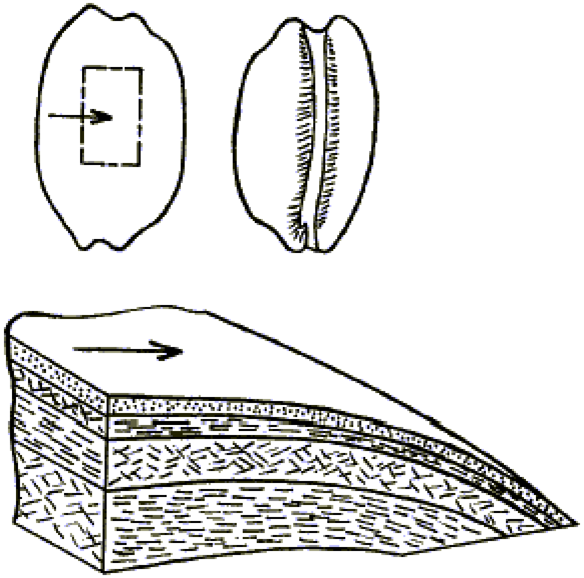


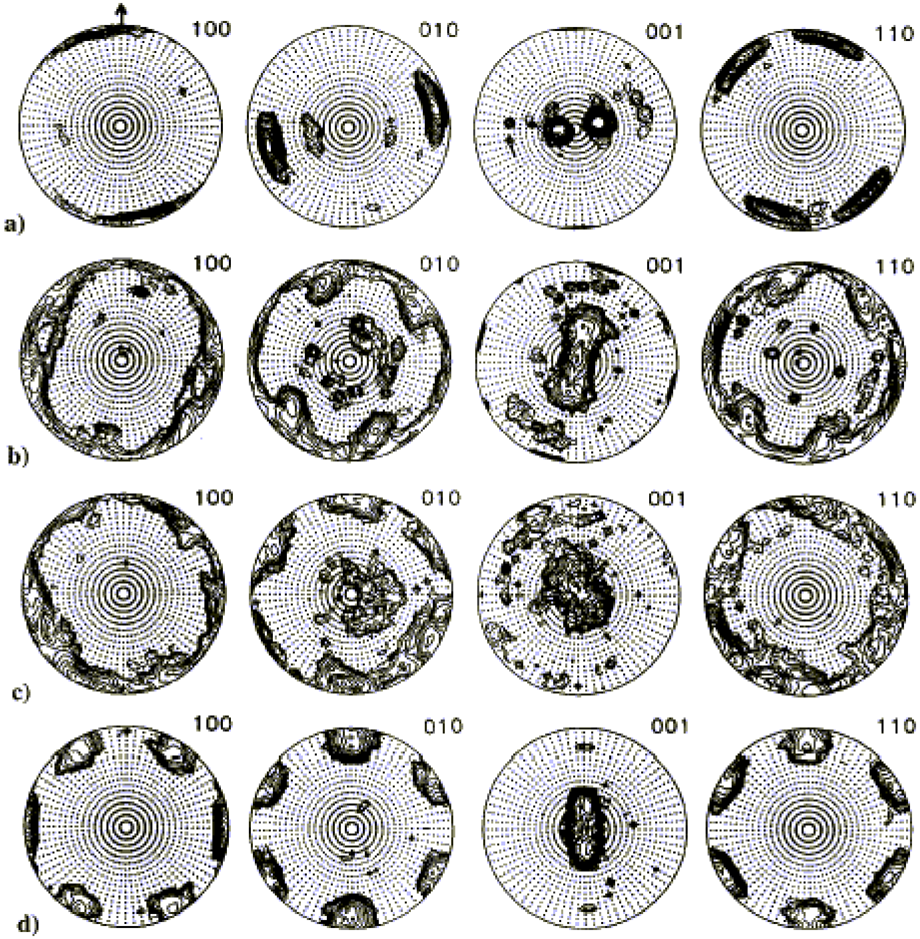
$\left\langle \perp|\mathrm{ICCL}|\mathbf{l}^{a,\,80} \right\rangle$





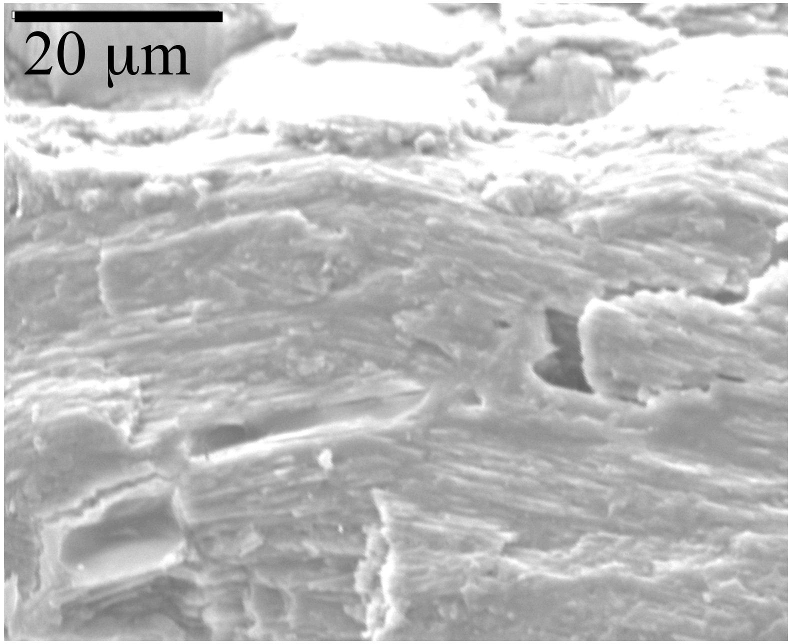
From ISN to OCCL layers of *Cypraea testudinaria* (cowry):
no inter-layer epitaxy

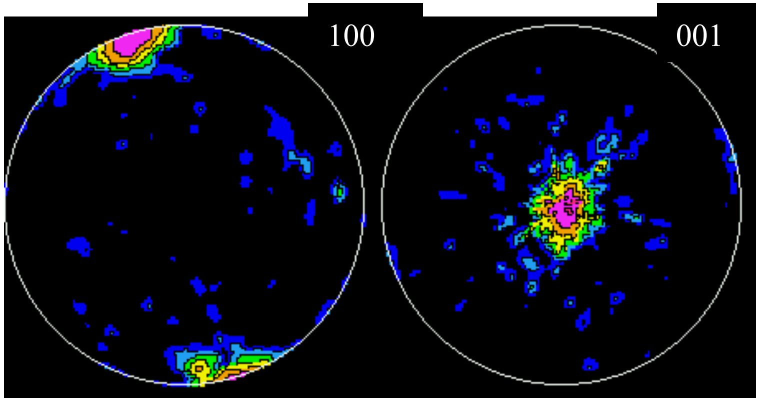


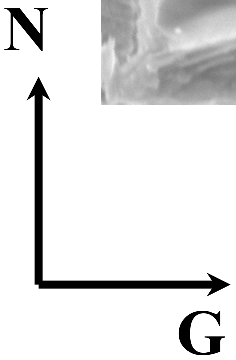


Organically driven growth

Cyclophorus woodianus: different SEM grain orientations look like single crystal from diffraction !



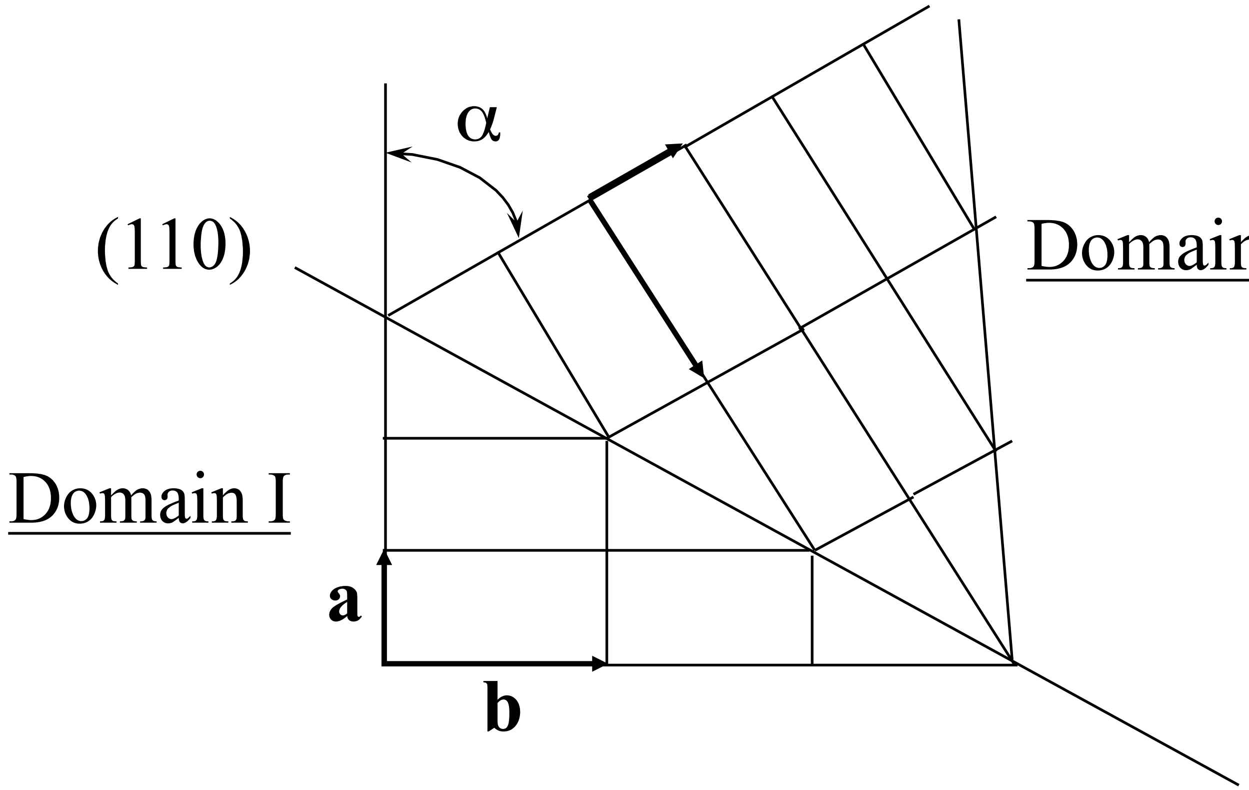




$$\left\langle \perp \middle| \mathrm{IRCL} \middle| \mathbf{l}^{a,\,20} \right\rangle$$

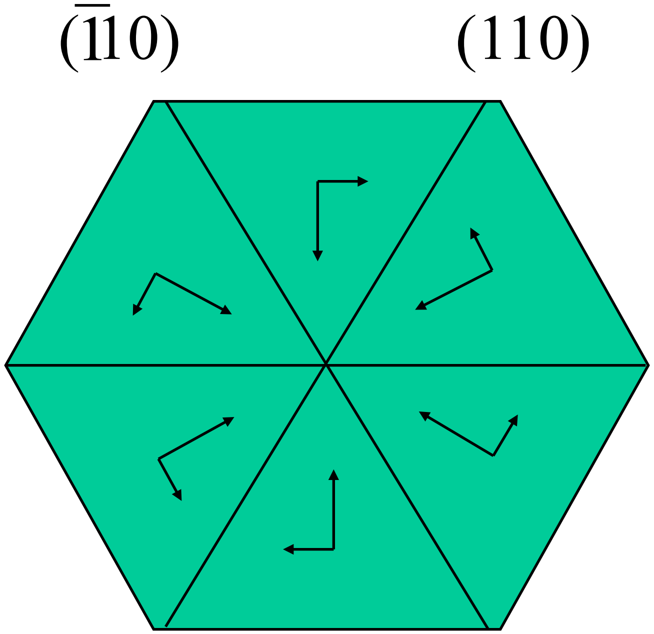
Texture parameters may deserve phylogenic analysis

Twinning in aragonite ...

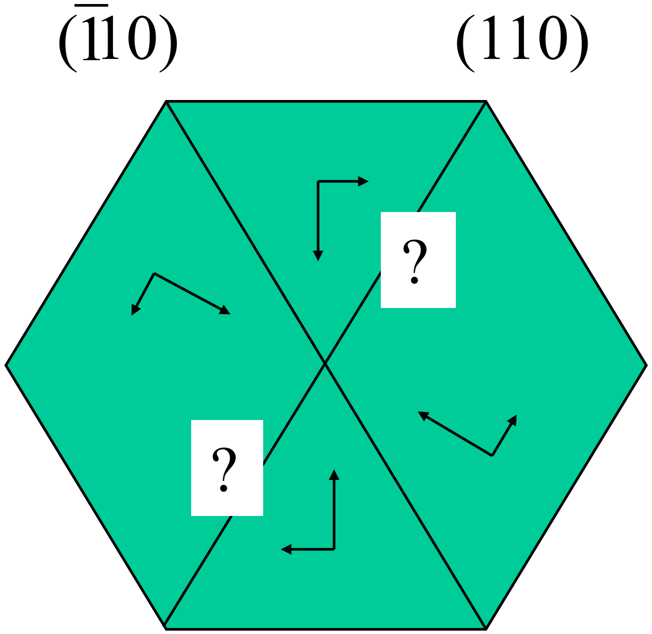


$\alpha = 2 \arctan(a/b) = 63.8^\circ$

… forms nacre platelets ...

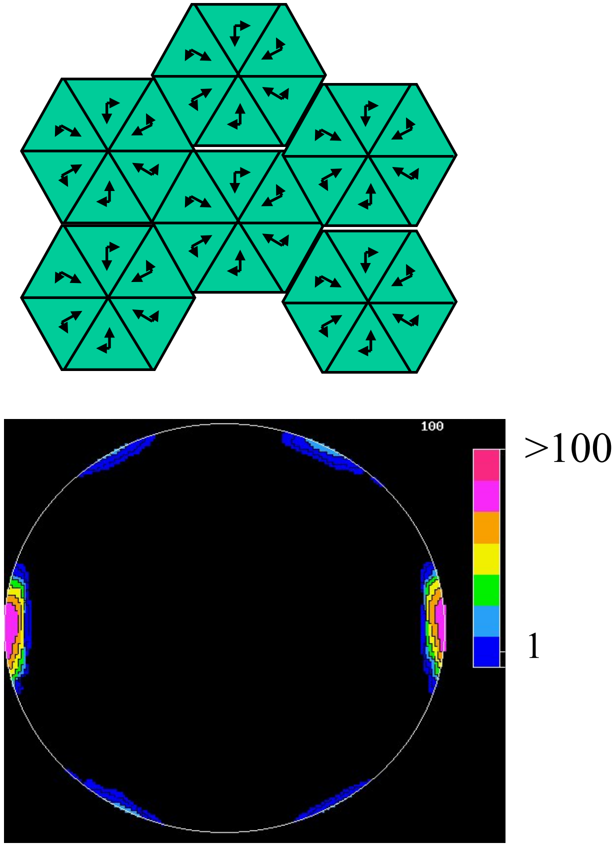


Bragg, 1937

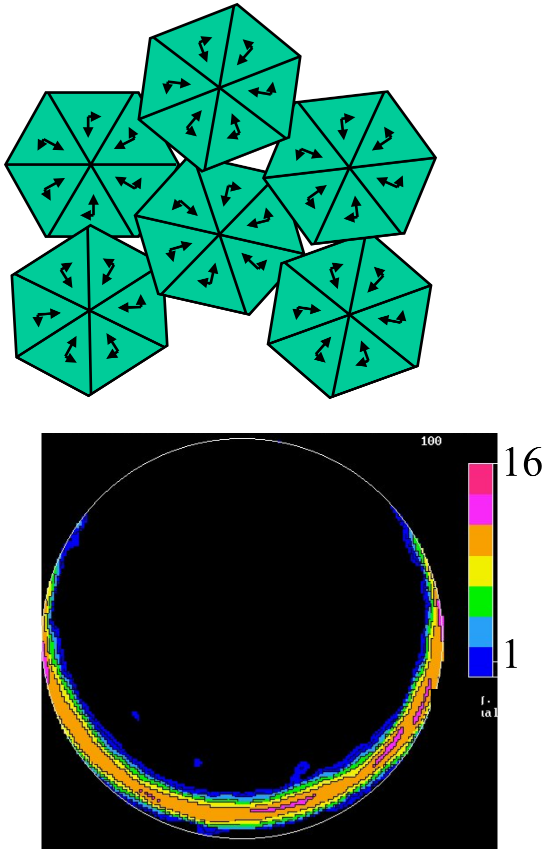


Mutvei, 1980

… that rearrange …



Pinctada margaritifera
(black pearl oyster: ISN)

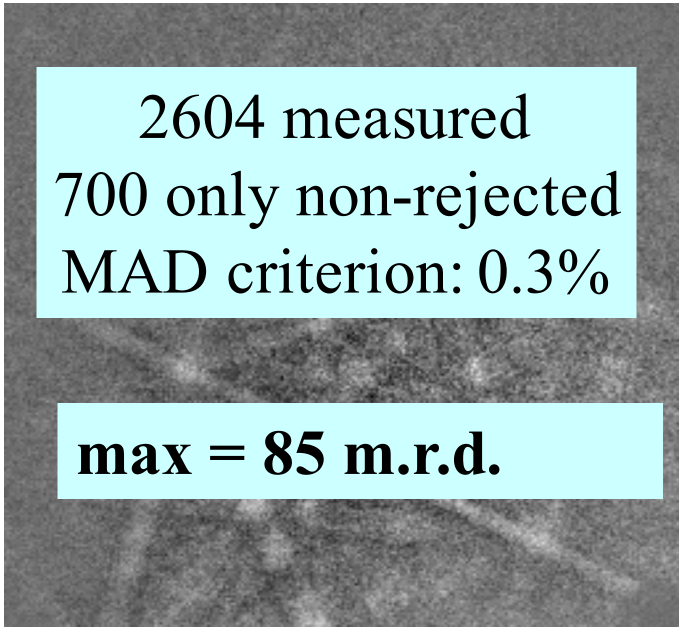


Haliotis cracherodi
(black abalone: ISN)

Global versus Local probes

Crassostrea gigas (common oyster: Inner foliated calcite)

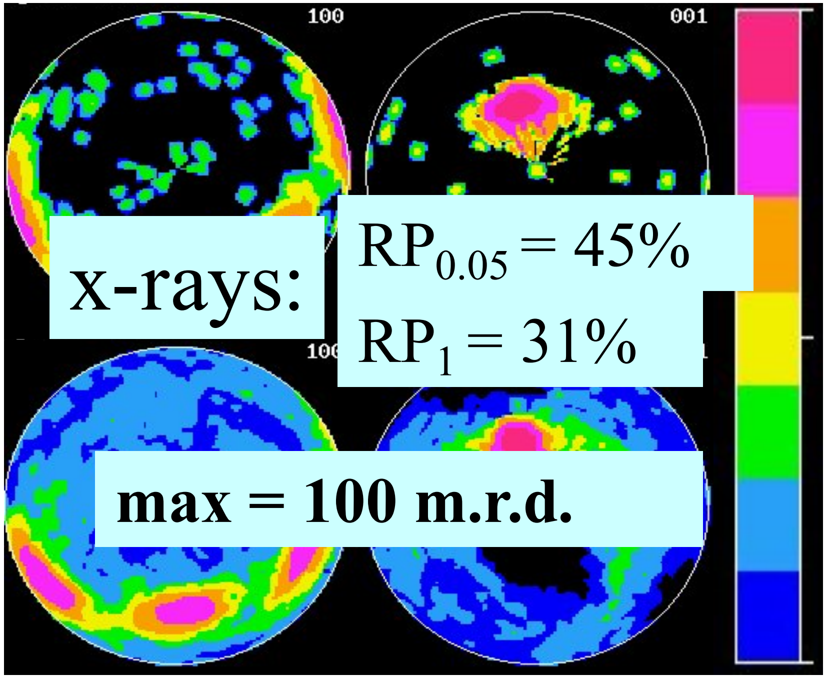
Electrons



2604 measured
700 only non-rejected
MAD criterion: 0.3%

max = 85 m.r.d.

Kikuchi diagrams



x-rays:

$RP_{0.05} = 45\%$

$RP_1 = 31\%$

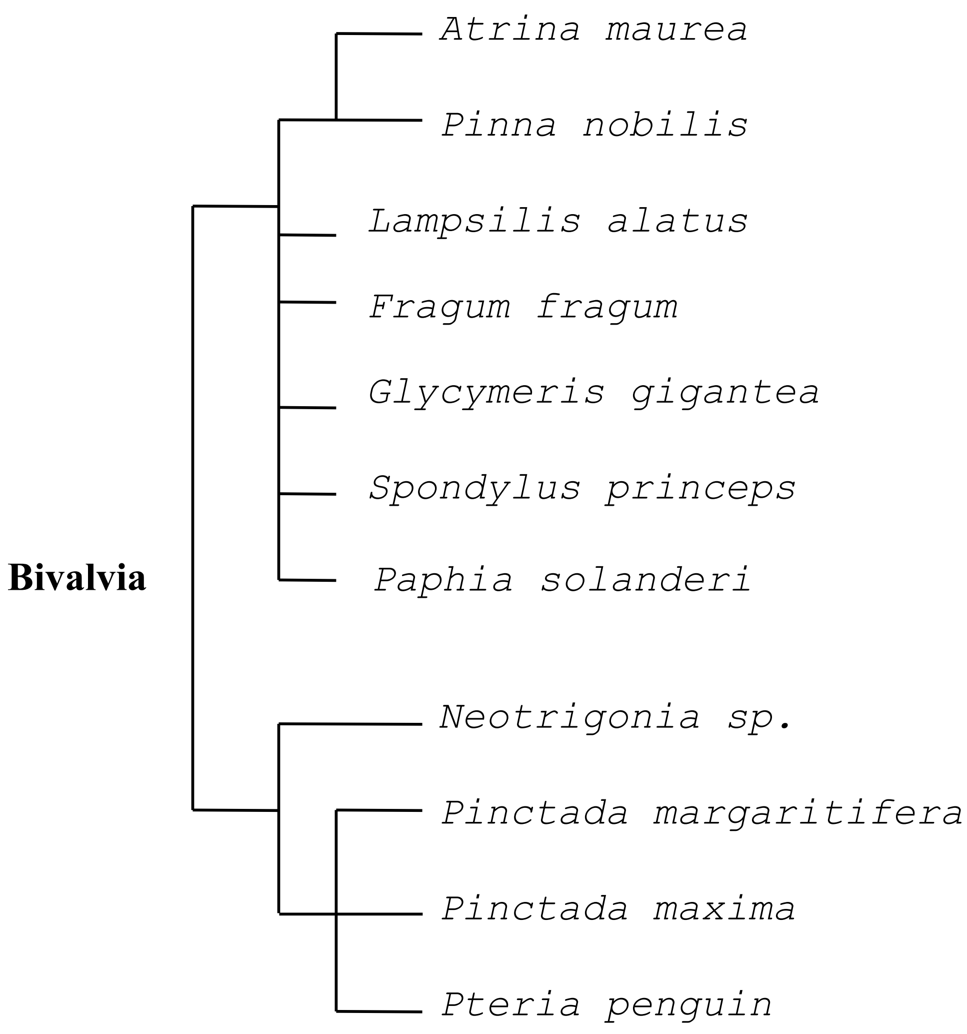
max = 100 m.r.d.

x-rays

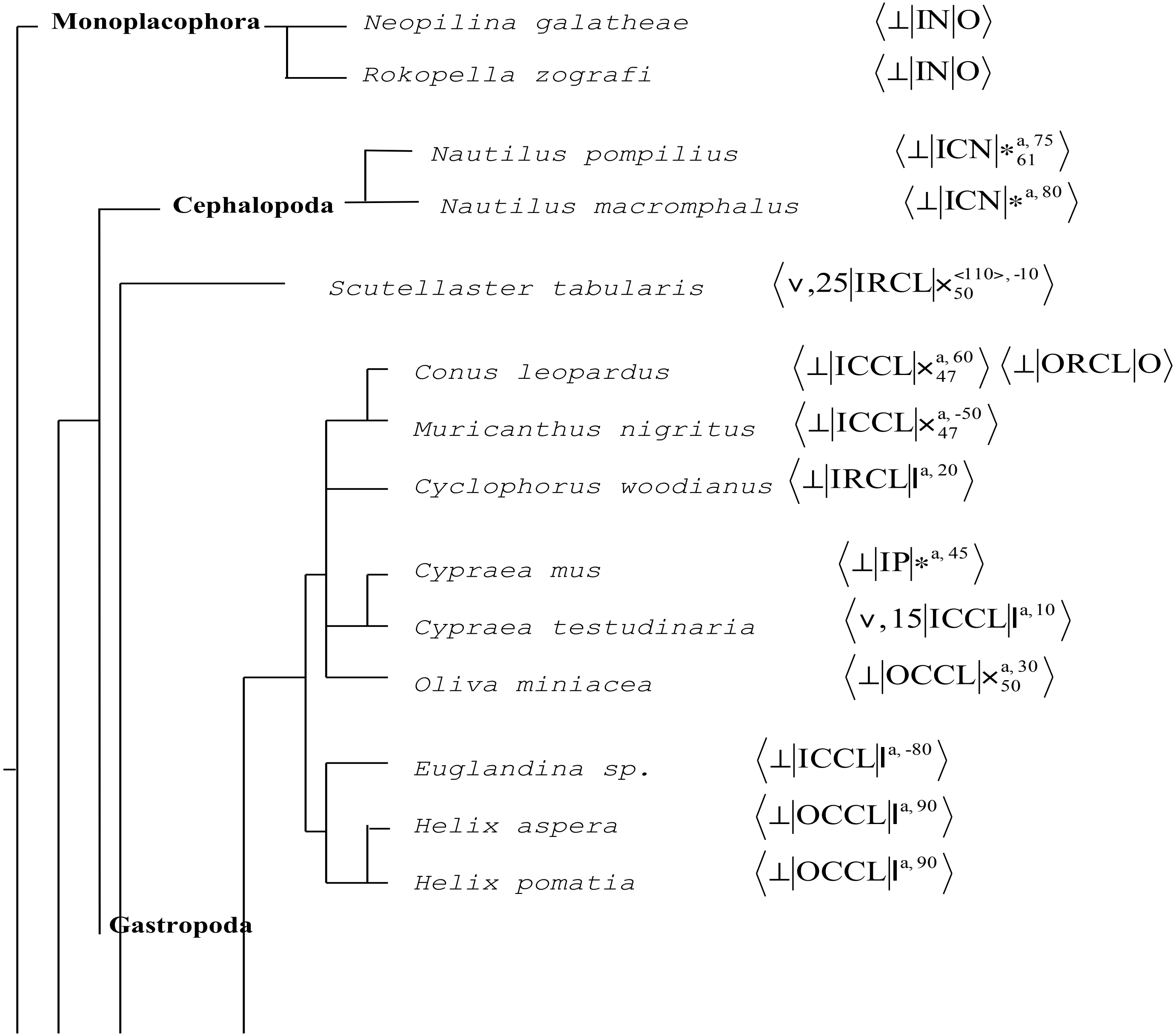
QTA and Mollusc's Phylogeny

From 70 mollusc species (gastropods, bivalves and cephalopods), around 150 layers studied

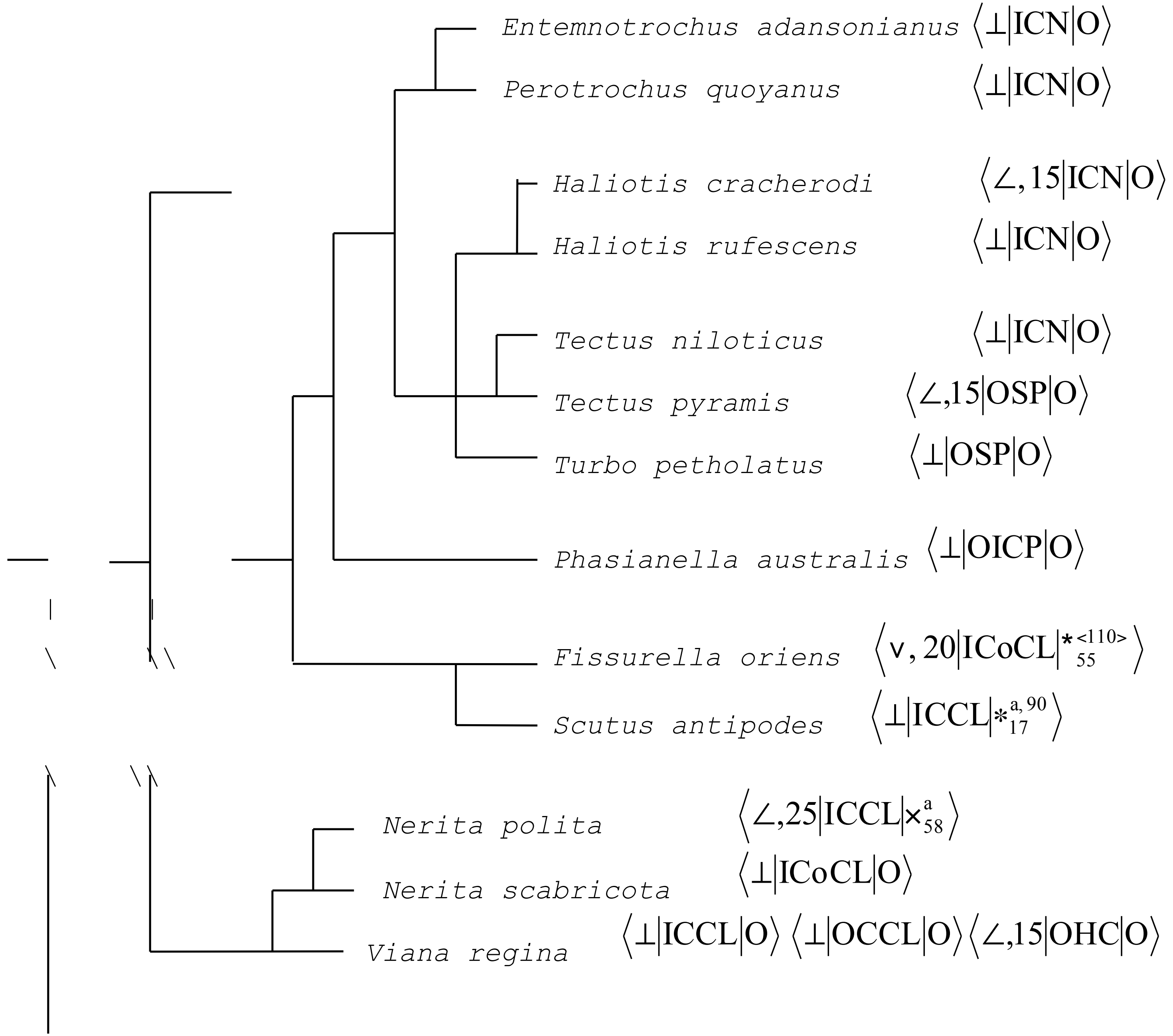
Closely related species, close textural characters, but significant variations: textural parameters can serve character analysis



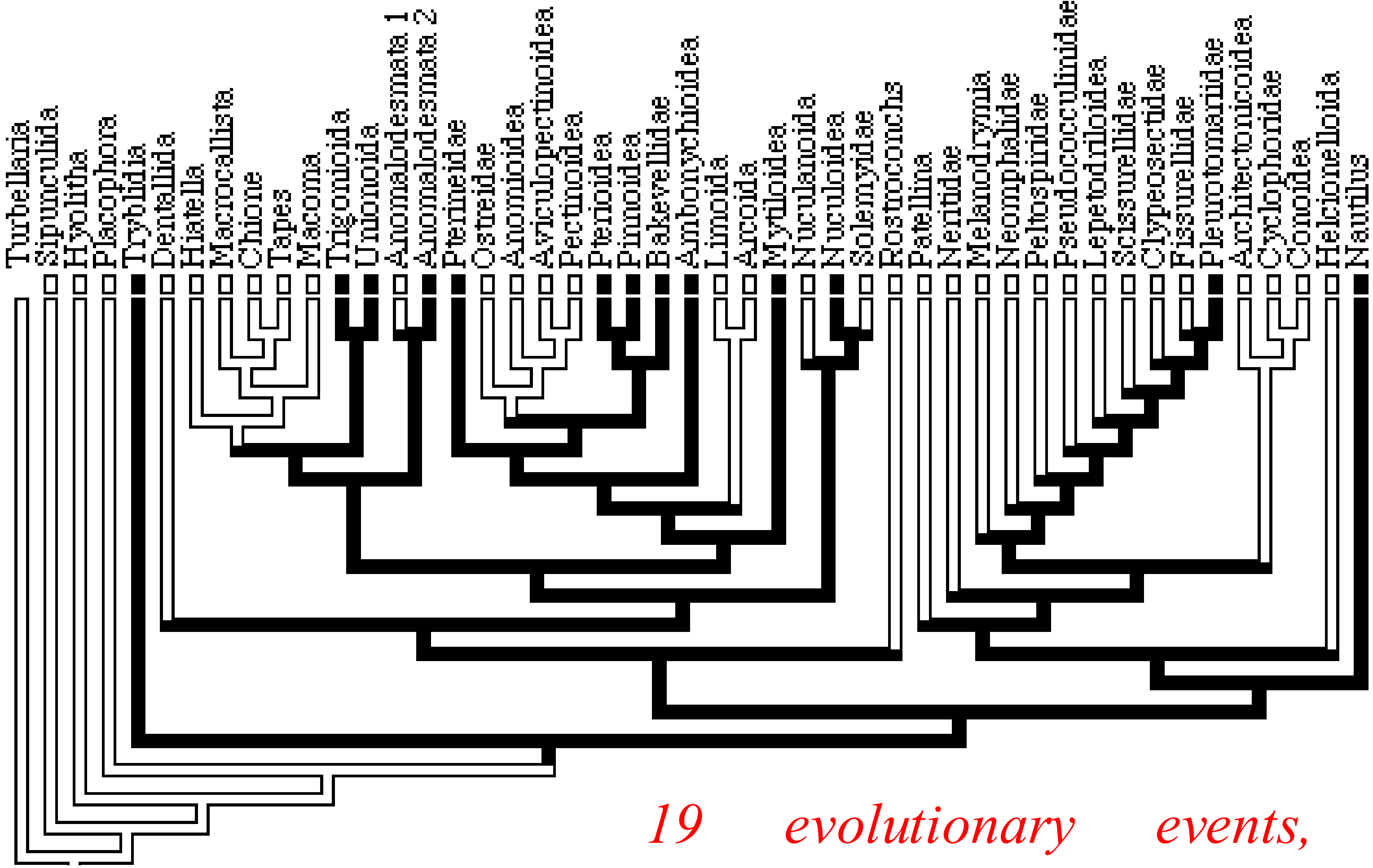
Atrina maurea	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,20}_{44} \right\rangle$
Pinna nobilis	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,95}_{25} \right\rangle$
Lampsilis alatus	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,90}_{25} \right\rangle$
Fragum fragum	$\left\langle \forall, 15 \middle| \mathrm{ICCL} \middle| \times^{<110>}_{50} \right\rangle$
Glycymeris gigantea	$\left\langle \forall, 15 \middle| \mathrm{ICCL} \middle| \times^{<110>}_{50} \right\rangle$
Spondylus princeps	$\left\langle \vee, 10 \middle| \mathrm{ICCL} \middle| \times^{<110>,\,-15}_{50} \right\rangle$
Paphia solanderi	$\left\langle \perp \middle| \mathrm{ICCL} \middle| \mathrm{O} \right\rangle \left\langle \angle, 20 \middle| \mathrm{OSiP} \middle| \mathrm{O} \right\rangle$
Neotrigonia sp.	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,90}_{12} \right\rangle$
Pinctada margaritifera	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,90}_{8} \right\rangle$
Pinctada maxima	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,90}_{14} \right\rangle$
Pteria penguin	$\left\langle \perp \middle| \mathrm{ISN} \middle| *^{a,\,-30}_{15} \right\rangle$


Monoplacophora
Neopilina galatheae
⟨⊥|IN|O⟩
Rokopella zografi
⟨⊥|IN|O⟩
Cephalopoda
Nautilus pompilius
$\langle \perp | \mathrm{ICN} | *^{a, 75}_{61} \rangle$
Nautilus macromphalus
$\langle \perp | \mathrm{ICN} | *^{a, 80} \rangle$
Scutellaster tabularis
$\langle \vee, 25 | \mathrm{IRCL} | \times^{<110>, -10}_{50} \rangle$
Conus leopardus
$\langle \perp | \mathrm{ICCL} | \times^{a, 60}_{47} \rangle \langle \perp | \mathrm{ORCL} | \mathrm{O} \rangle$
Muricanthus nigritus
$\langle \perp | \mathrm{ICCL} | \times^{a, -50}_{47} \rangle$
Cyclophorus woodianus
$\langle \perp | \mathrm{IRCL} | \mathrm{I}^{a, 20} \rangle$
Cypraea mus
$\langle \perp | \mathrm{IP} | *^{a, 45} \rangle$
Cypraea testudinaria
$\langle \vee, 15 | \mathrm{ICCL} | \mathrm{I}^{a, 10} \rangle$
Oliva miniacea
$\langle \perp | \mathrm{OCCL} | \times^{a, 30}_{50} \rangle$
Euglandina sp.
$\langle \perp | \mathrm{ICCL} | \mathrm{I}^{a, -80} \rangle$
Helix aspera
$\langle \perp | \mathrm{OCCL} | \mathrm{I}^{a, 90} \rangle$
Helix pomatia
$\langle \perp | \mathrm{OCCL} | \mathrm{I}^{a, 90} \rangle$
Gastropoda

Gastropoda

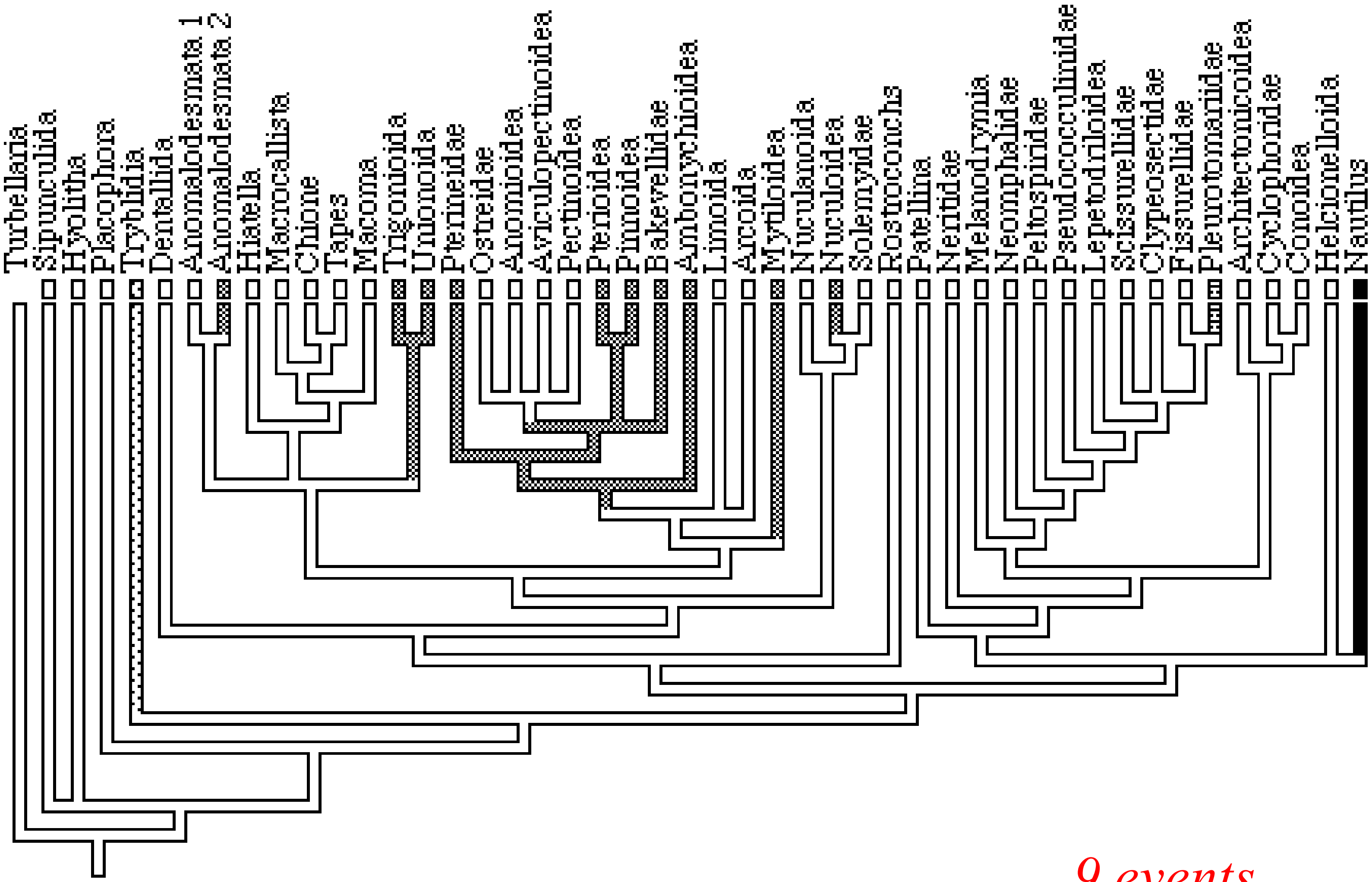

Entemnotrochus adansonianus ⟨⊥|ICN|O⟩
Perotrochus quoyanus ⟨⊥|ICN|O⟩
Haliotis cracherodi ⟨∠, 15|ICN|O⟩
Haliotis rufescens ⟨⊥|ICN|O⟩
Tectus niloticus ⟨⊥|ICN|O⟩
Tectus pyramis ⟨∠,15|OSP|O⟩
Turbo petholatus ⟨⊥|OSP|O⟩
Phasianella australis ⟨⊥|OICP|O⟩
Fissurella oriens ⟨∨, 20|ICoCL|$*_{55}^{<110>}$⟩
Scutus antipodes ⟨⊥|ICCL|$*_{17}^{a, 90}$⟩
Nerita polita ⟨∠,25|ICCL|$\times_{58}^{a}$⟩
Nerita scabricota ⟨⊥|ICoCL|O⟩
Viana regina ⟨⊥|ICCL|O⟩ ⟨⊥|OCCL|O⟩ ⟨∠,15|OHC|O⟩

Phylogenic interest: nacre = ancestral (Carter & Clarck, 1985)



19 evolutionary events, from cladistics charactere analysis

nacre not ancestral



9 events

Calcitic fossils: trichites

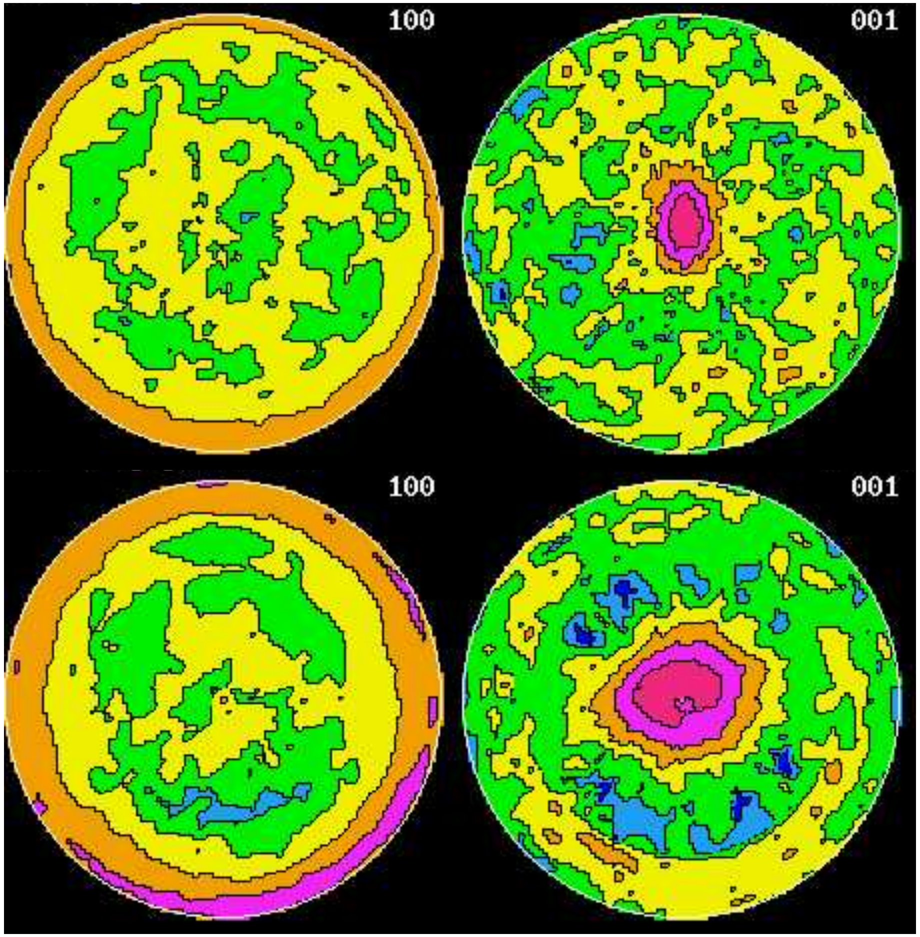
- Fragments of the large bivalve *Trichites* relatively abundant in shallow marine sediments from the Middle to Upper Jurassic of Europe, Asia and Africa

- Entire individuals are rare and the palaeobiology of the genus is poorly understood because of this

- Studied specimens are thick, some fragments up to 3 cm in thickness, composed of a coarse simple prismatic calcite

- Taxonomic position of Trichites remains problematic: pinnoids ?

Pinnoid and Pterioid prismatic layers

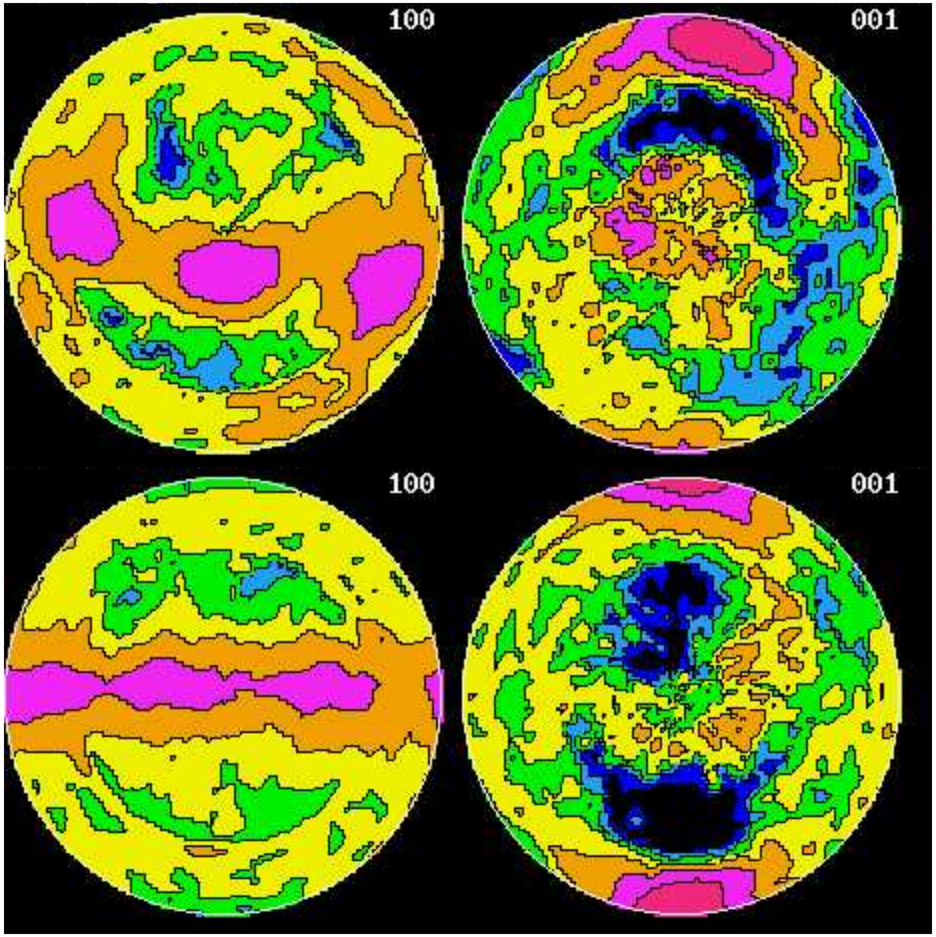


Pinna nobilis

c-axes // N
a-axes at random

Pteria penguin

Mussels prismatic layers



Mytilus edulis

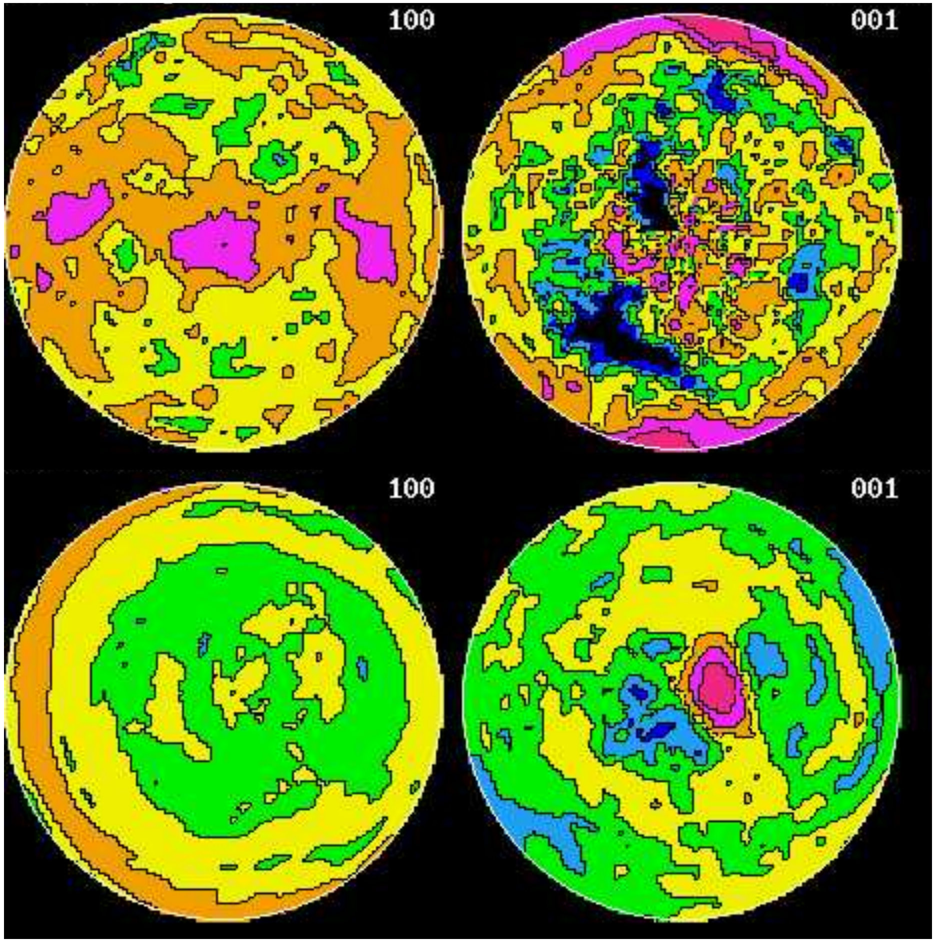
c-axes ∠ N

a-axes single-crystal like

c-axes ⊥ N, // G

Bathymodiolus thermophilus

Scallop and trichite prismatic layers



Amussium parpiraceum
(scallop)

c-axes ⊥ N, // G
a-axes single-crystal like

Trichites
(fossil)

c-axes ∠ N
a-axes random

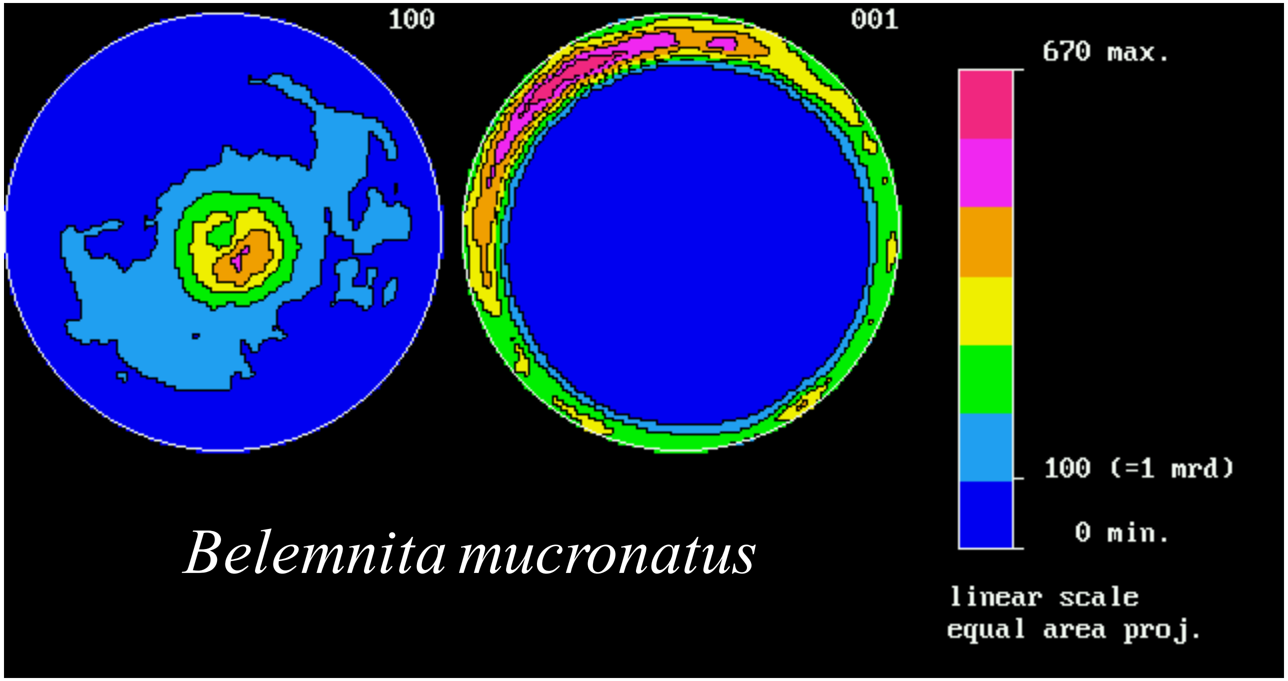
Texture Analysis results

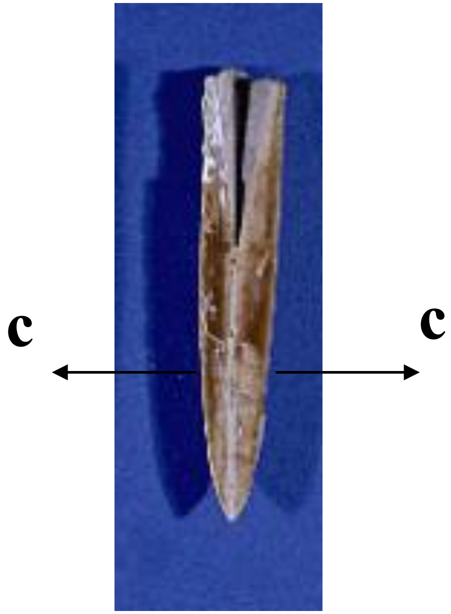
	Layer type	**ODF Max (mrd)**	**ODF min (mrd)**	**RP0 (%)**	**RP1 (%)**	**c-axis**	**a-axis**	**{001} Max (mrd)**	**F^2 (mrd^2)**	**- S**
Pinna nobilis	OP	303	0	50	29	// N	random	68	29	2.3
Pteria penguin	OP	84	0	29	15	// N	random	31	13	1.9
Amussium parpiraceum	OP	330	0	53	33	// G	<110> // M	20	31	2.6
Bathymodiolus thermophilus	OP	63	0	25	18	// G	// M	27	13	1.9
Mytilus edulis	OP	207	0	41	25	75° from N	<110> // M	23	21	2.2
Trichites	P	390	0	52	28	15° from N	random	56	41	2.2
Crassostrea gigas	IF	908	0	45	31	35° from N	// M	>100	329	5.1

No DNA is available on fossils like Trichites, but Trichite's textural parameters are close to the ones of *pinnoids* or *pterioids*: interesting for the classification of extinct species

Materials Science Forum, ***408-412****, 2002, 1687-1692*

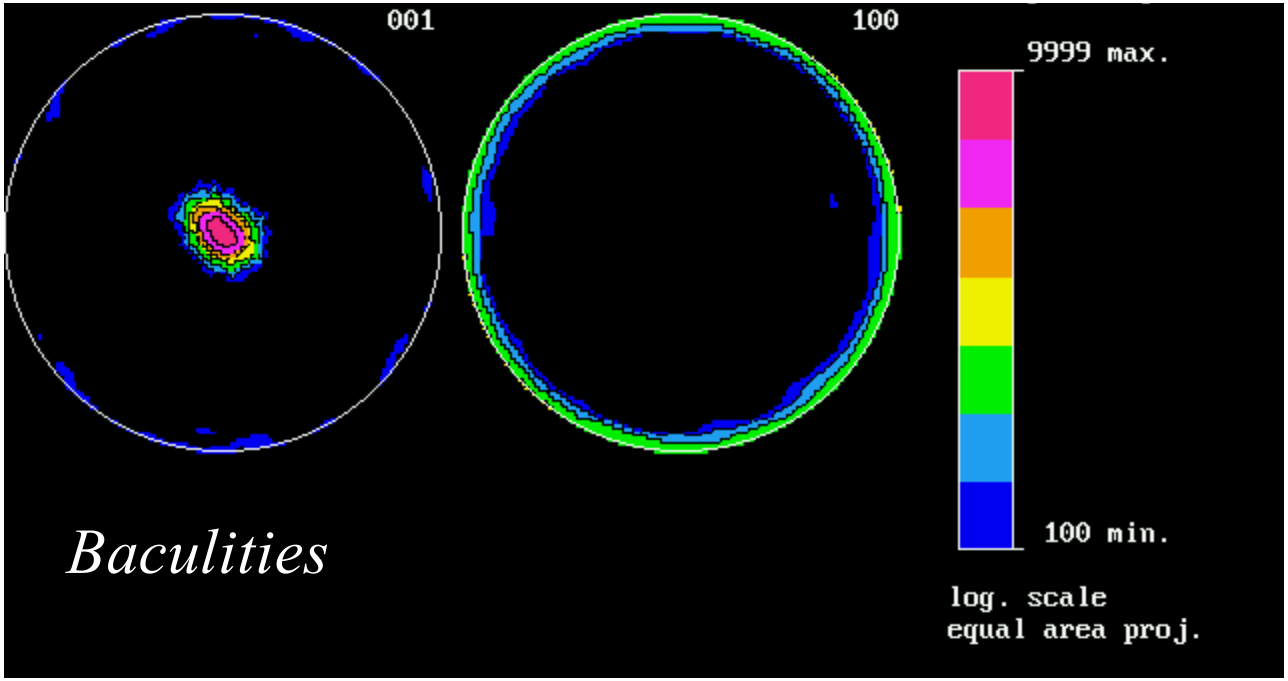
Calcitic fossils: *Belemnites*





c-axes perp. to the shell: as in other cephalopods

Aragonite fossils: *Baculities sp.*

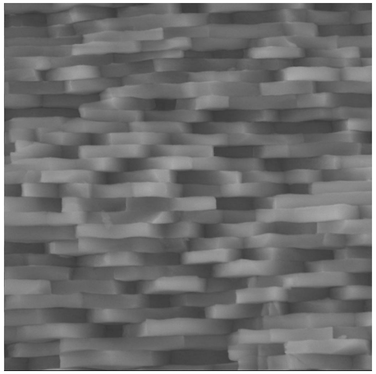


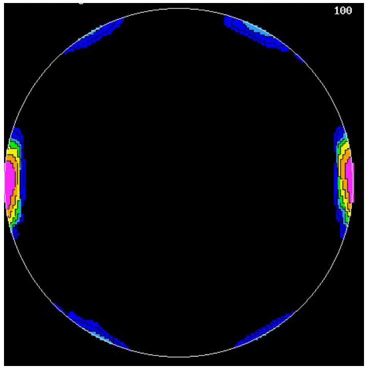
c-axes perp. to the shell: as in other cephalopods, strong **c**-calcite to **c**-aragonite fossils interaction

QTA and Mollusc's prothaetics

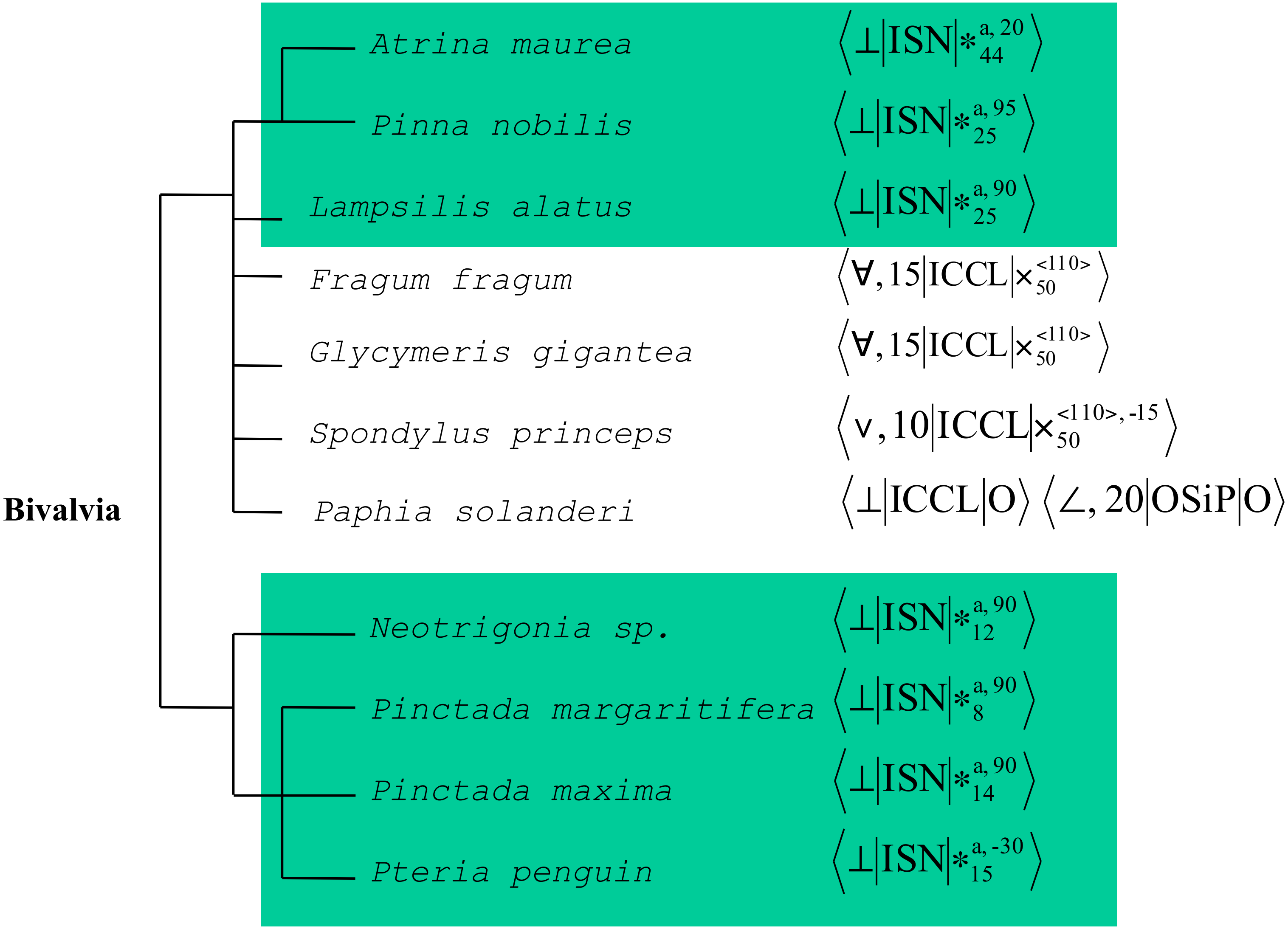
Pinctada margaritifera, P. maxima and *P. Nobilis* nacres:

Bio-compatible and bio-inductive layers for rabbit bones (E. Lopez (MNHN, Paris)





P. Margaritifera



Bivalvia

Atrina maurea	$\langle \perp \| \mathrm{ISN} \| *^{a,\,20}_{44} \rangle$
Pinna nobilis	$\langle \perp \| \mathrm{ISN} \| *^{a,\,95}_{25} \rangle$
Lampsilis alatus	$\langle \perp \| \mathrm{ISN} \| *^{a,\,90}_{25} \rangle$
Fragum fragum	$\langle \forall, 15 \| \mathrm{ICCL} \| \times^{<110>}_{50} \rangle$
Glycymeris gigantea	$\langle \forall, 15 \| \mathrm{ICCL} \| \times^{<110>}_{50} \rangle$
Spondylus princeps	$\langle \vee, 10 \| \mathrm{ICCL} \| \times^{<110>,\,-15}_{50} \rangle$
Paphia solanderi	$\langle \perp \| \mathrm{ICCL} \| \mathrm{O} \rangle \langle \angle, 20 \| \mathrm{OSiP} \| \mathrm{O} \rangle$
Neotrigonia sp.	$\langle \perp \| \mathrm{ISN} \| *^{a,\,90}_{12} \rangle$
Pinctada margaritifera	$\langle \perp \| \mathrm{ISN} \| *^{a,\,90}_{8} \rangle$
Pinctada maxima	$\langle \perp \| \mathrm{ISN} \| *^{a,\,90}_{14} \rangle$
Pteria penguin	$\langle \perp \| \mathrm{ISN} \| *^{a,\,-30}_{15} \rangle$

Some conclusions

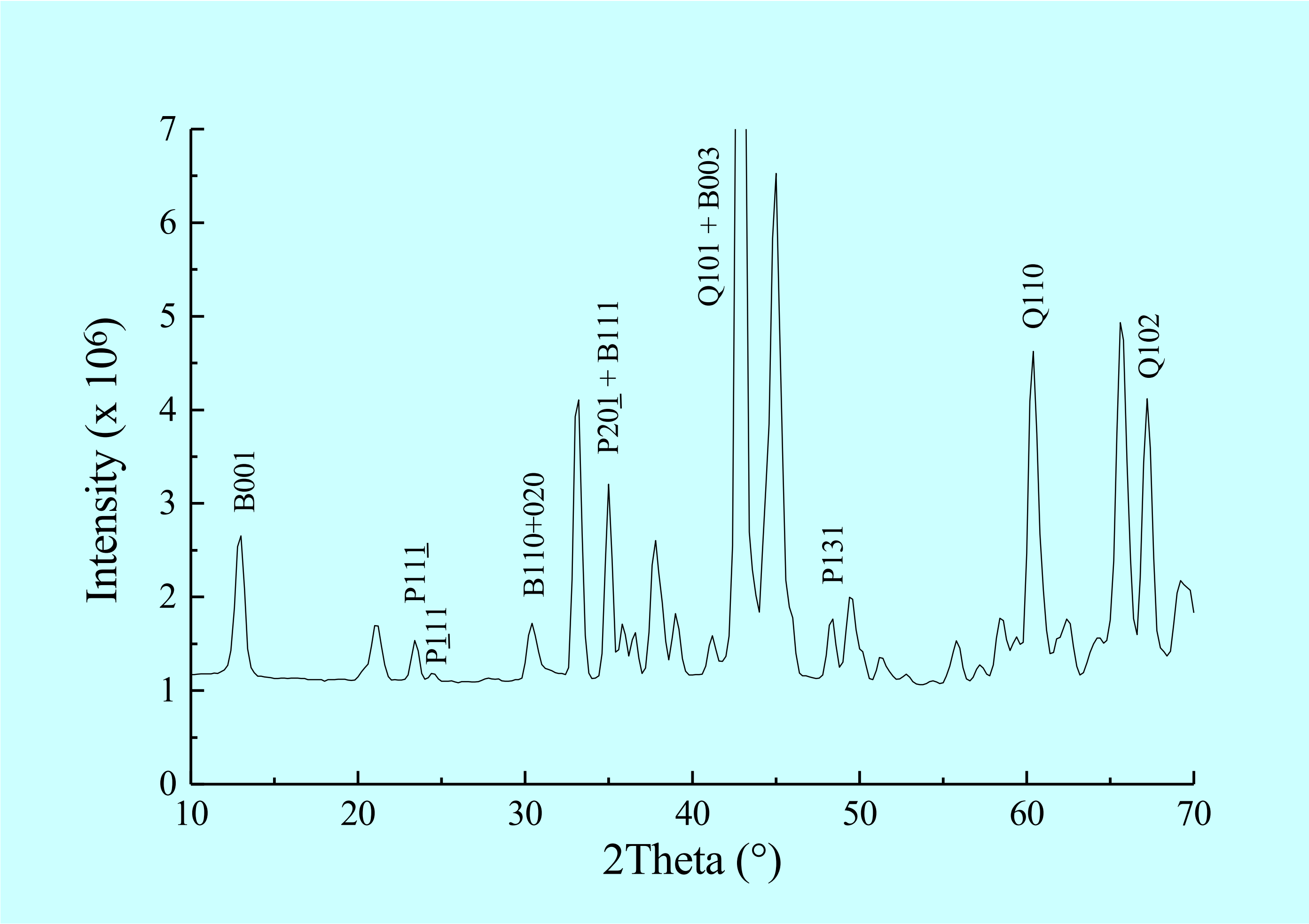
- Shells exhibit a large variety of texture patterns, in their aragonite and calcite layers
- Textural parameters are similar for close species, different for distant species, they confirm organically driven growth and refute mineral epitaxy
- Texture and microstructure analyses give non-redundant information in shells
- "Texture" characters can be relevant for classification and phylogenetic interpretation, either for living or extinct species
- Texture may serve as a tool to predict bio-compatible species, and mechanical behaviours of shells

Polyphased Mylonite (Palm Canyon, CA)

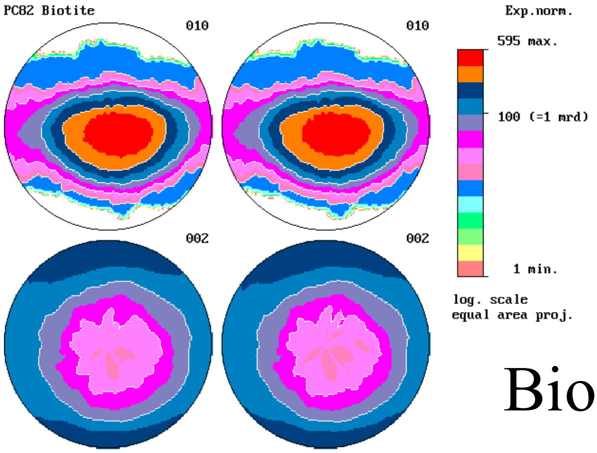
Strongly deformed ensemble, late Cretaceous (H.-R. Wenk, DEPS, Berkeley; B. Ouladdiaf ILL, Grenoble)

PC 82 mylonite	Biotite	Quartz	Albite	Anorthite	K-spar
Composition (weight %)	9.0	24.2	31.7	17.4	14.1
Space group	C2/m	R3	C-1		

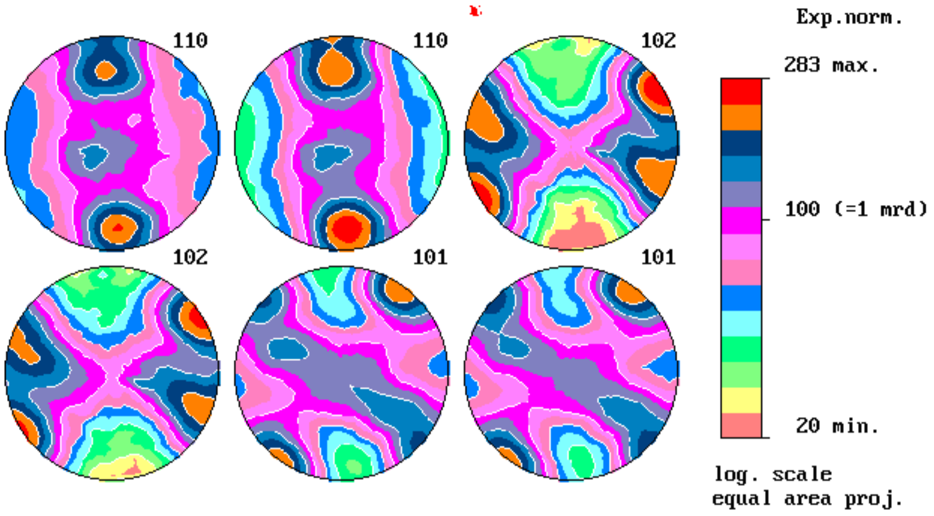
Textures & Microstructures **33**, 1999, 35-43



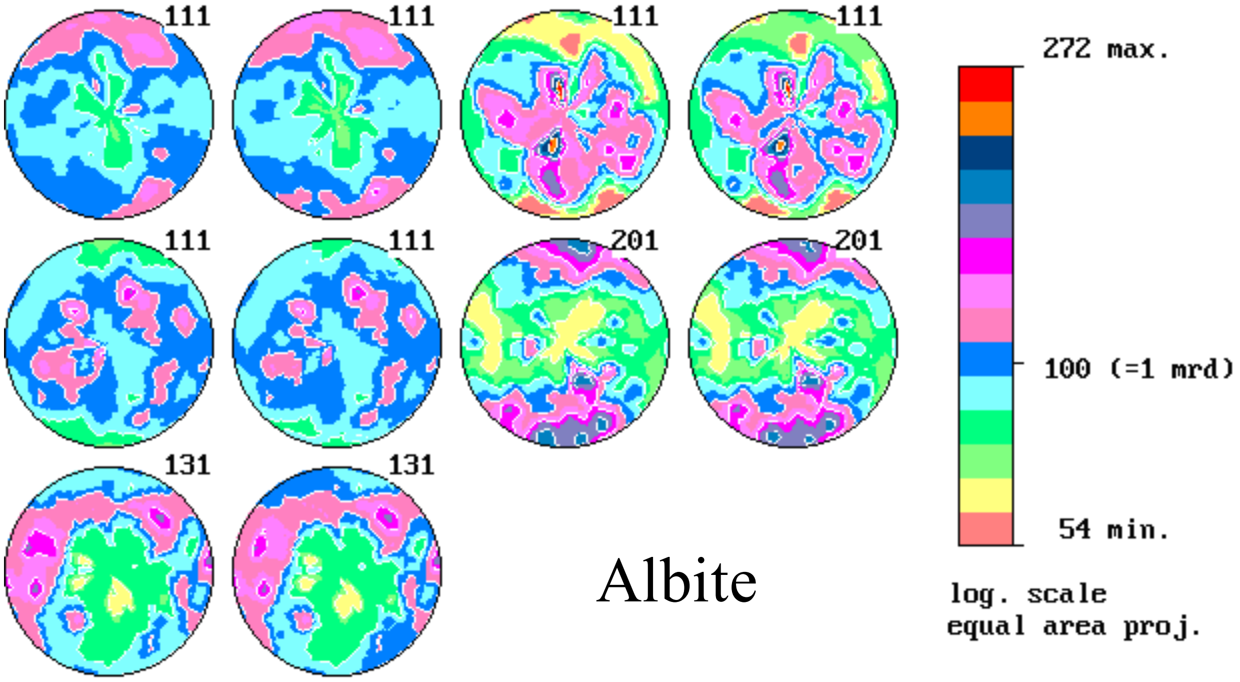
Strongly overlapped peaks, intra- and inter-phases: using point detectors is hardly manageable



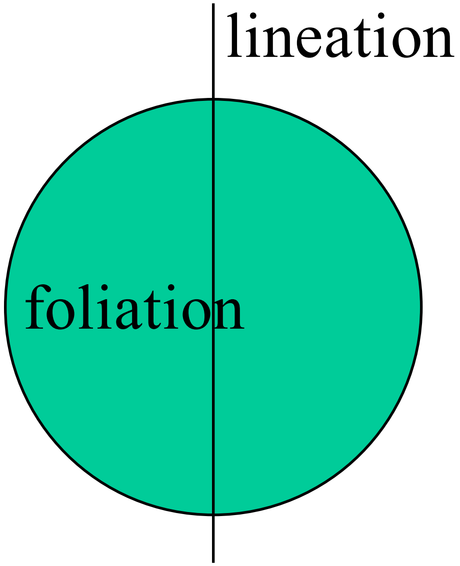
Biotite



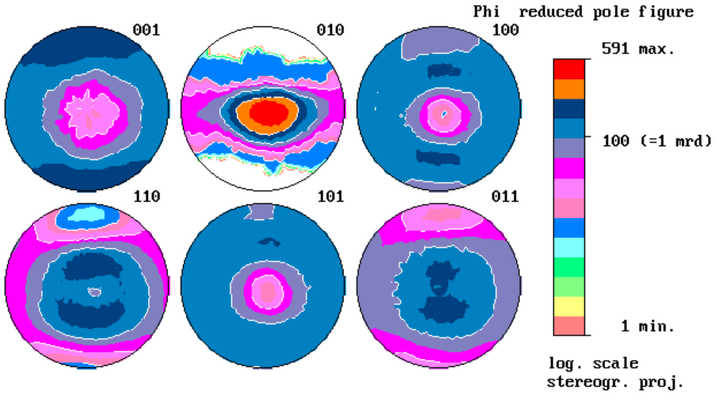
Quartz



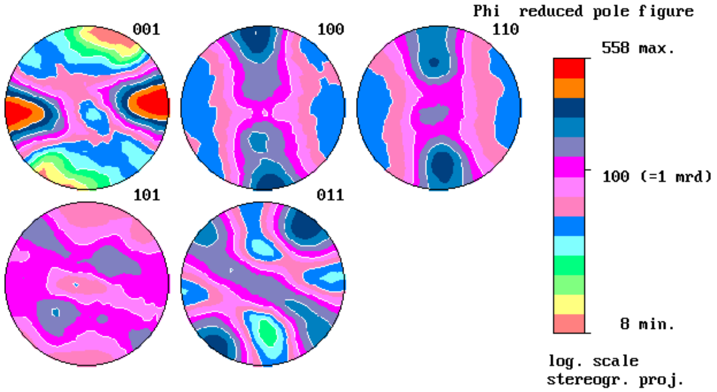
Albite



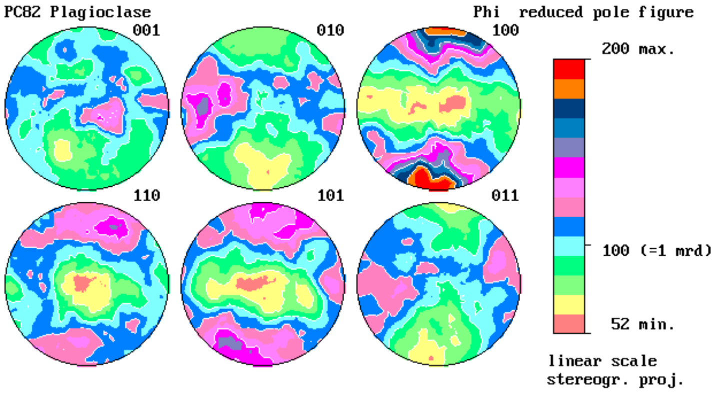
B



Q



A



	Biotite	Quartz	Albite
Used reflections	010 002 + 110	110 $\bar{1}$ 102 + 012 101 + 011	$\bar{1}$1, 1 1, 11$\bar{1}$, 20 131
Declared overlaps	002/110	102/012 101/011	-
OD minima (m.r.d.)	0	0	0.1
OD maxima (m.r.d.)	11.3	12.1	9.9
S	-0.81	-0.58	-0.15
F^2 (m.r.d.^{2})	3	2.8	1.3
RP_0 (%)	2	9	2.3
RP_1 (%)	1.2	5.9	2
Rw_0 (%)	1.3	4.8	1.5
Rw_1 (%)	1.2	3.7	1.5

// Lineation:

<100>*-quartz // <100>*-albite

<010>*-biotite at 90°

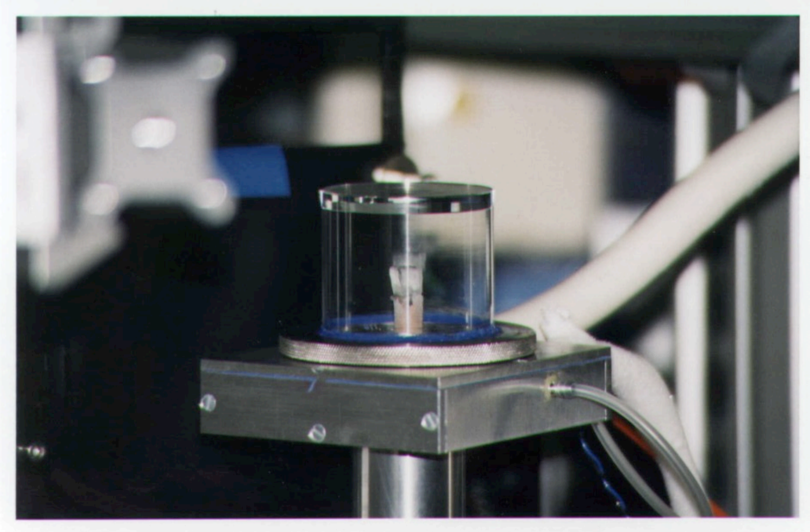
// foliation:

<001>*-quartz // <100>*-biotite

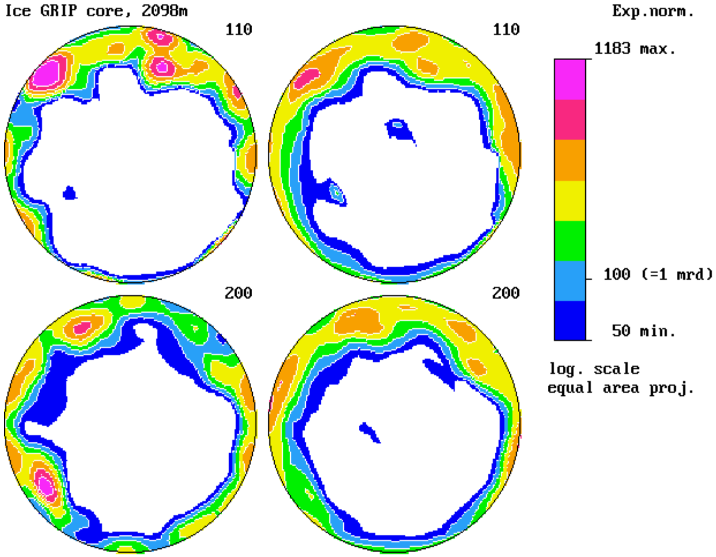
quite <100>* fibre albite

Ice From the Greenland GRIP core

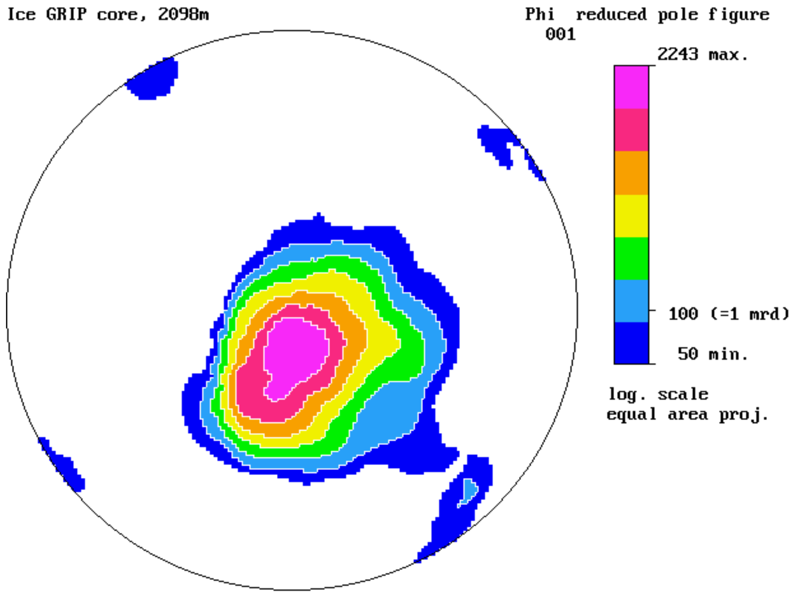
- 60°C Neutron diffraction studies of -2098 m deep natural ice (P. Duval, Glaciology Lab, Grenoble)



Ice cube at -60°C, on beam line



Experimental-Normalized and Recalculated {110} and {200} neutron pole figures



{001} Recalculated neutron pole figure

Pole dispersion corresponds to polarised light microscopy analyses and to deformation-recrystallisation-rotation models

Metamorphic amphiboles from the Alps

(M. Zucali, G. Gosso, DES, Milano)

Metamorphic amphiboles have been studied within **polymineralic** rocks; the **combined approach** allows extracting experimental pole figures for most of the rock-forming minerals.

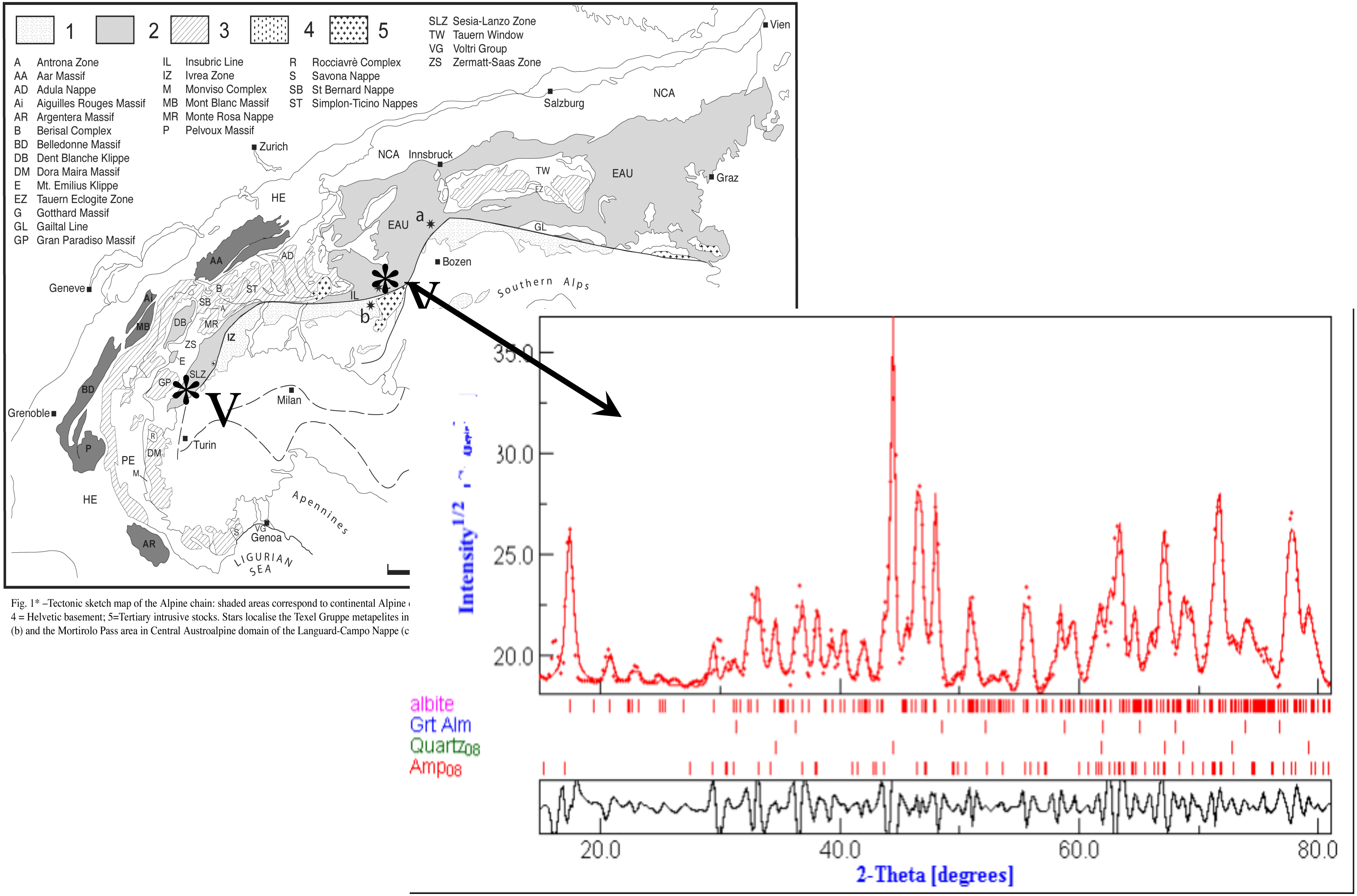


Fig. 1* –Tectonic sketch map of the Alpine chain: shaded areas correspond to continental Alpine
4 = Helvetic basement; 5=Tertiary intrusive stocks. Stars localise the Texel Gruppe metapelites in
(b) and the Mortirolo Pass area in Central Austroalpine domain of the Languard-Campo Nappe (c

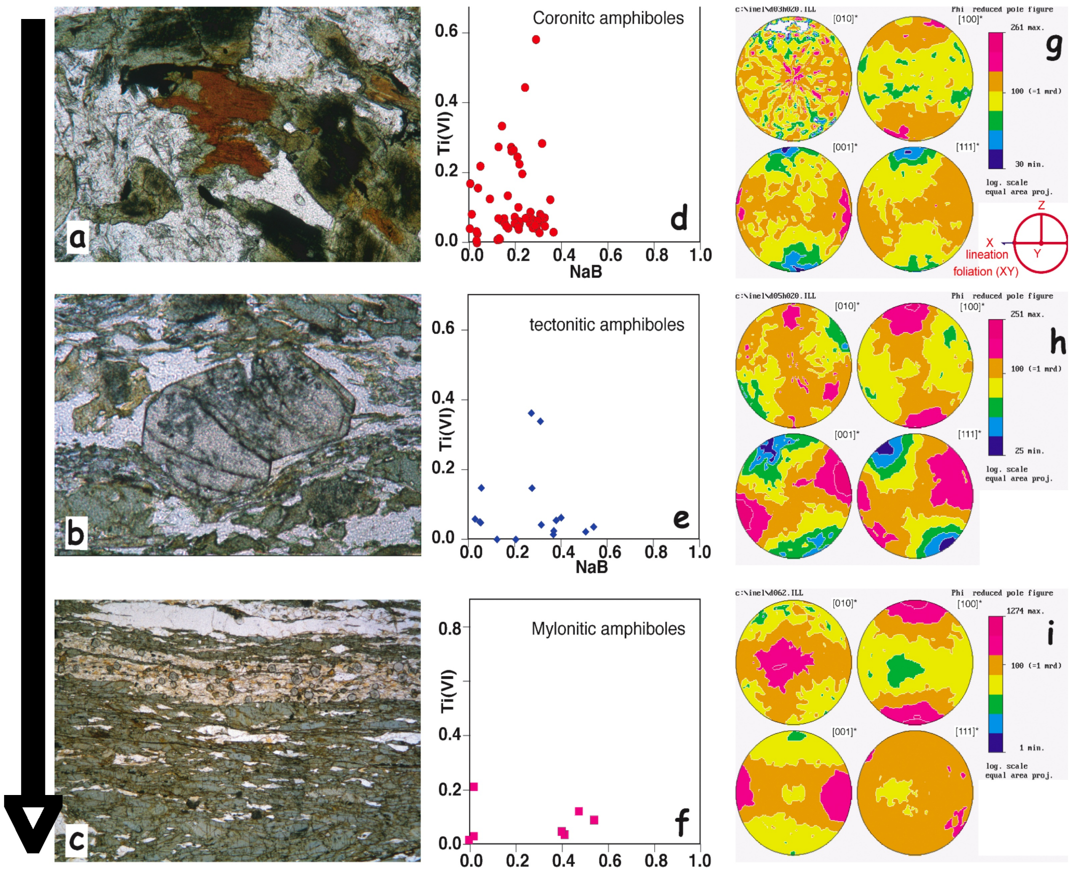
Geol. Soc.London, ***200****, 2002, 239-253*

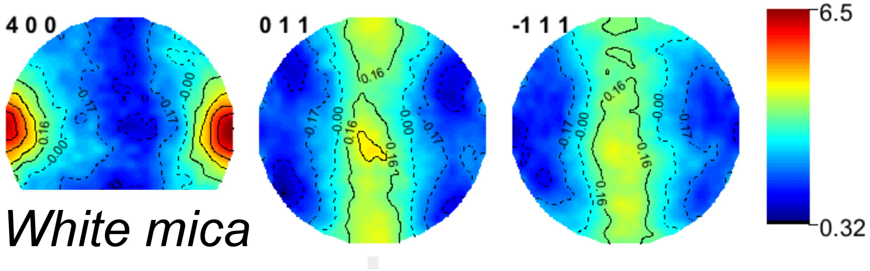
Degree of fabric evolution, due to:

- deformation partitioning at metric-scale

- degree of chemical changes within amphiboles

- evolving metamorphic conditions during Alpine subduction (60-100 Million years).



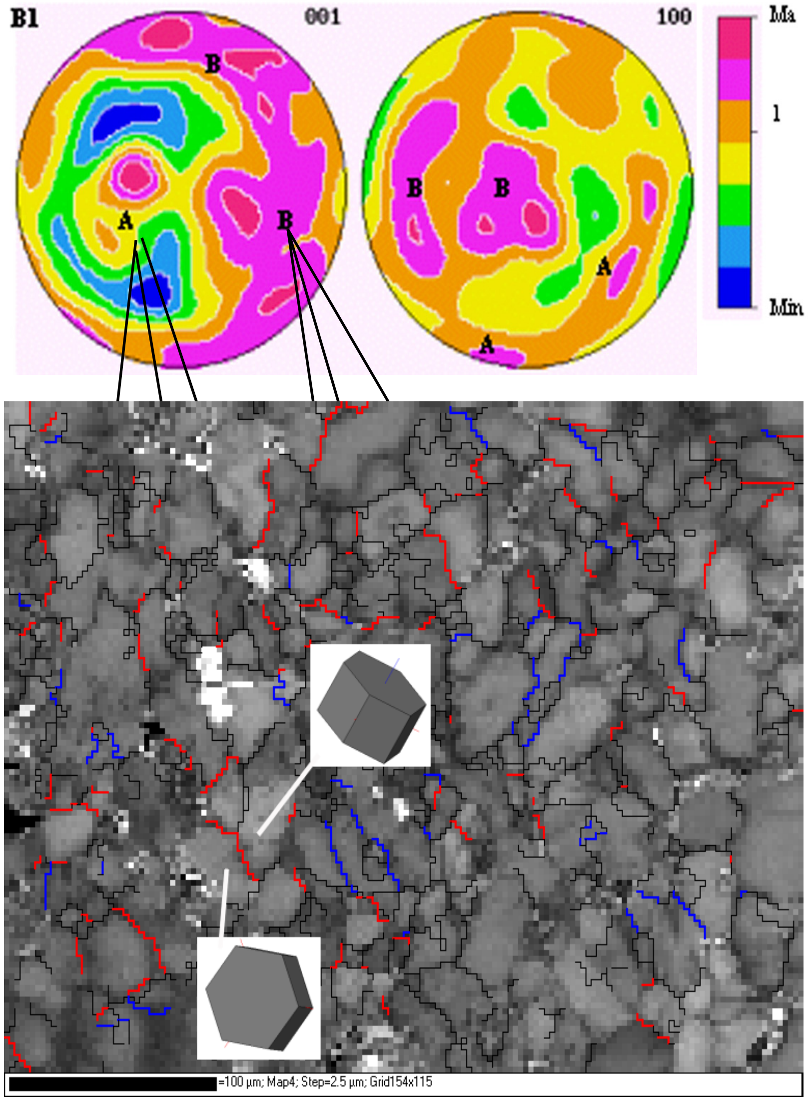


Siliceous Crust-Type microquartz horizons

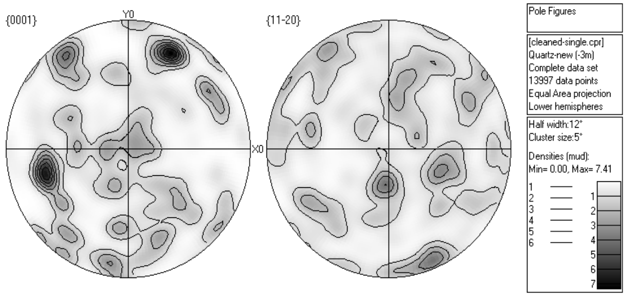
(G. Camana, G. Artioli, DES, Milano)

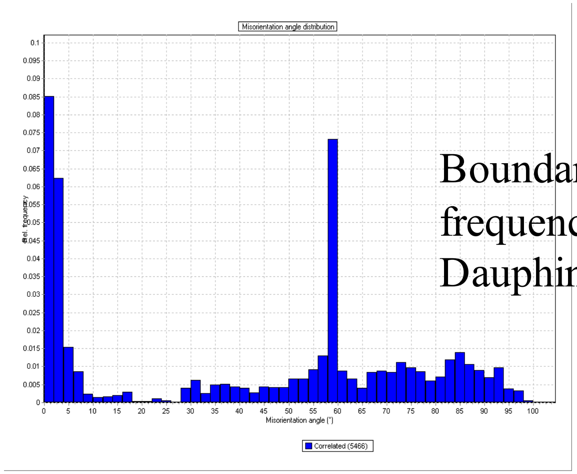
American Mineralogist **87(8-9)**, 2002, 1128-1138

X-ray pole figures



EBSD





Boundary misorientation frequency distribution: Dauphiné twins

neutrons