“Producing each of its creations ... nature intermingled the **harmony of beauty and** the harmony of **expediency** and shaped it into the unique form which is perfect from the point of view of an engineer.”

(M. Tupolev)

Tribology of biomineralised structures

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Priority Program 1117 of the Deutsche Forschungs-Gemeinschaft "Principles of Biomineralisation"

Outline

- Introduction to **tribology**
- MEMS
- Examples for tribology in **biology**
- **Diatom** tribology
  - Adhesives
  - Lubrication
  - Hinges & interlocking devices
- Conclusions and outlook

Tribology

Tribology is the branch of engineering that deals with the **interaction of surfaces** in relative motion (as in bearings or gears):

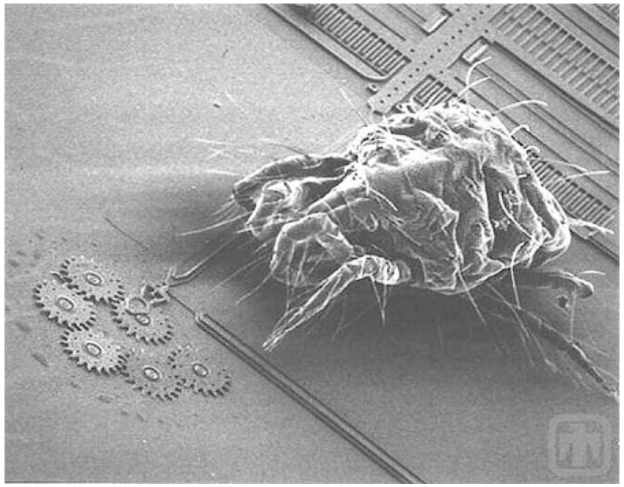
- their **design**
- **friction**
- **adhesion**
- **lubrication**
- and **wear**.

© WSW Bearings, China

Micro- and Nanotribology

Micro- and nanotribology deals with tribology on length scales of **functional elements** from **100 micrometers** down to a few **nanometers**.

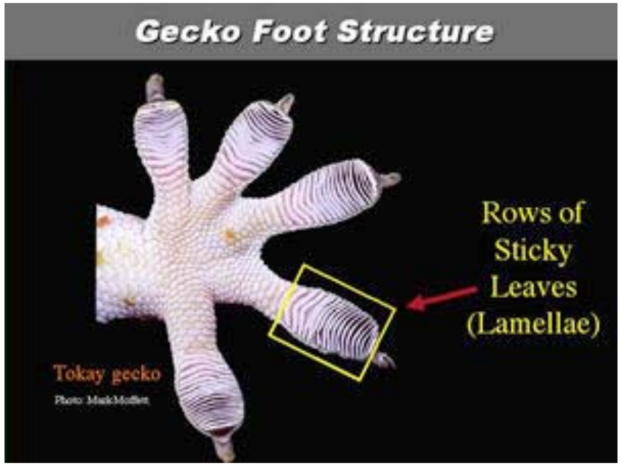
The boom of microsystem technology (silicon technology, **MEMS**) and the development of novel nano-electromechanical systems (**NEMS**) calls for detailed understanding of tribological phenomena also at this scale.



Biotribology

The aim of biotribology is to gather information about friction, adhesion, lubrication and wear of **biological systems** and to apply this knowledge to technological innovation as well as to development of environmentally sound products.

This new interdisciplinary field of research combines methods and knowledge of physics, chemistry, mechanics and biology.



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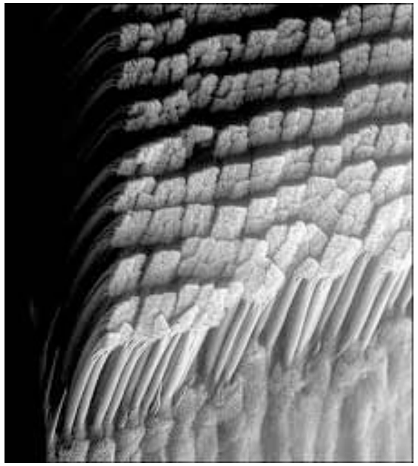
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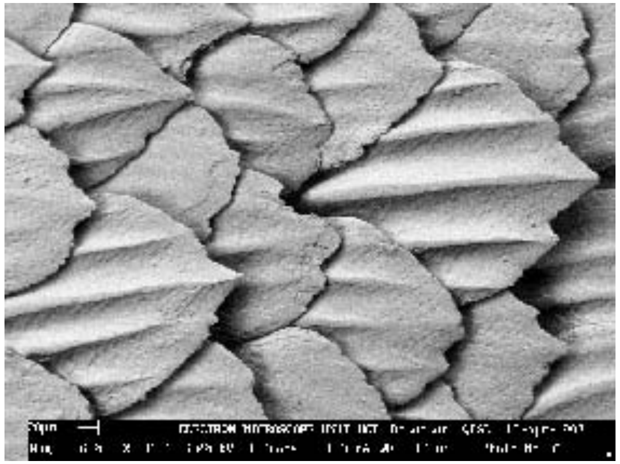
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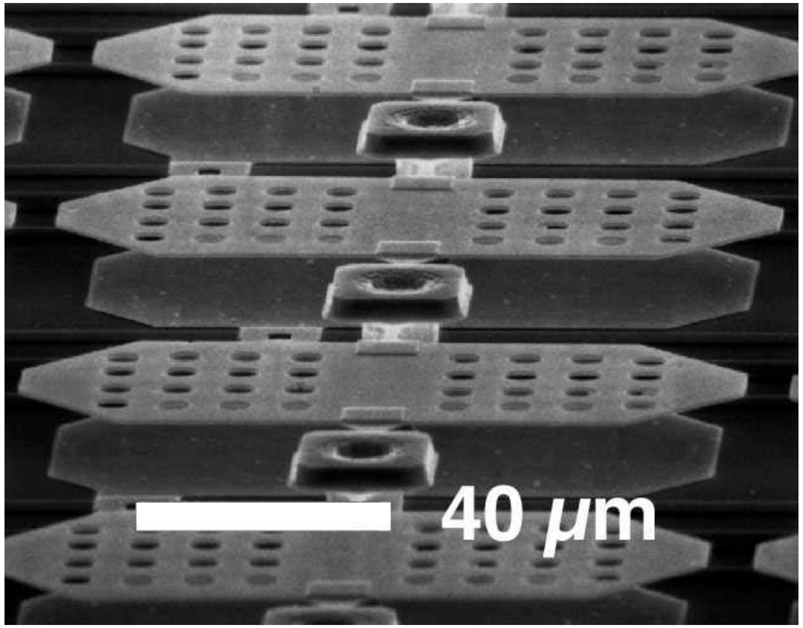
Why bio*micro* and -*nano*tribology ?

Continuous **miniaturization** of technological devices like hard disk drives and biosensors increases the necessity for the fundamental **understanding** of tribological **phenomena at the micro- and nanoscale**.

Biological systems excel also at this scale and therefore their strategies can serve as templates for new engineering devices.

Gebeshuber I.C. *et al.* Nanosci. Nanotechnol. (2005) 5(1), 79-87
Gebeshuber I.C. *et al.* (2005) Tribol. Interf. Eng. Ser. 48, 365-370

man-made



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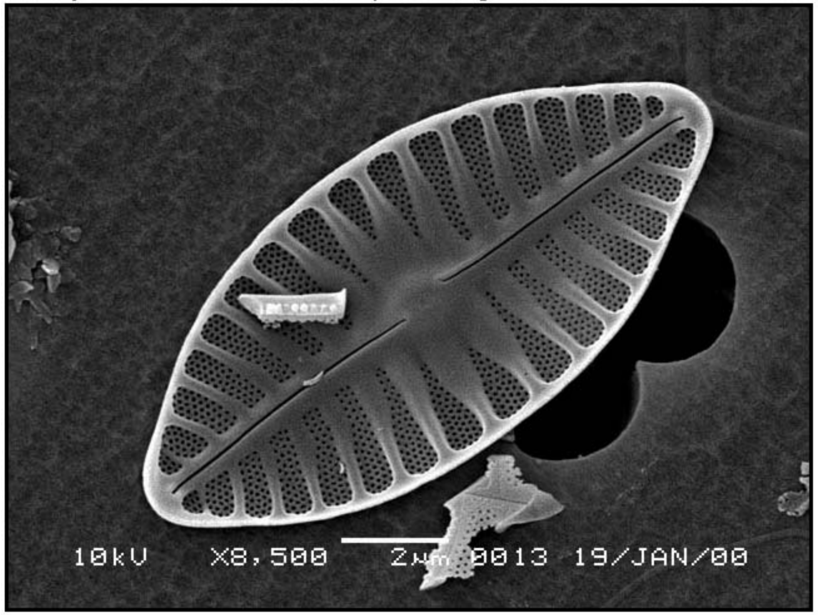
natural



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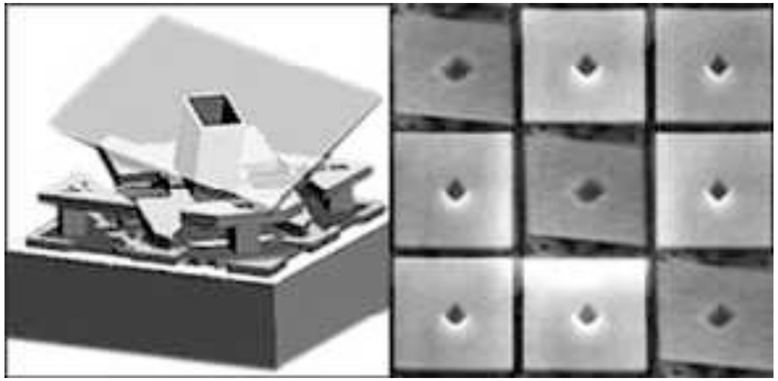
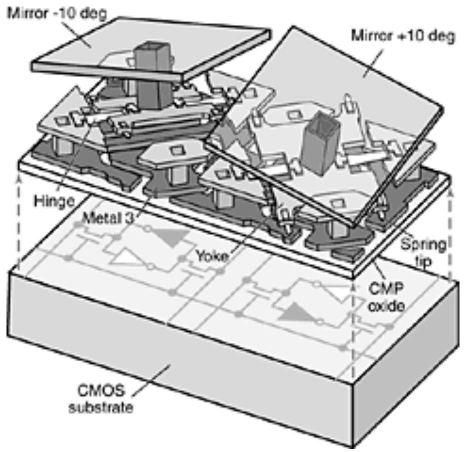
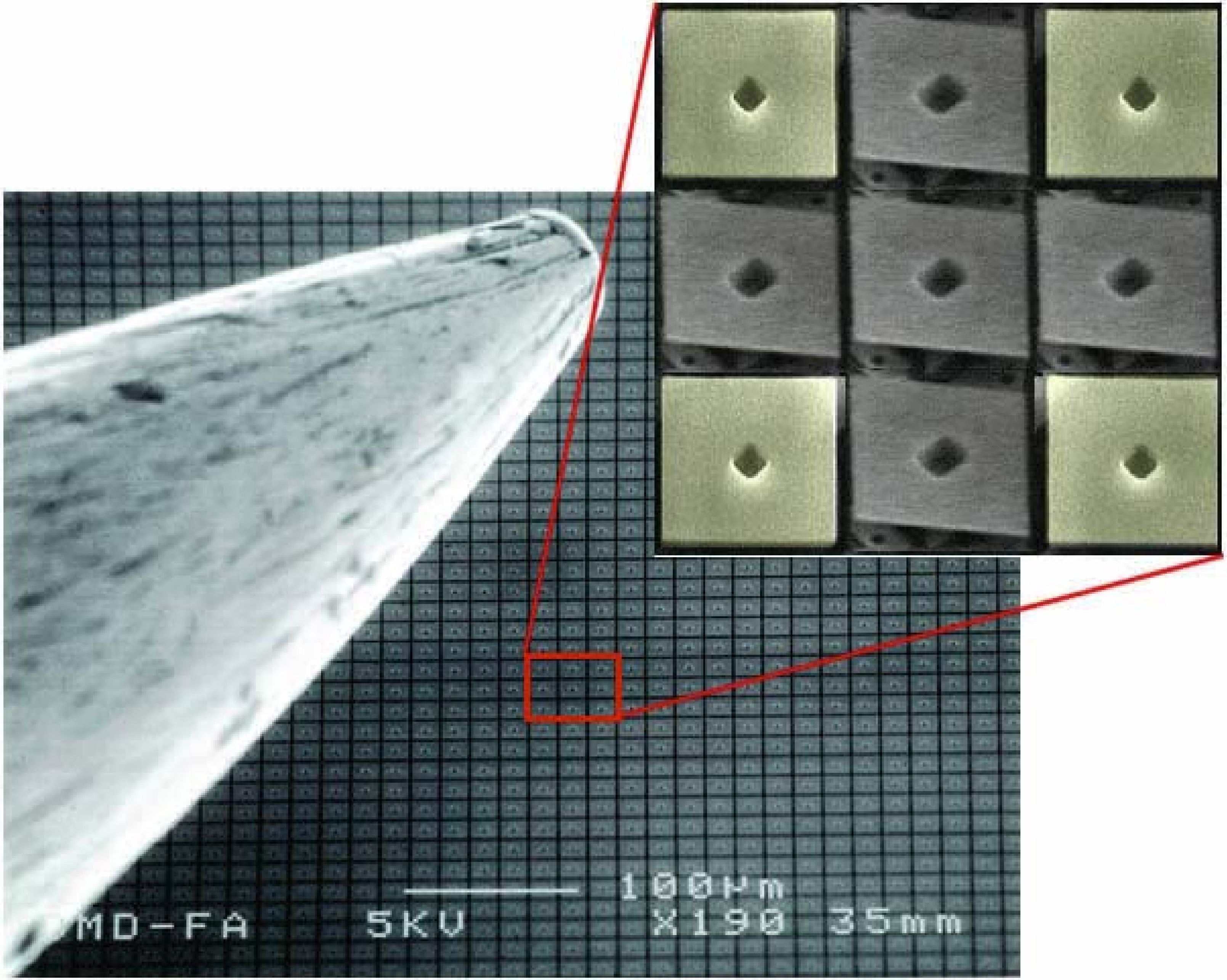
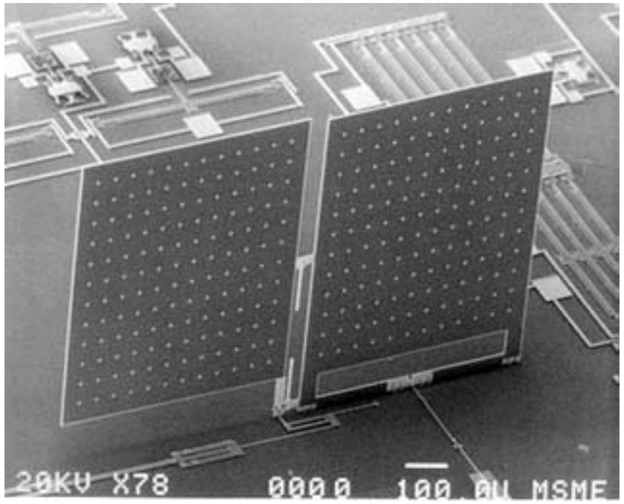
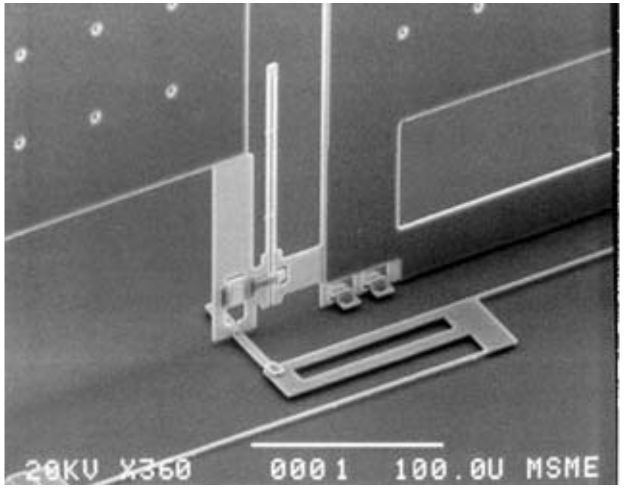
Digital Micromirror Devices






100µm
MD-FA
5KV
X190
35mm


20KV X78 0000 100.0U MSME

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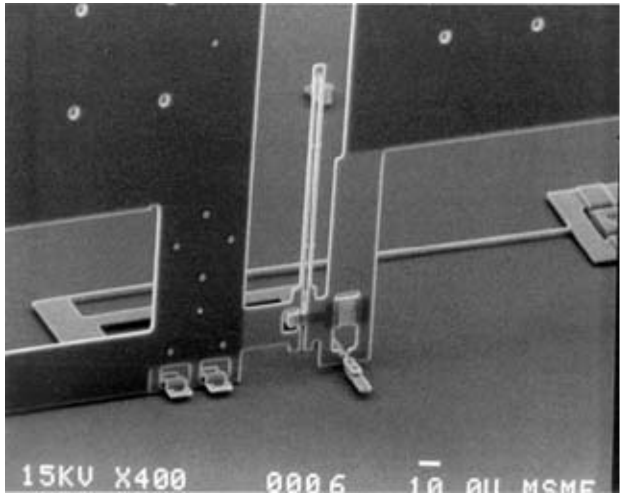
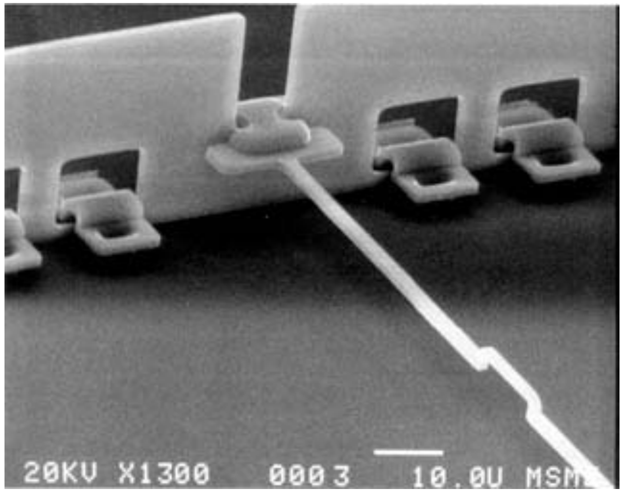

15KV X400 0006

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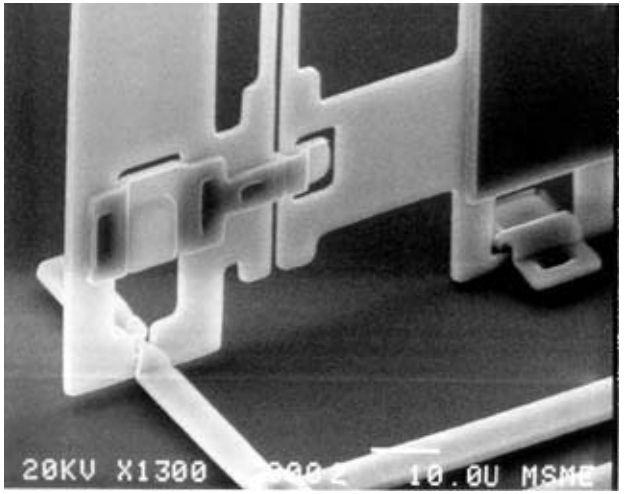
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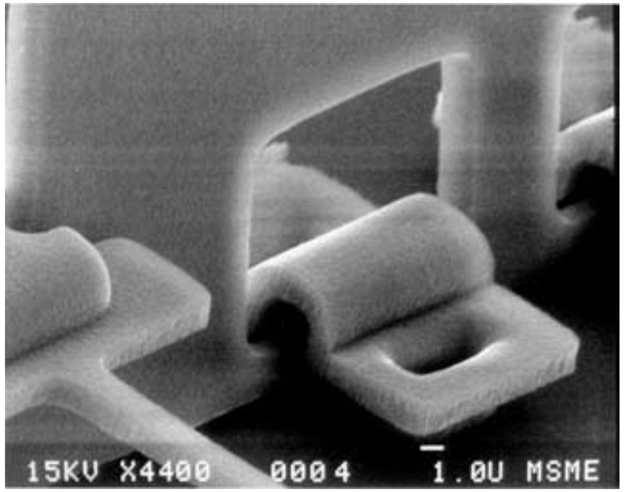
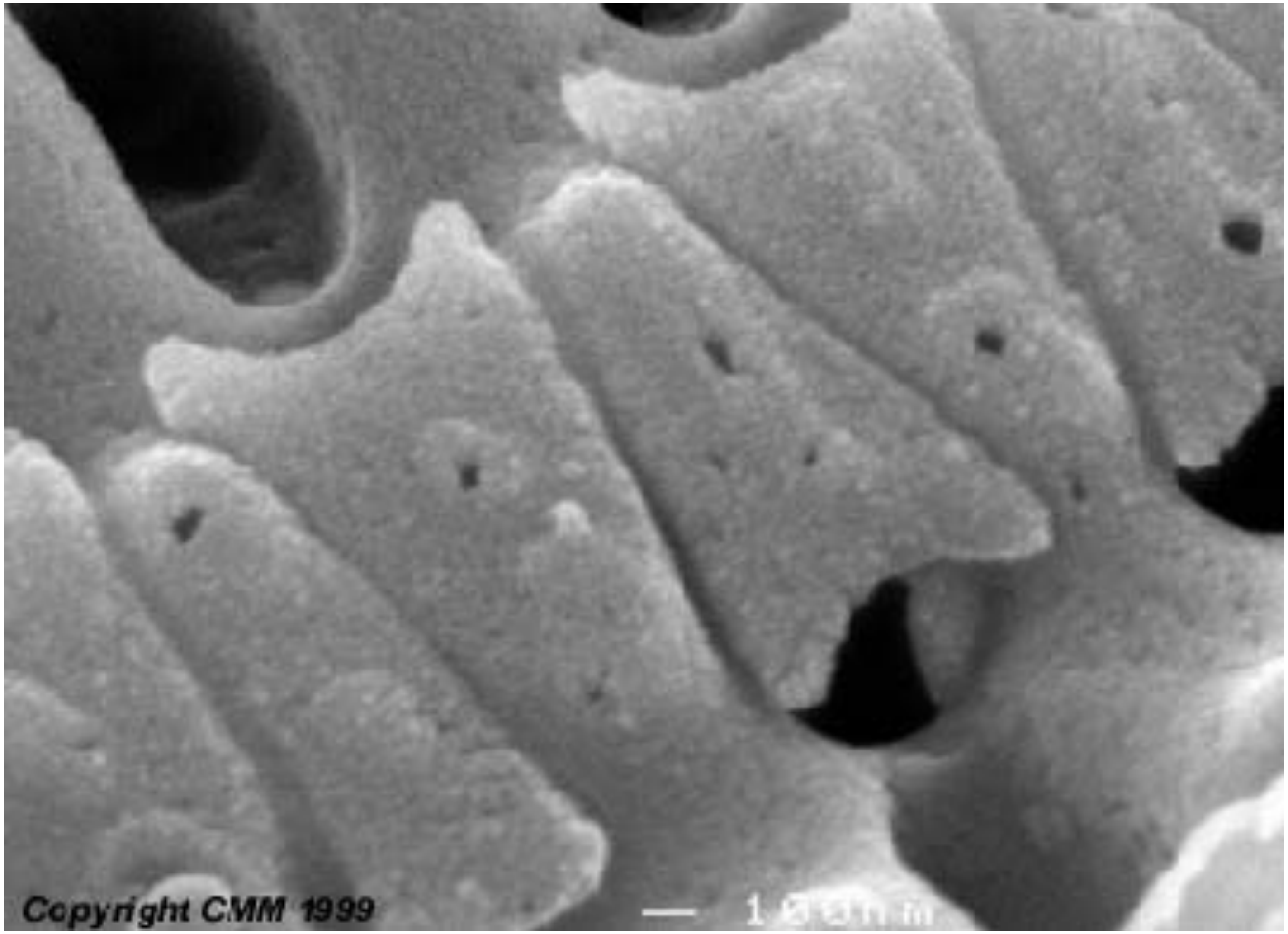

15KV X4400 0004 1.0U MSME

200nm wide linking structures



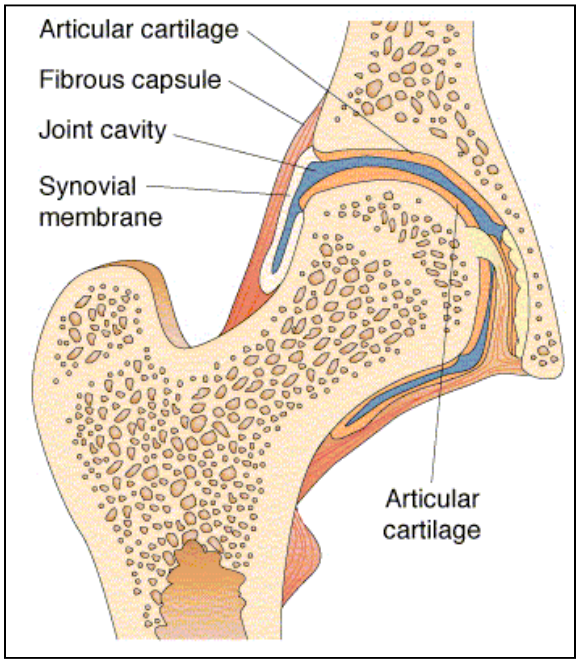
Aulacoseira granulata (?), Scale bar 100 nm

Examples for tribology in biology

- Tribology is omnipresent in biology.
- Surfaces in relative motion occur e.g. in joints, in the blinking with the eye, in the foetus moving in the mothers womb.

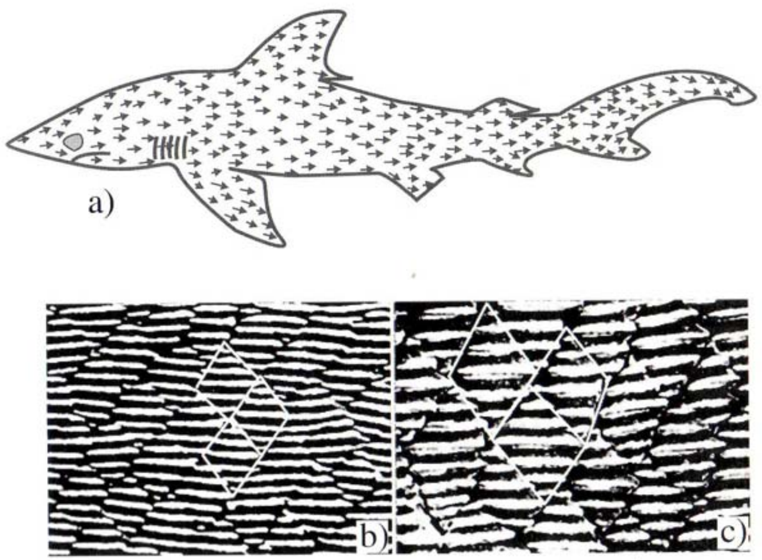
Examples for tribology in biology

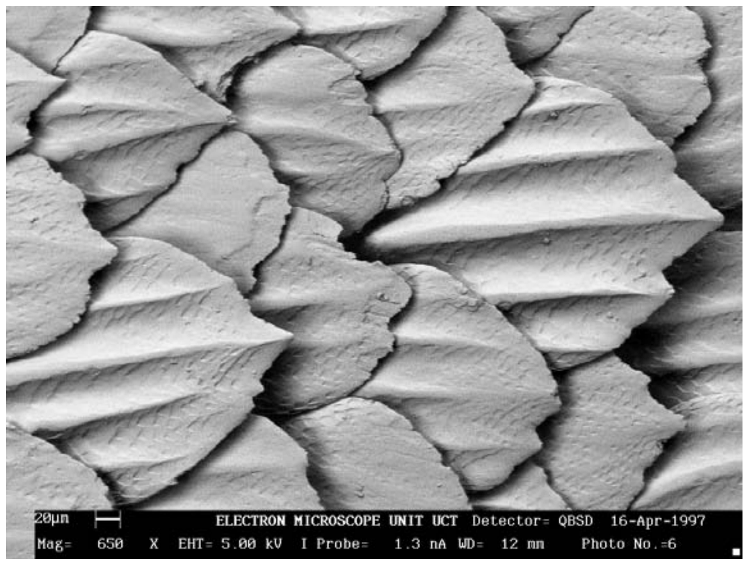
- **Systems with reduced friction**
  - joints and articular cartilage



Examples for tribology in biology

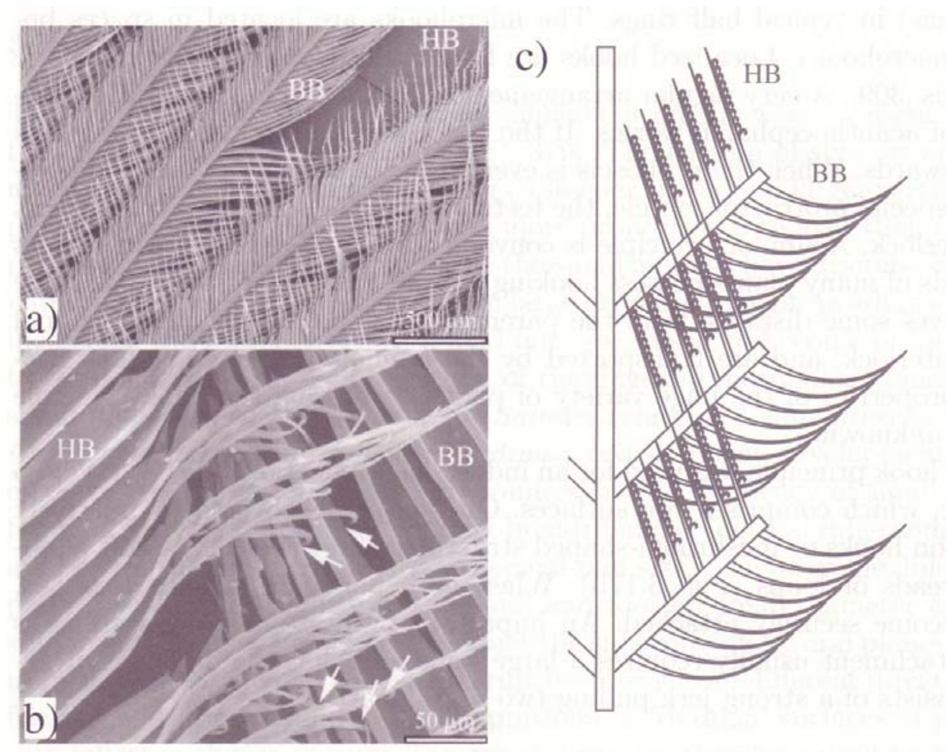
- **Systems with reduced friction**
  - shark skin





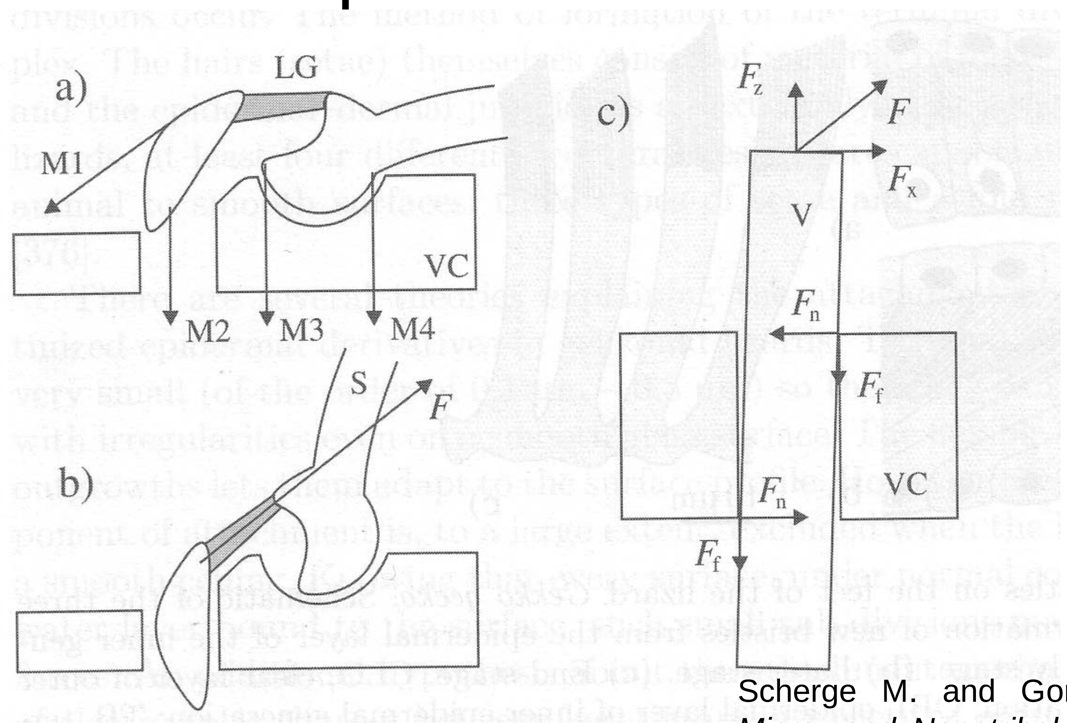
Examples for tribology in biology

- **Systems with increased friction**
  - bird feather interlocking devices



Examples for tribology in biology

- **Systems with increased friction**
  - friction in fish spines



Scherge M. and Gorb S. (2001) *Biological Micro- and Nanotribology - Nature´s solutions*, Nanoscience and Technology Series, Springer Verlag.

Examples for tribology in biology

- **Systems with increased adhesion**
  - sticking in tree frogs
  - adhesion pads in insects
  - stable, strong and self-healing underwater adhesives

Volume 5 Number 1 January 2005

Journal of NANOSCIENCE and NANOTECHNOLOGY

Editor-in-Chief: Hari Singh Nalwa, USA www.aspbs.com/jnn

A Special Issue on

Diatom Nanotechnology

GUEST EDITORS

Richard Gordon, Frithjof Sterrenburg, and Kenneth Sandhage

AMERICAN SCIENTIFIC PUBLISHERS

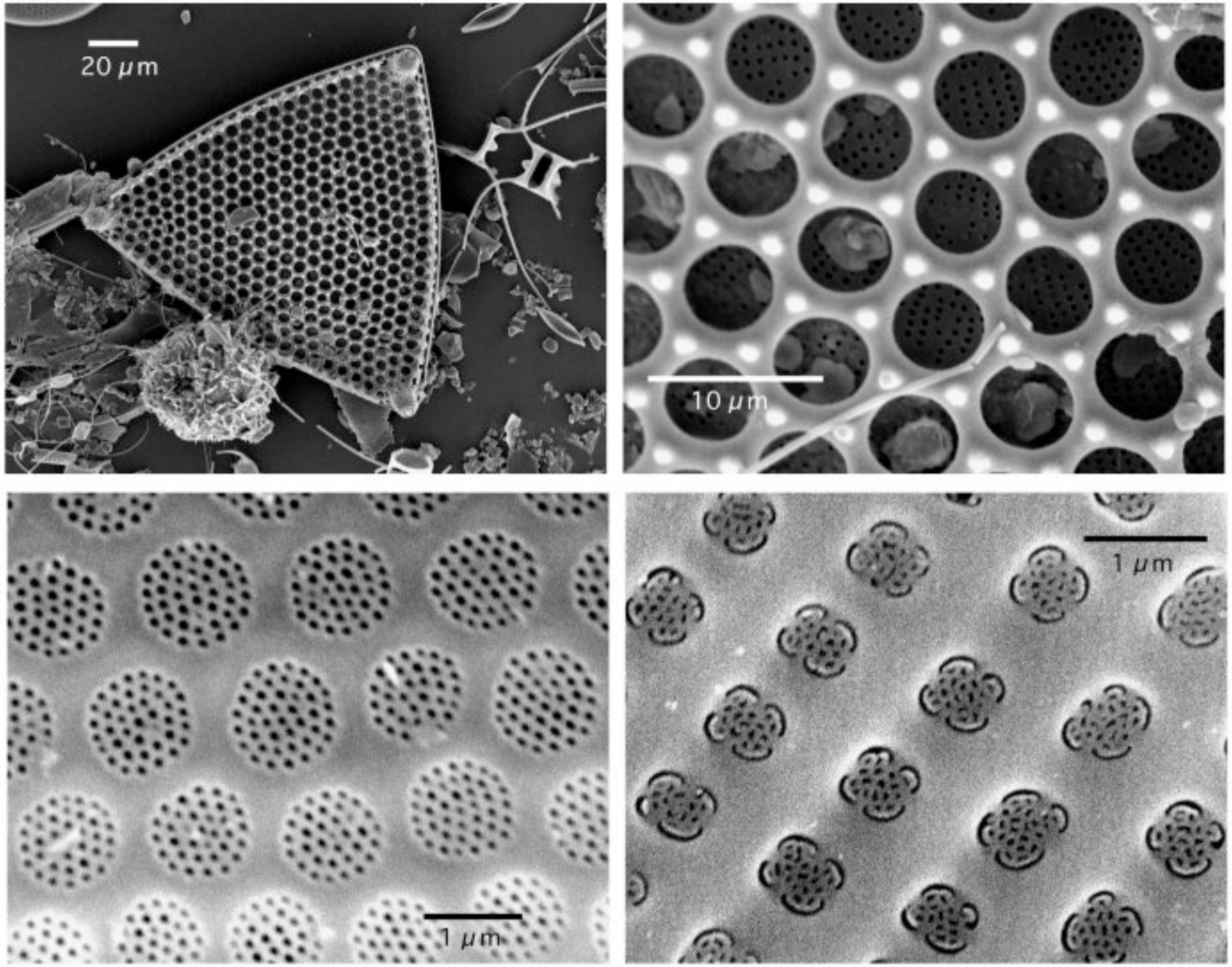
JNN Special issue on DIATOM NANOTECHNOLOGY, vol 5, no 1, January 2005

- Diatomics: Toward Diatom Functional **Genomics**
- Nanostructures in Diatom Frustules: Functional Morphology of Valvocopulae in Cocconeidacean Monoraphid Taxa
- Nature's Batik: A Computer **Evolution** Model of Diatom Valve Morphogenesis
- Potential Roles for Diatomists in Nanotechnology
- Biosynthesis of Silicon-Germanium Oxide Nanocomposites by the Marine Diatom Nitzschia frustulum
- Investigation of Mechanical Properties of Diatom Frustules Using **Nanoindentation**
- Comments on Recent Progress Toward Reconstructing the Diatom Phylogeny
- Ceramic Nanoparticle Assemblies with **Tailored Shapes** and **Tailored Chemistries** via Biosculpting and Shape-Preserving Inorganic Conversion
- Controlled Silica Synthesis Inspired by Diatom Silicon **Biomineralization**
- Diatom **Bionanotribology**-Biological Surfaces in Relative Motion: Their Design, Friction, Adhesion, Lubrication and Wear
- Engineering and Medical Applications of Diatoms
- Zeolitisation of Diatoms
- Frustules to Fragments, Diatoms to Dust: How Degradation of Microfossil Shape and Microstructures Can Teach Us How Ice Sheets Work
- Crystal Palaces - Diatoms for Engineers
- The Evolution of **Advanced Mechanical Defenses** and Potential **Technological Applications** of Diatom Shells
- Geometry and Topology of Diatom Shape and Surface Morphogenesis for Use in Applications of Nanotechnology
- Diatom Auxospore Scales and Early Stages in Diatom Frustule Morphogenesis: Their Potential for Use in Nanotechnology
- Valve Morphogenesis in the Diatom Genus Pleurosigma W. Smith (Bacillariophyceae): Nature's Alternative Sandwich
- Prospects of Manipulating Diatom Silica Nanostructure
- Approaches for Functional Characterization of Diatom Silicic Acid Transporters
- Comparison of Diatoms, Exfoliated Graphite, Single-Wall Nanotubes, Multiwall Nanotubes, and Silica for the Synthesis of the **Nanomagnet** Mn12
- A Guide to the Diatom Literature for Diatom Nanotechnologists

Diatoms

© W. Oschmann

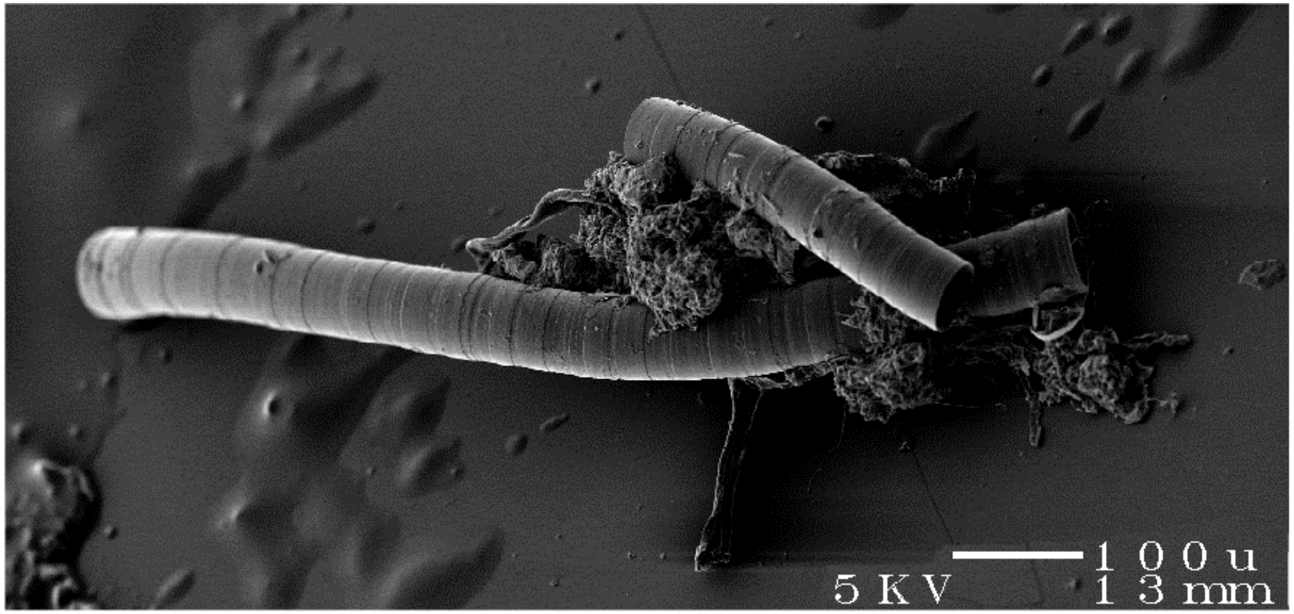
- single cellular organisms
- size some micrometers
- 10 000s different species
- reproduce via cell division
- under ideal conditions, within ten days the offspring of one single cell number one billion cells (*Fließband*, i.e. assembly line production of nanostructures !)
- nanostructured surfaces made from amorphous silicates

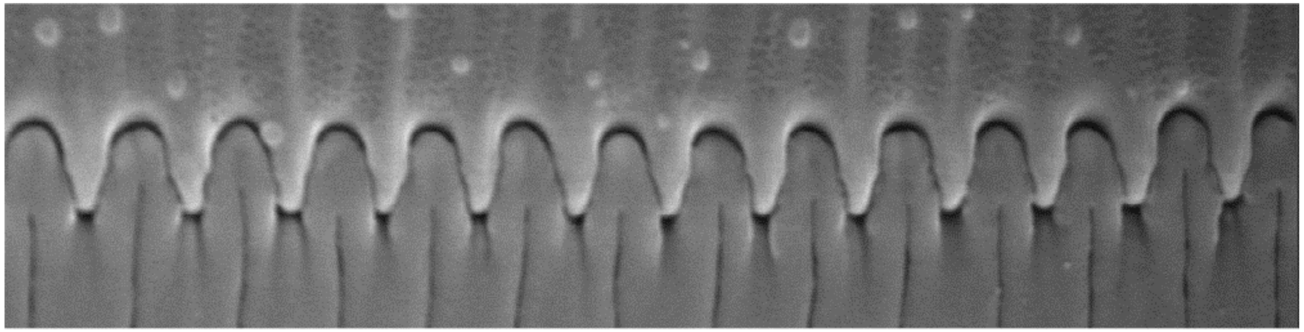


Top: *Tricaeratium favus*, bottom left: *Roperia tessellata*,
bottom right: *Achnathes brevipes* © Gebeshuber *et al.*, J. Mat. Sci. 2002

Diatom biotribology

Ellerbeckia arenaria – the „rubberband“ diatoms:

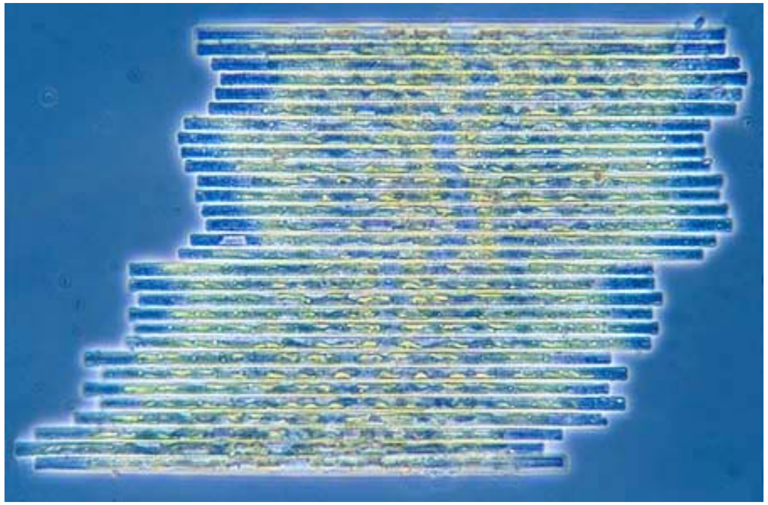


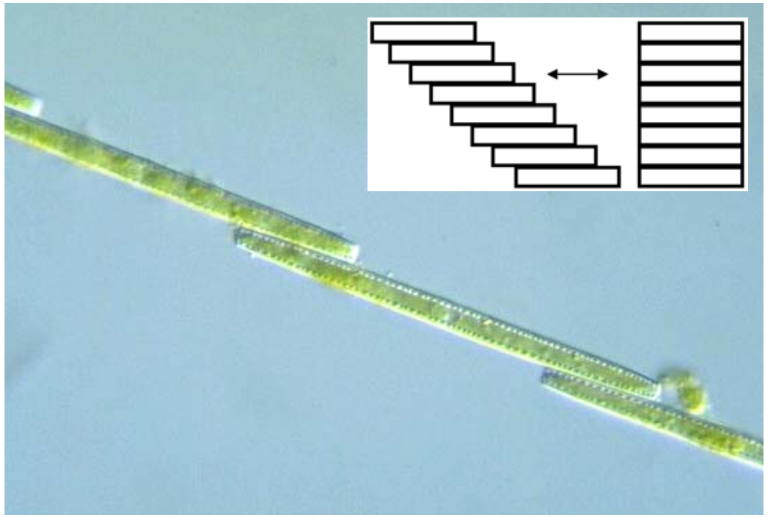


1μm

Diatom biotribology

Bacillaria paxillifer – the moving diatoms:





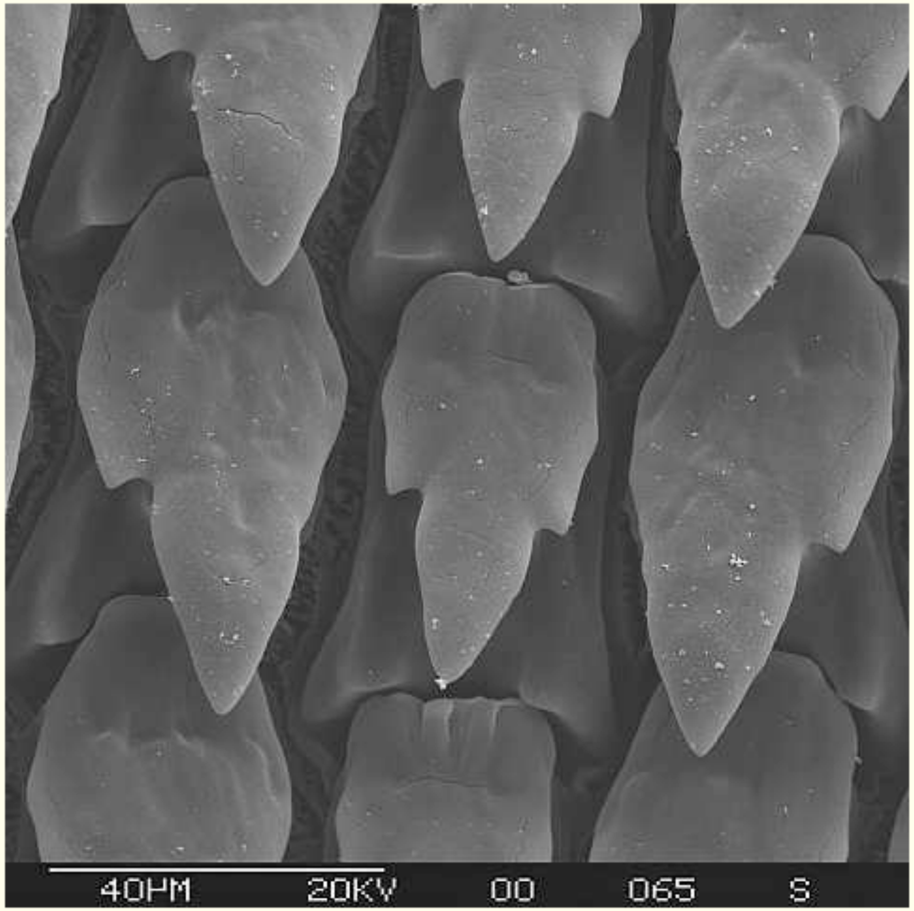
Diatom biotribology

Bacillaria paxillifer – the moving diatoms:

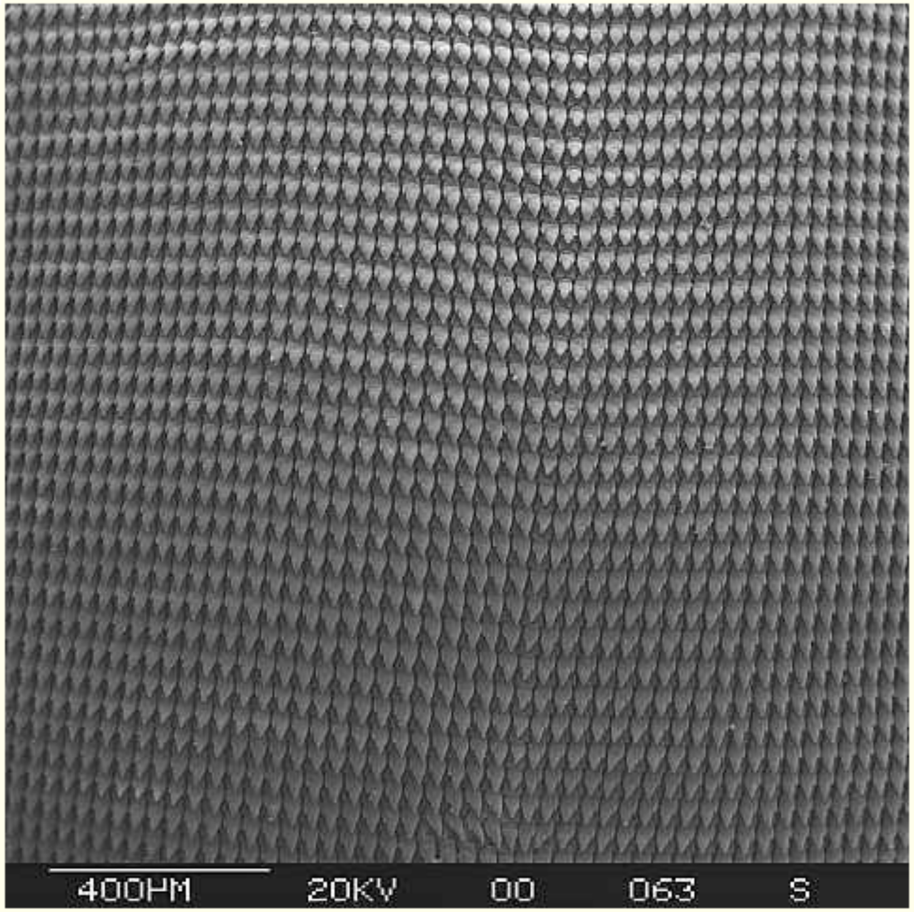
Teeth

of snails

Radulae

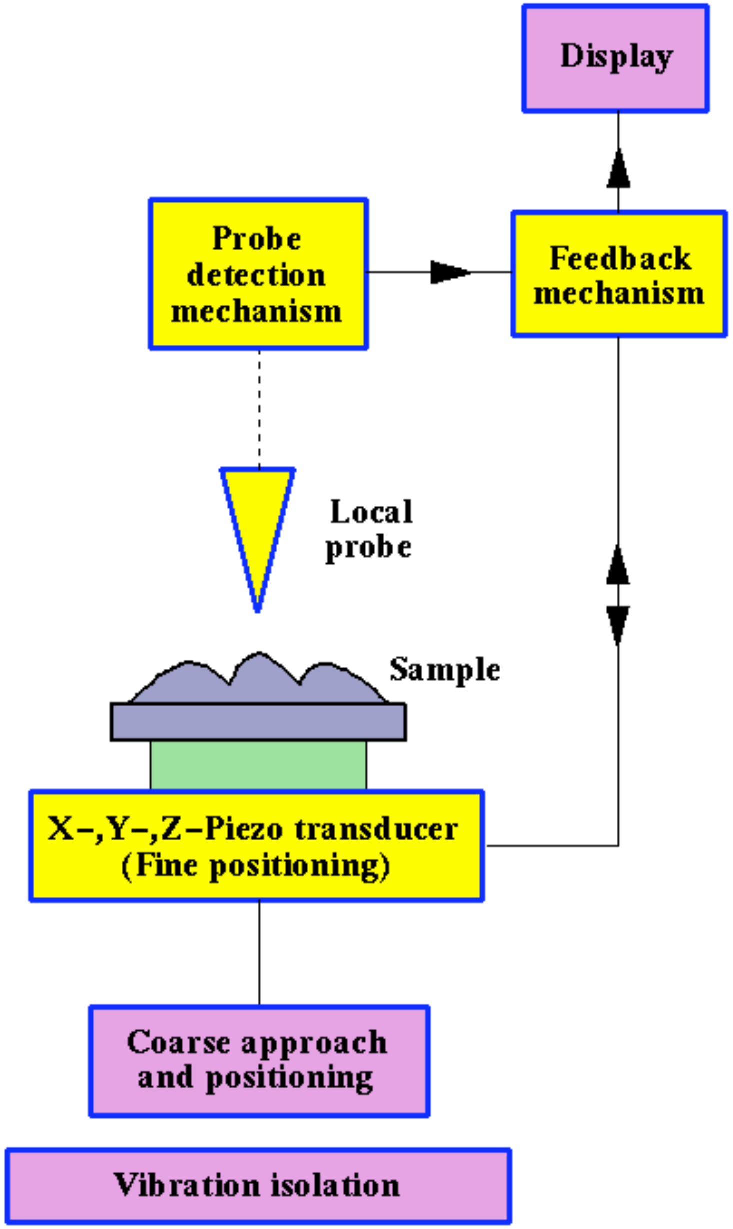


Source: Salzburg University (Josef Ramsauer).



Source: Salzburg University (Josef Ramsauer).

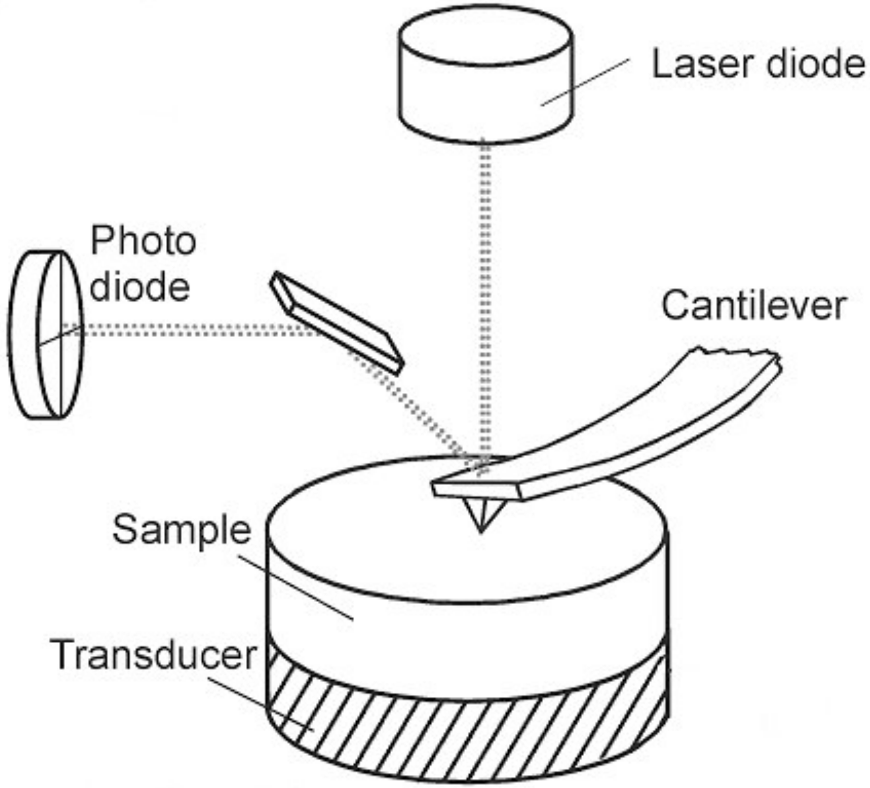
Scanning Probe Microscopy



Investigation of **mechanical**, **electrical**, **optical**, **chemical** and **magnetic** properties.

In **air**, **vacuum** and in **fluids**.

Atomic Force Microscopy (AFM)

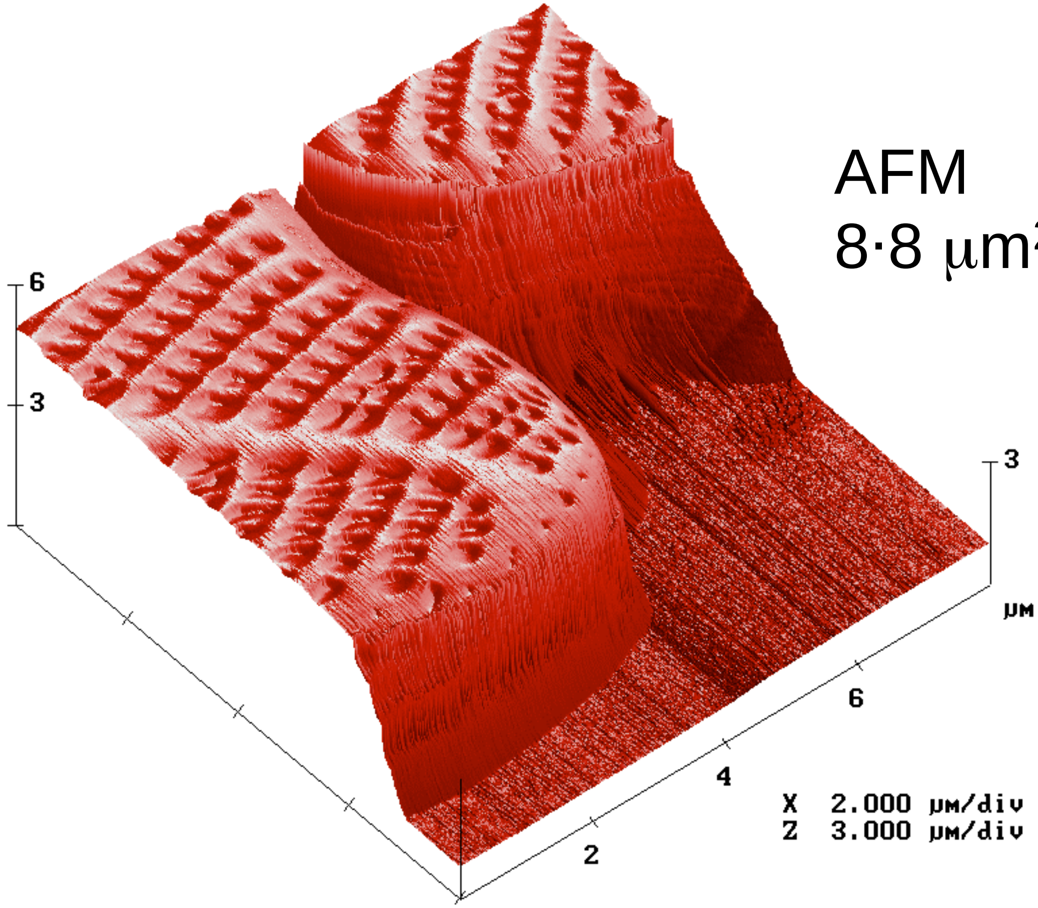


© P. Hansma, UCSB

The AFM measures the **force** between the probe tip and the sample.

AFM of living diatoms I:
Navicula seminulum

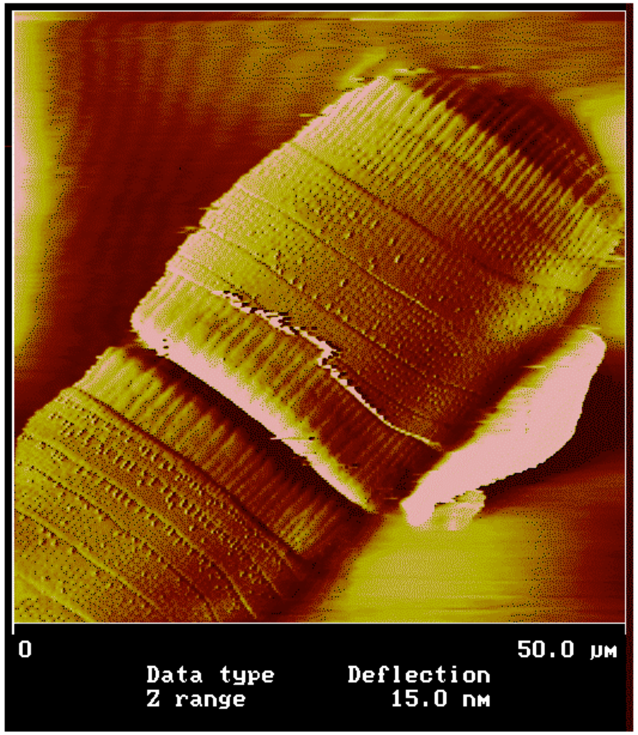
AFM
8·8 μm^2

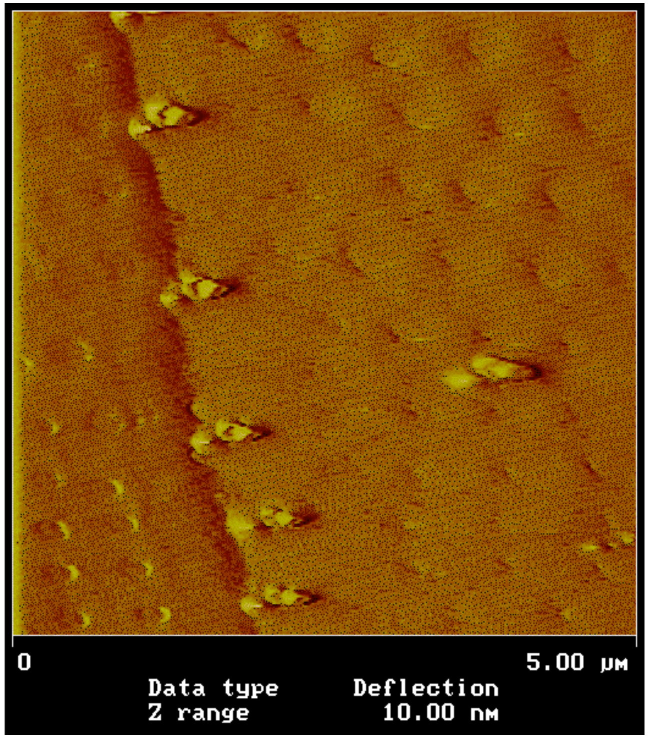


Gebeshuber I.C. *et al.* (2003) *"Atomic force microscopy study of living diatoms in ambient conditions"*, J. Microsc. Oxf. **212**, pp. 292-299.

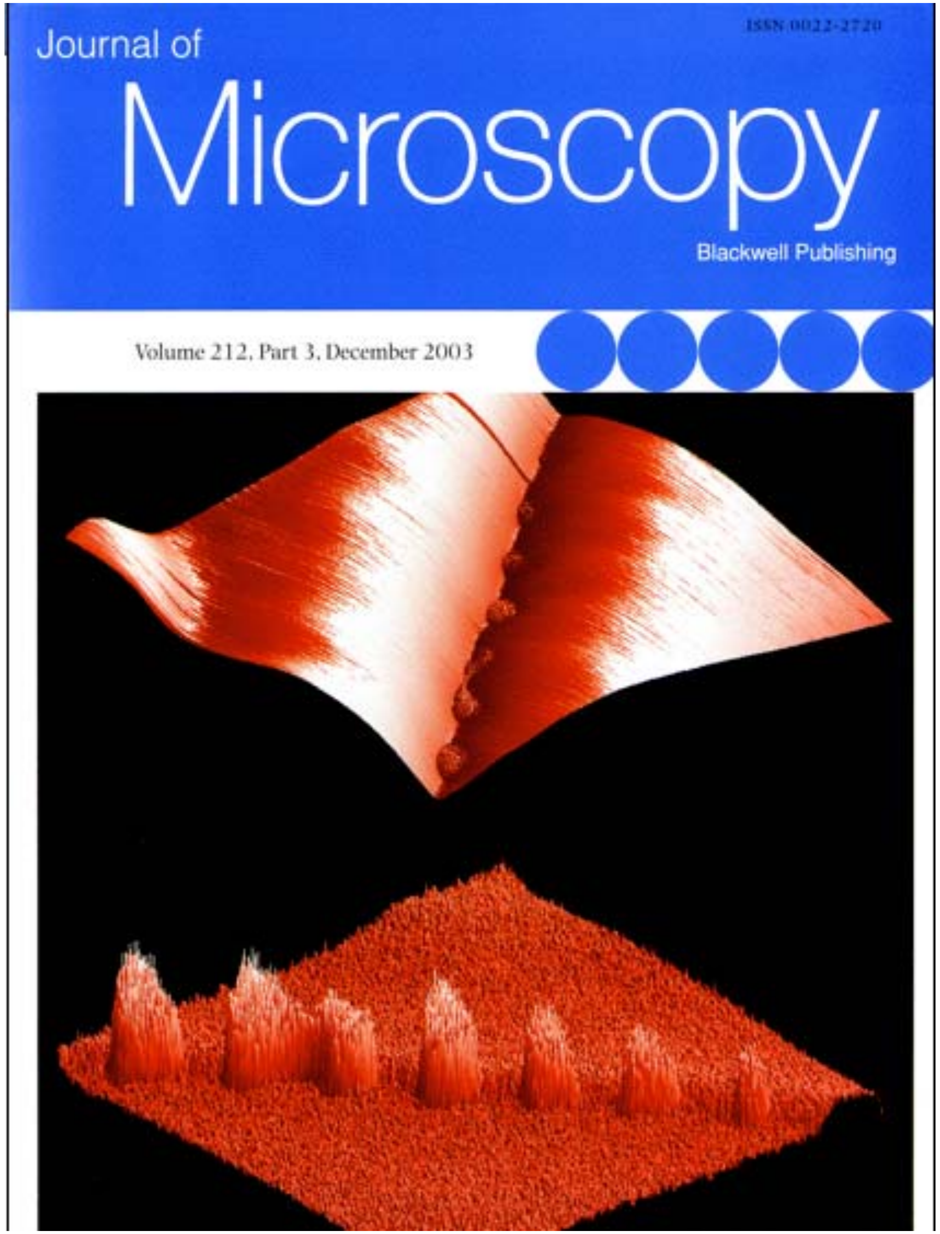
Diatom biotribology

Ballbearings? Solid lubricants? In a protist ?!
An unidentified diatom visualised *in vivo* with an atomic force microscope:



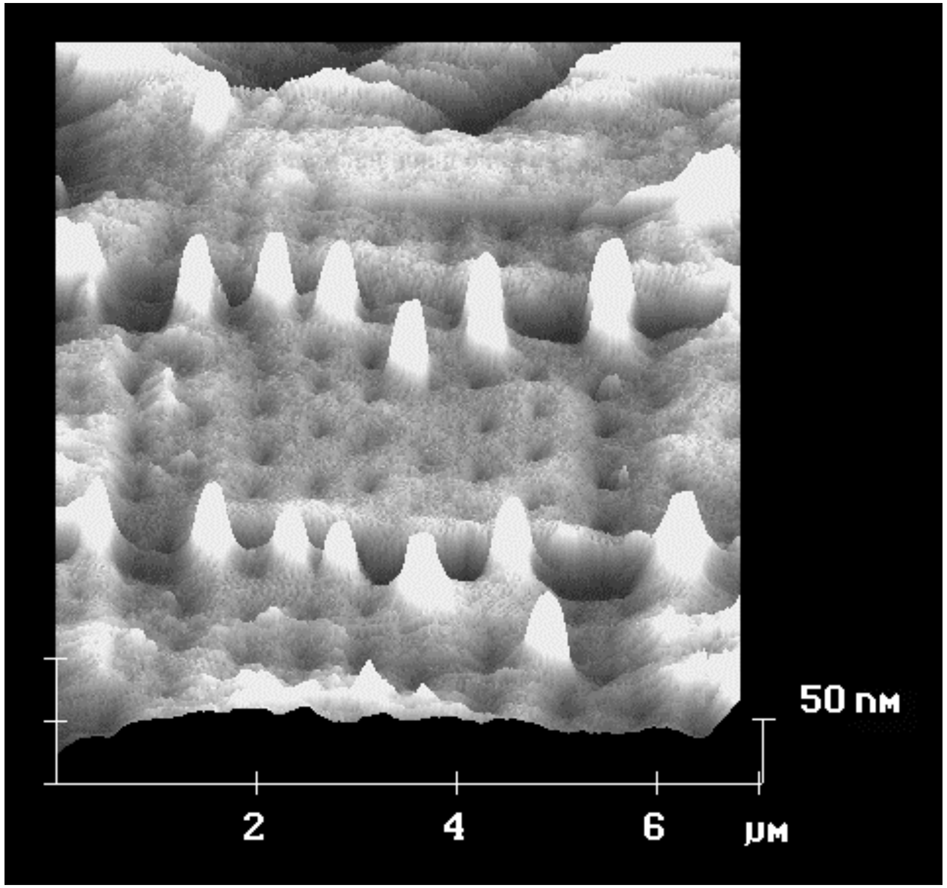


Biogenic adhesives



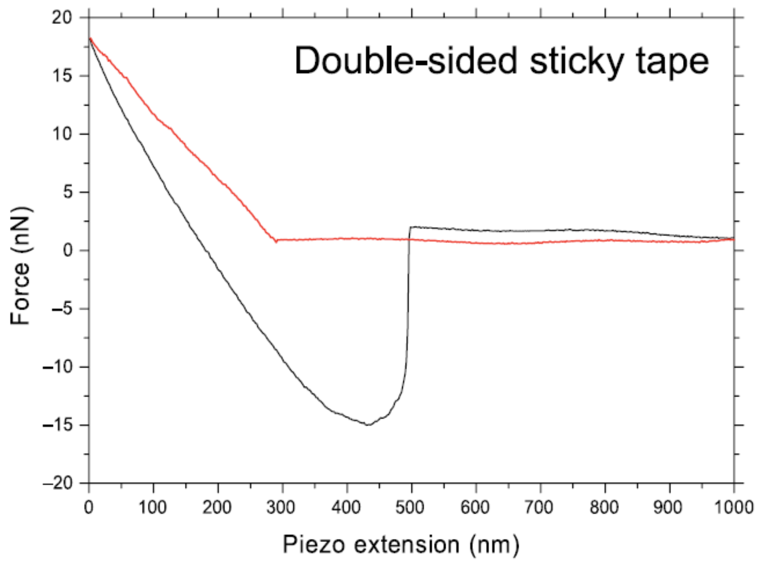
Gebeshuber I.C. *et al.* (2002) *"In vivo nanoscale atomic force microscopy investigation of diatom adhesion properties"*, Mat. Sci. Technol. **18**, pp. 763-766.
Gebeshuber I.C. *et al.* (2003) *"Atomic force microscopy study of living diatoms in ambient conditions"*, J. Microsc. Oxf. **212**, pp. 292-299.

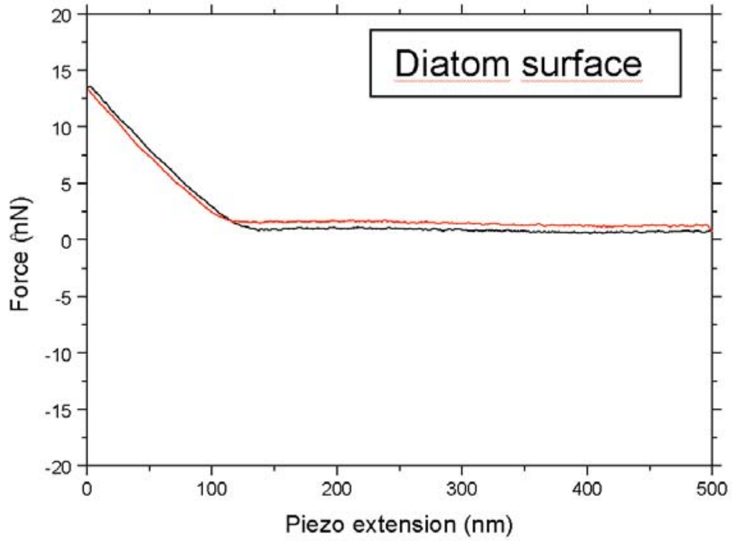
AFM of living diatoms II

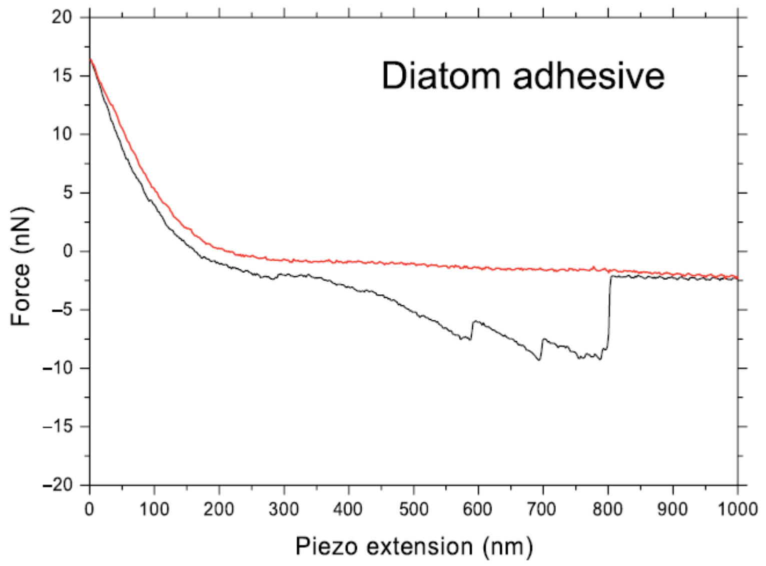


Gebeshuber I.C. *et al.* (2003) *"Atomic force microscopy study of living diatoms in ambient conditions"*, J. Microsc. Oxf. **212**, pp. 292-299.

Biogenic adhesives

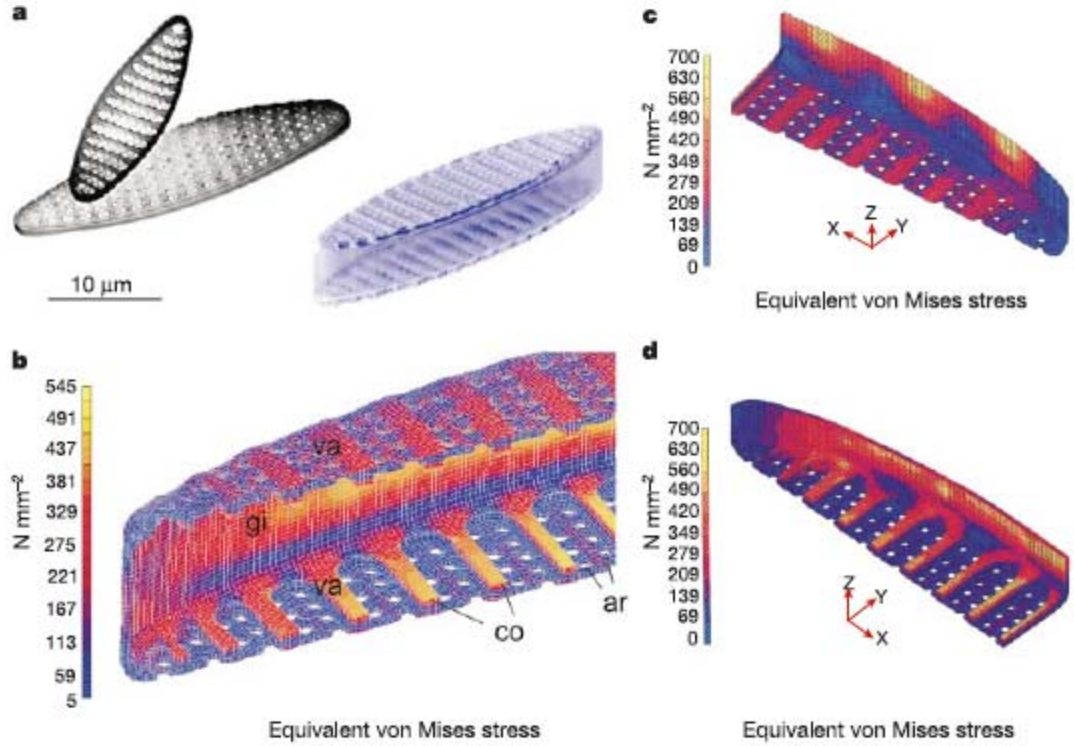


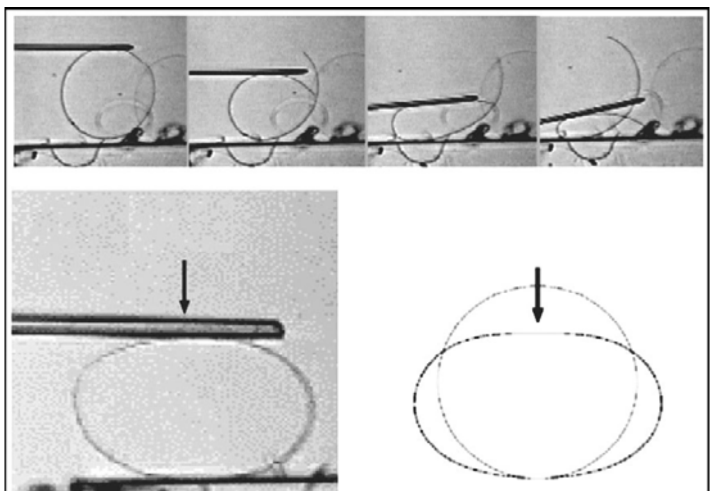




Gebeshuber I.C. *et al.* (2003) *"Atomic force microscopy study of living diatoms in ambient conditions"*, J. Microsc. Oxf. **212**, pp. 292-299.

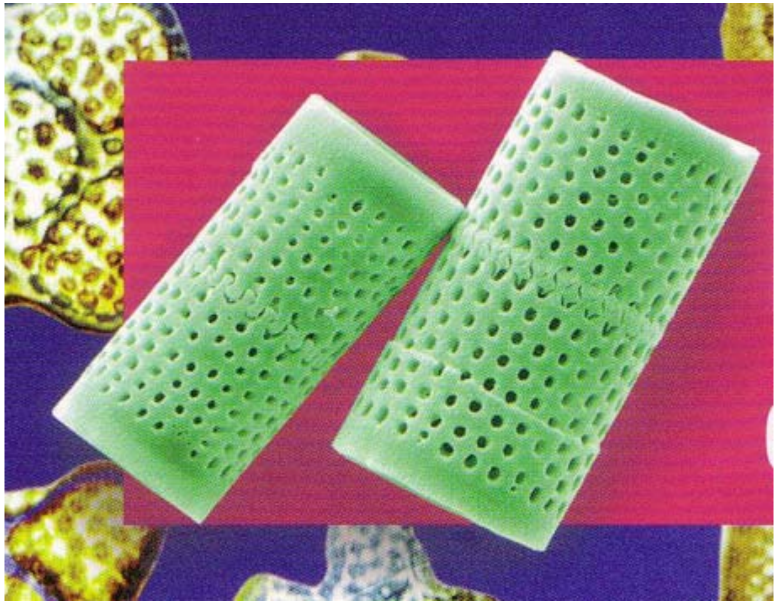
Mechanical stability





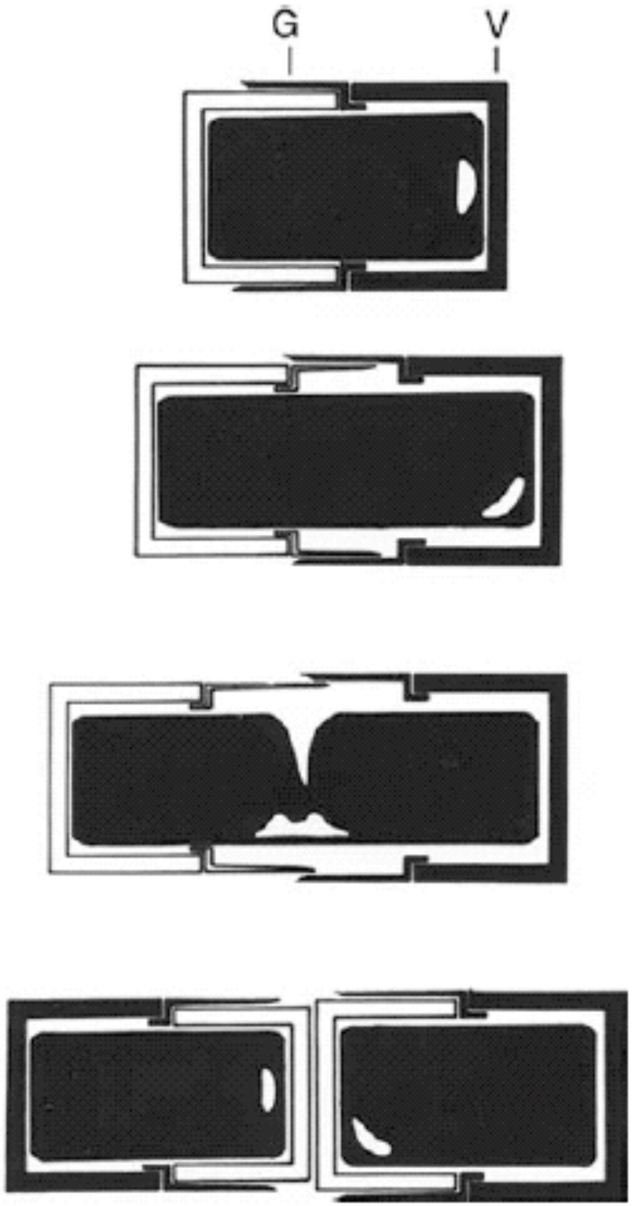
C.E. Hamm et al. (2003) *"Architecture and material properties of diatom shells provide effective mechanical protection"*, Nature **421**, pp. 841-843.

Hinges and linking devices



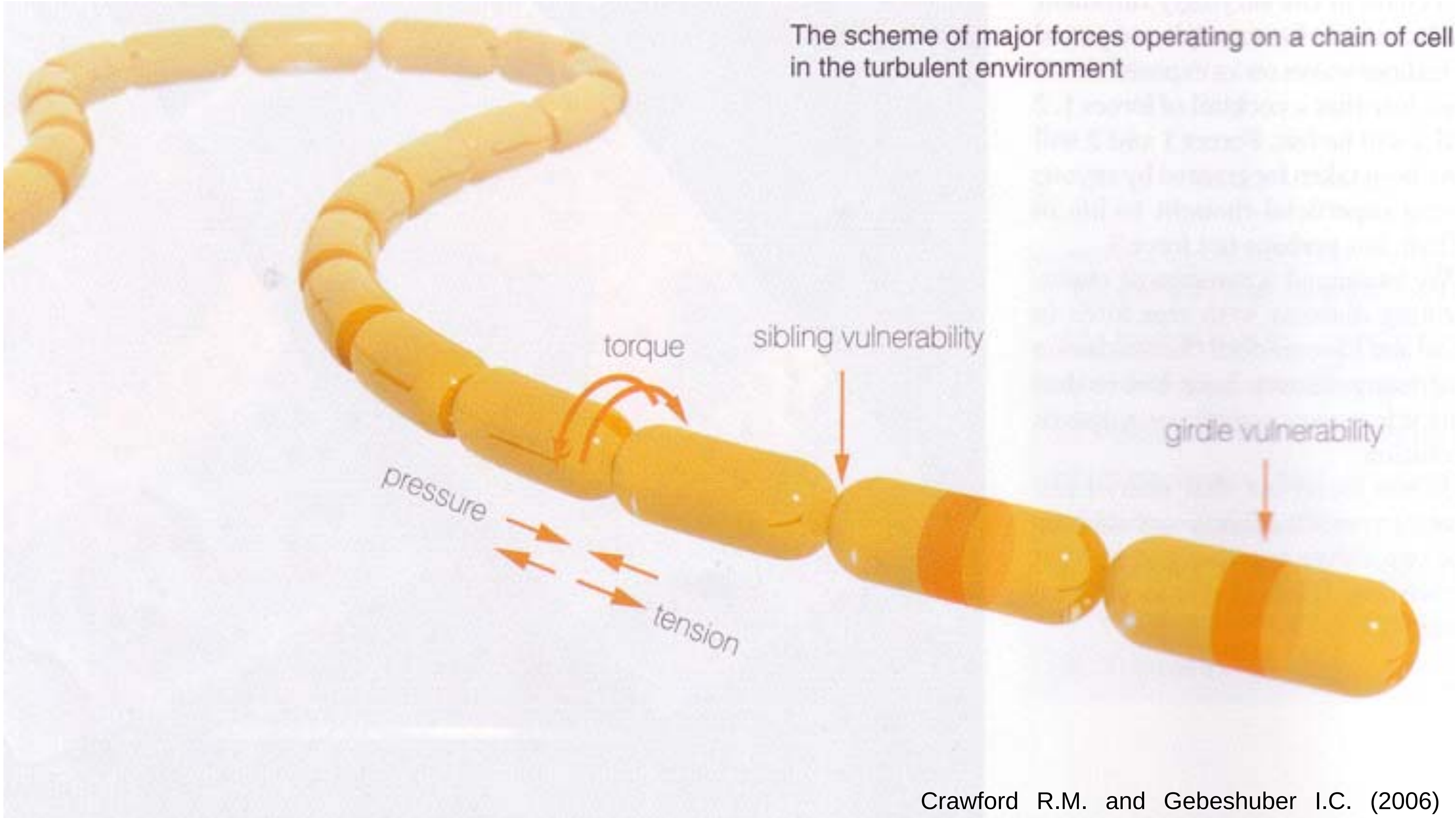
Crawford R.M. and Gebeshuber I.C. (2006) *"Harmony of beauty and expediency"*, Science First Hand 5(10), pp. 30-34.
Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

Cell division



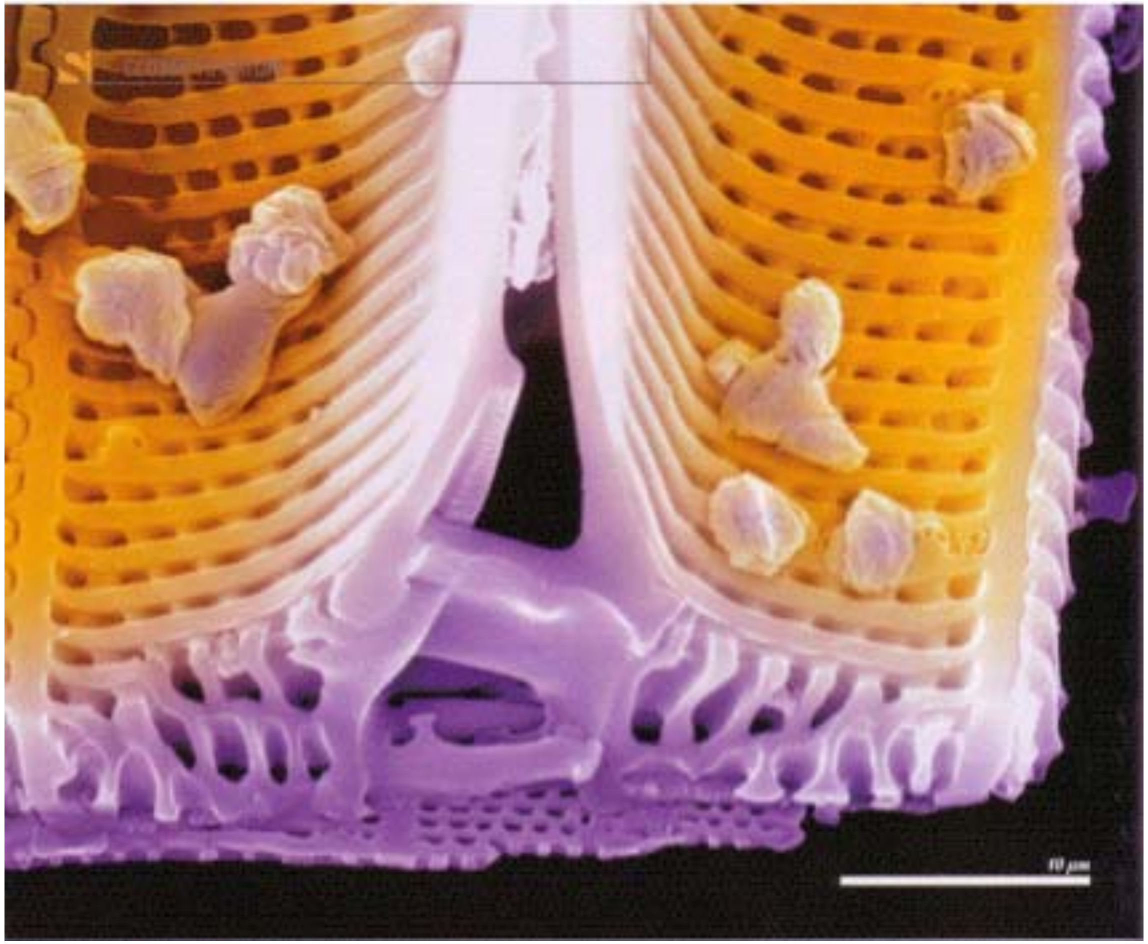
Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

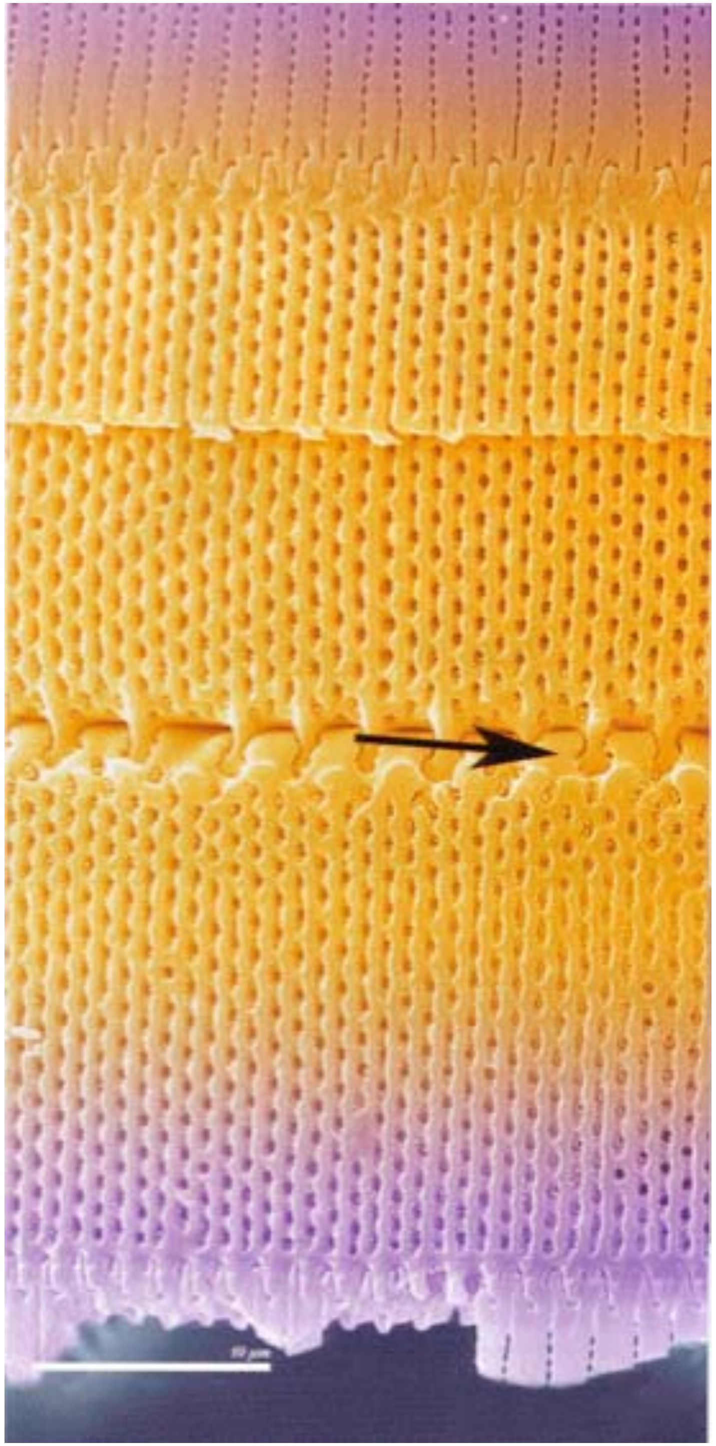
Forces and moments acting on the diatom chain



Crawford R.M. and Gebeshuber I.C. (2006) *"Harmony of beauty and expediency"*, Science First Hand 5(10), pp. 30-34.

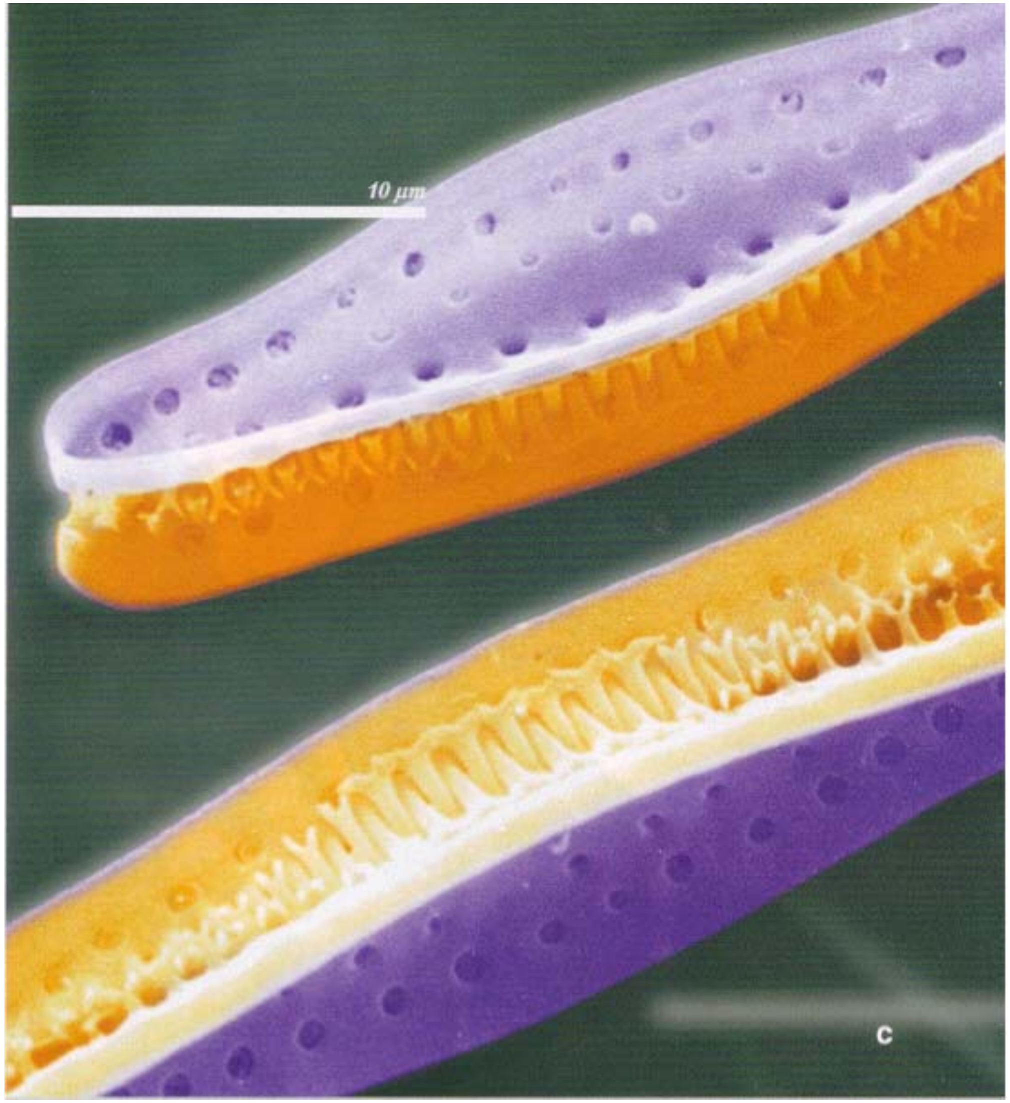
Ellerbeckia sp.





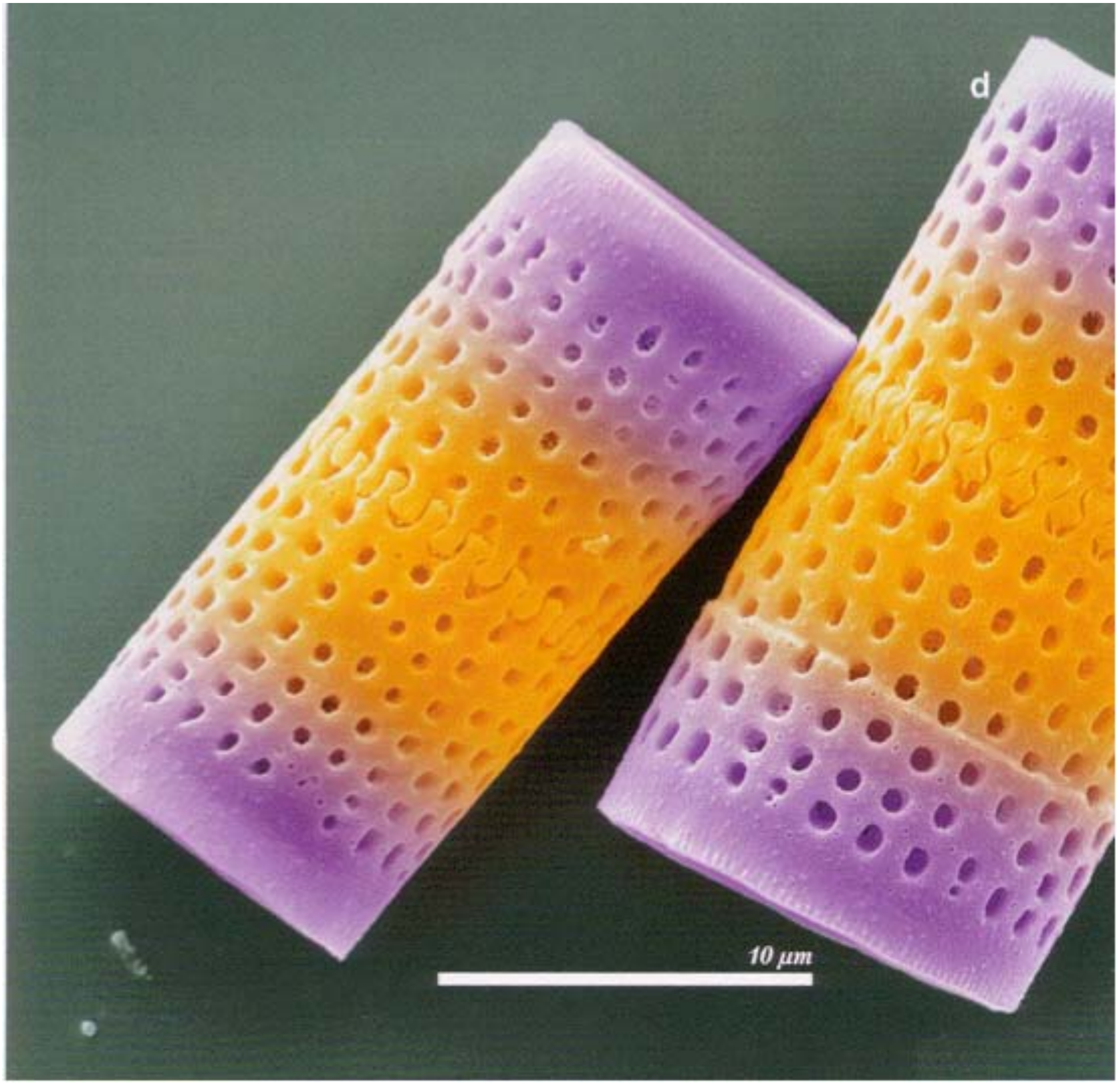
Crawford R.M. and Gebeshuber I.C. (2006) *"Harmony of beauty and expediency"*, Science First Hand 5(10), pp. 30-34.

Cymatoseira belgica Grunow



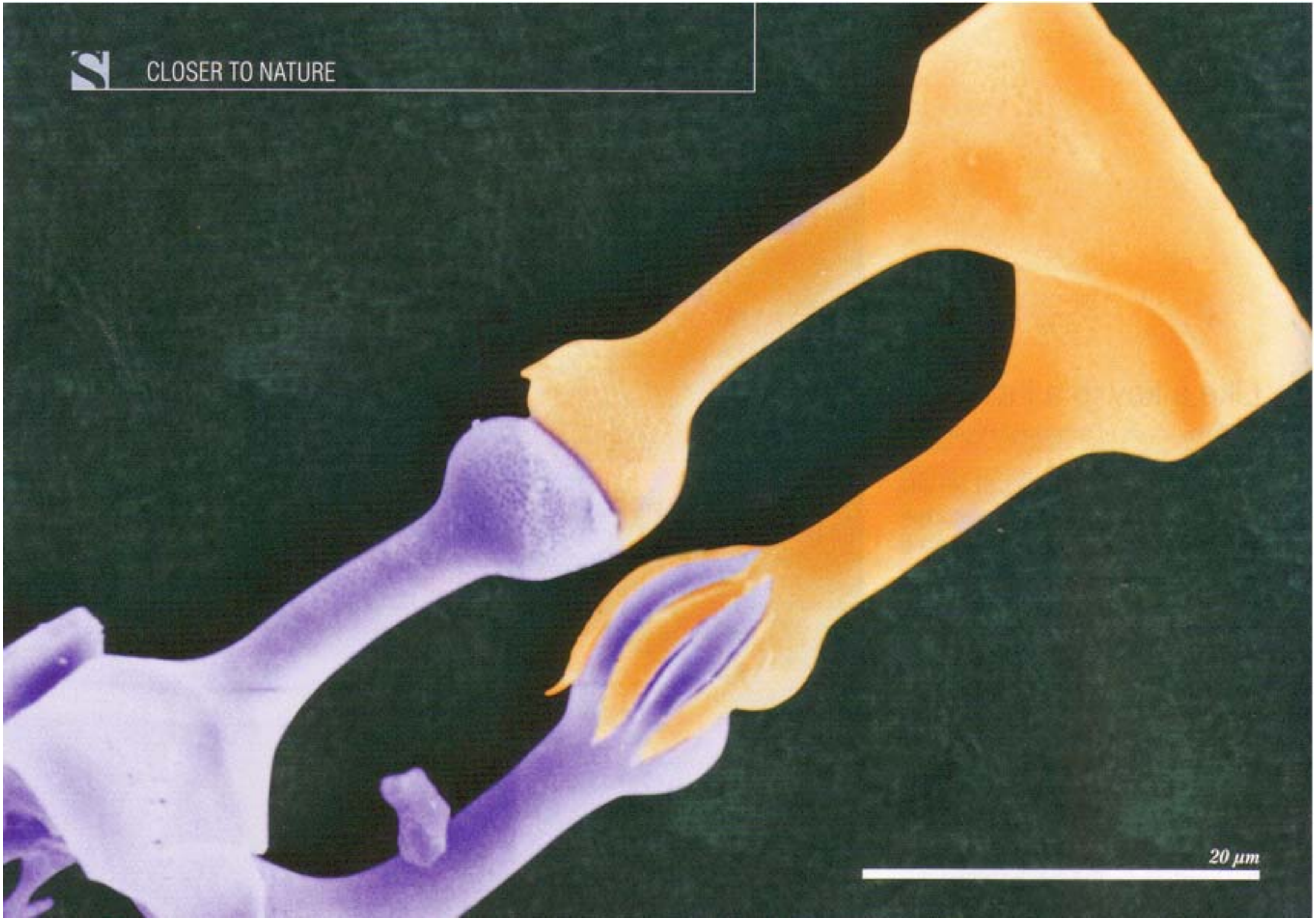
Crawford R.M. and Gebeshuber I.C. (2006) *"Harmony of beauty and expediency"*, Science First Hand 5(10), pp. 30-34.

Aulacoseira sp.

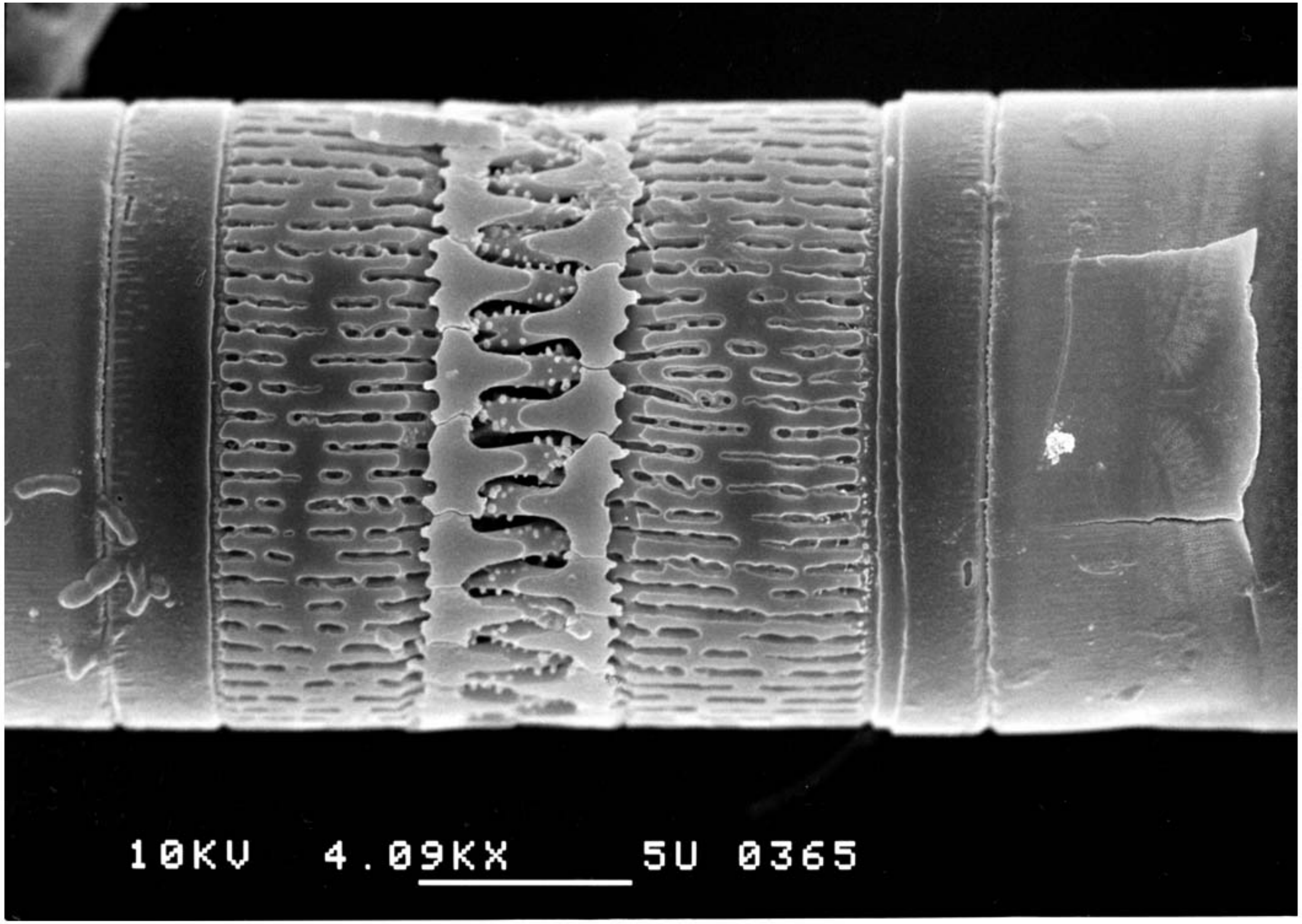


Crawford R.M. and Gebeshuber I.C. (2006) *"Harmony of beauty and expediency"*, Science First Hand 5(10), pp. 30-34.

Briggera sp.

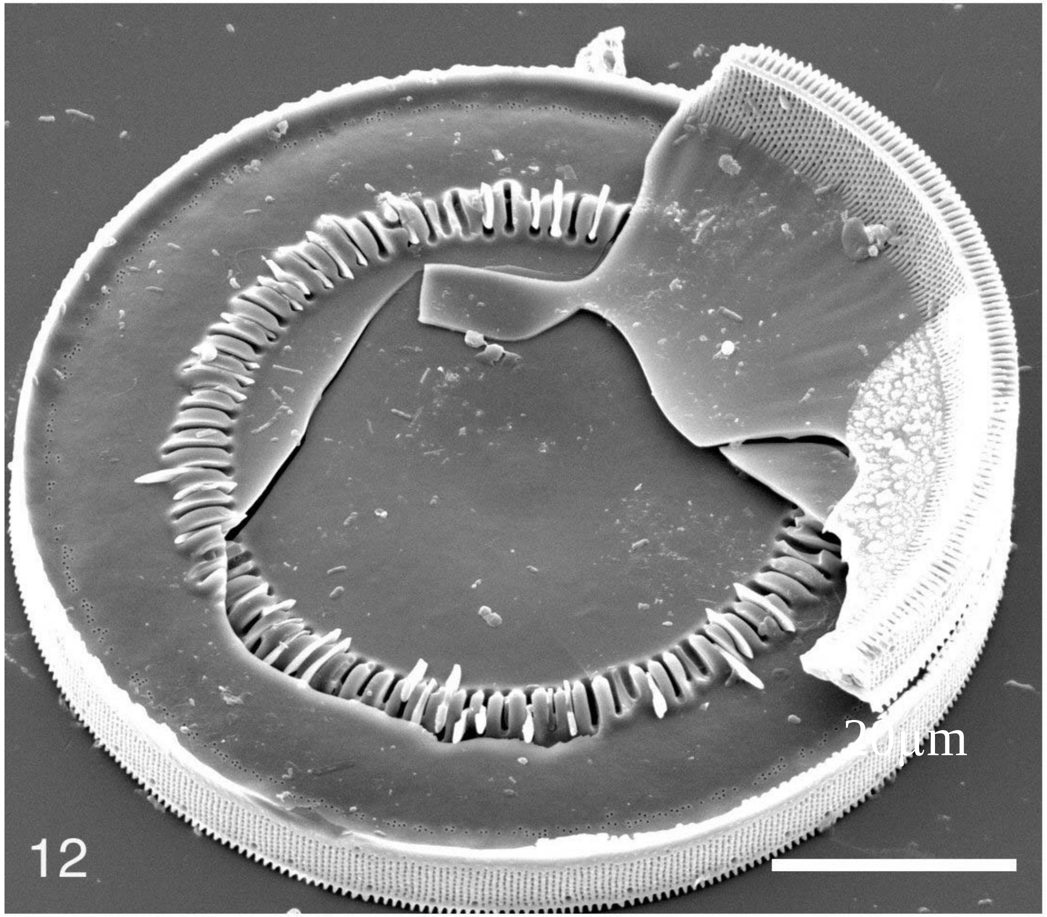


Spatulate shaped spines in *Aulacoseira*



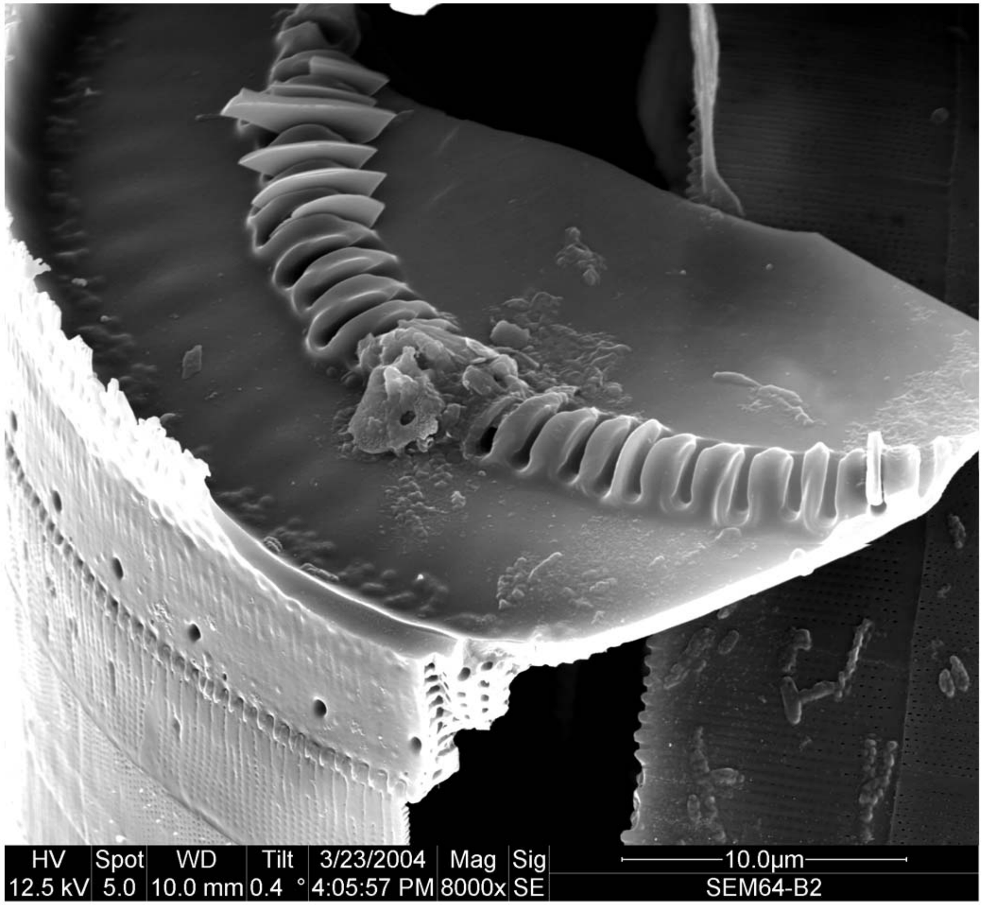
Aulacoseria italica. © RM Crawford, AWI Bremerhaven

Cameo and intaglio linking structures



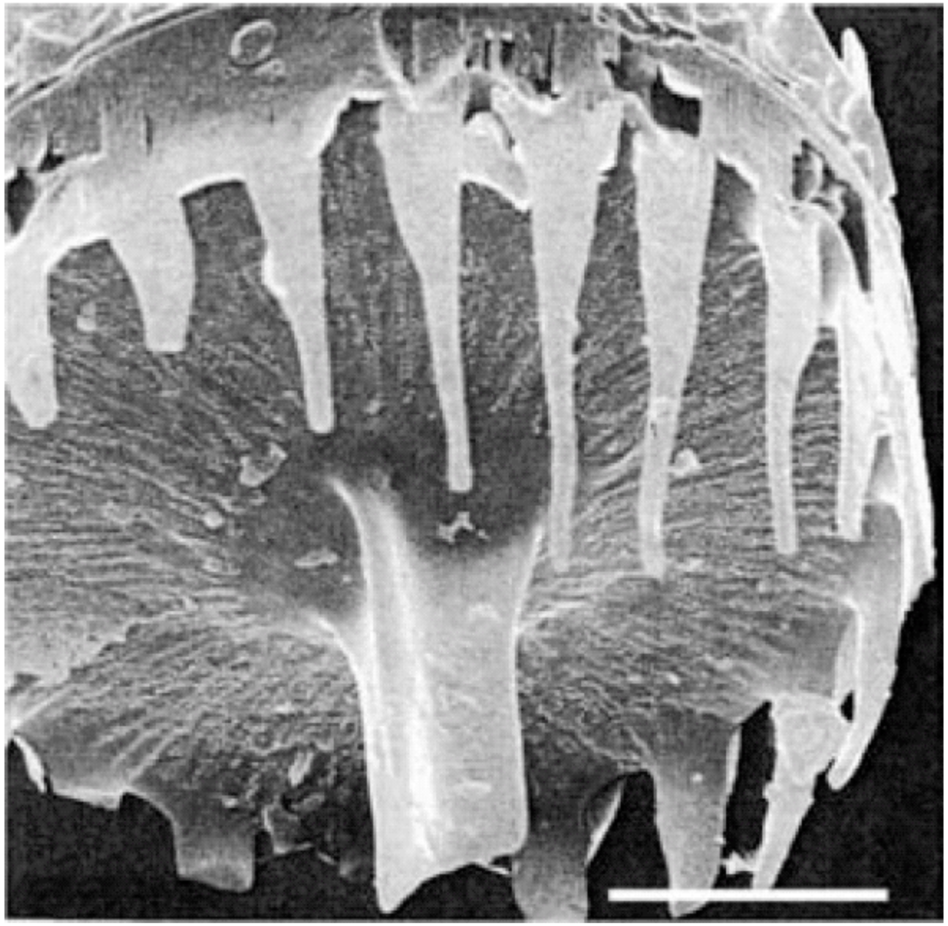
Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

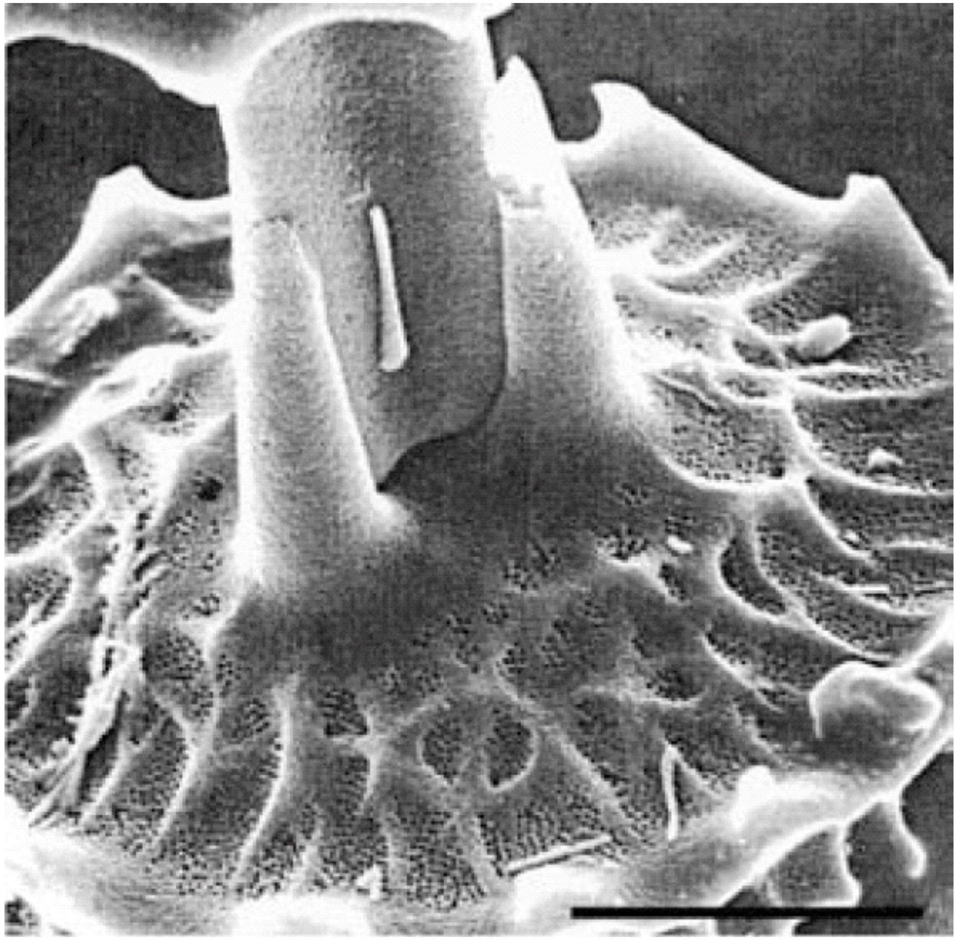
Cameo and intaglio linking structures



Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

Trochosira



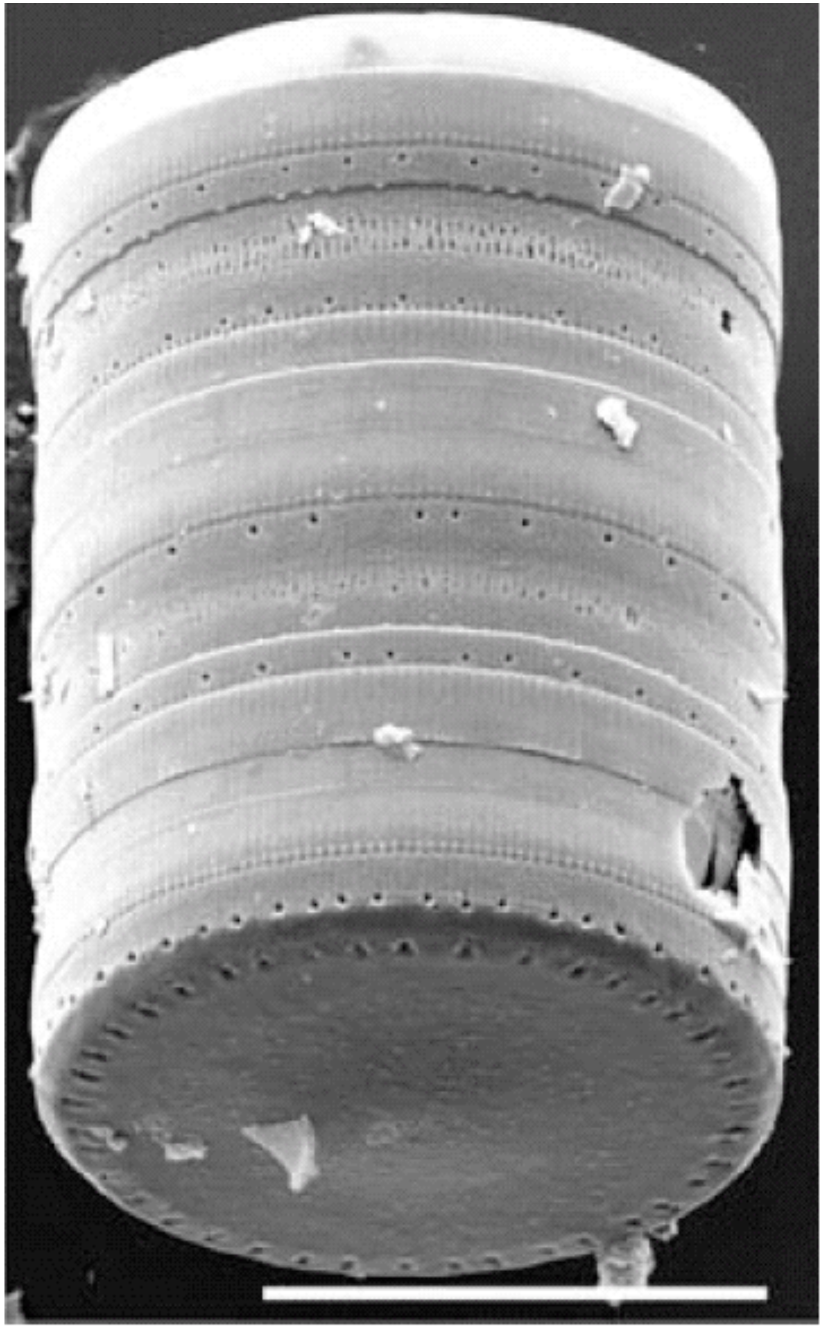


scale bar 50 μm

Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

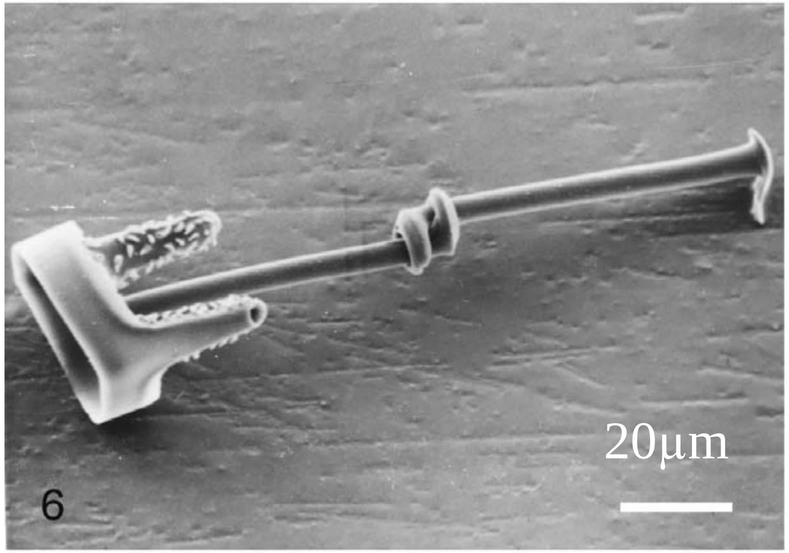
Ellerbeckia sp. with end valve

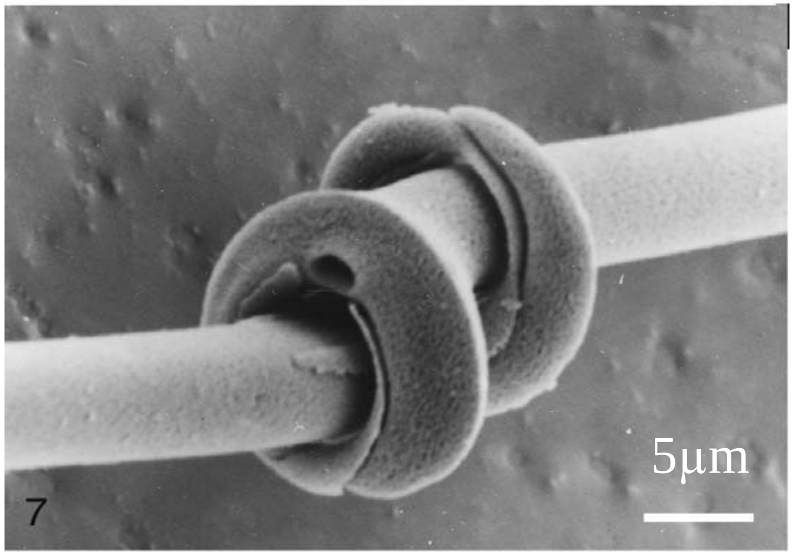
scale bar 25 μm



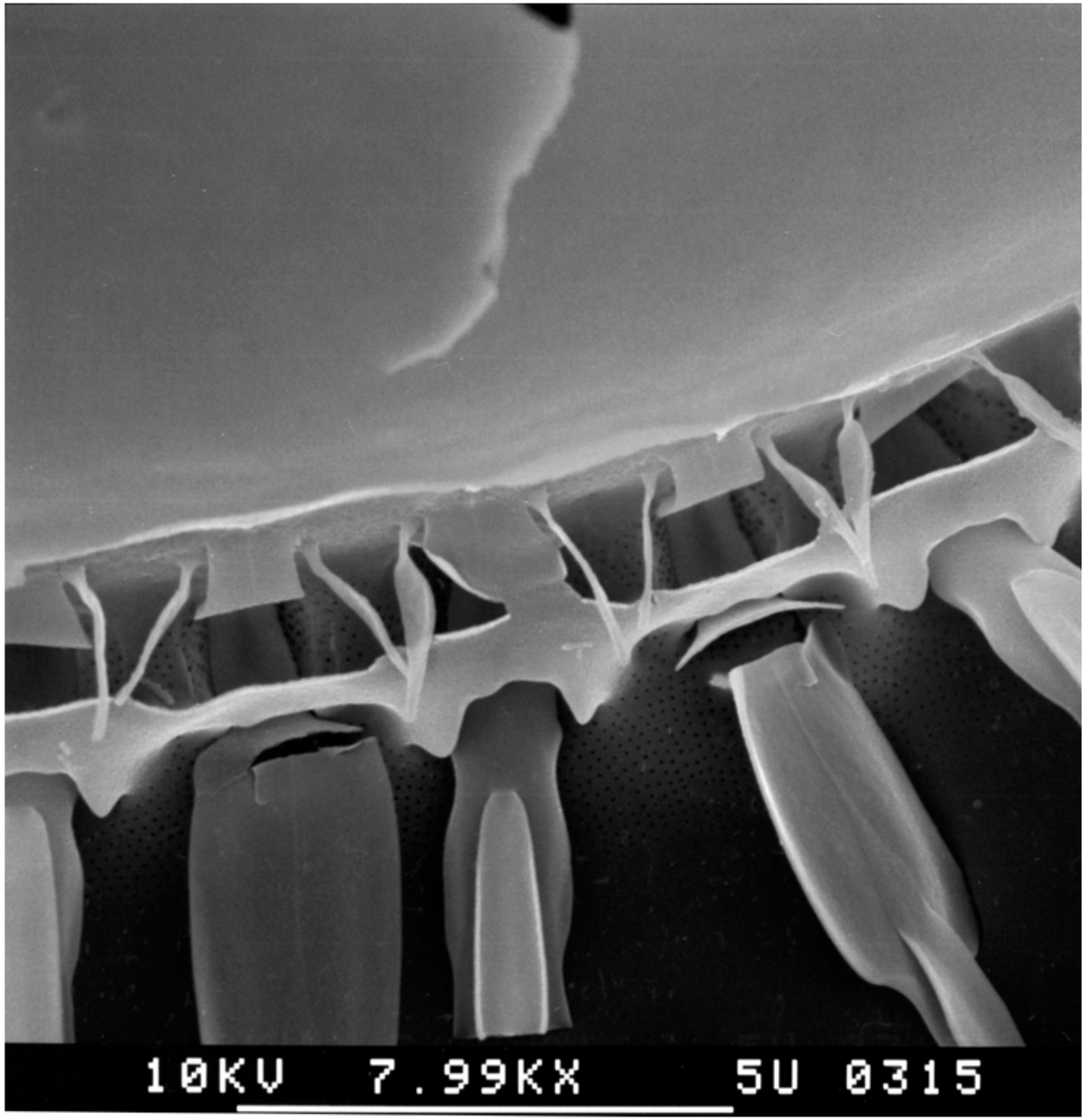
Gebeshuber I.C. and Crawford R.M. *"Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

Syndetocystis

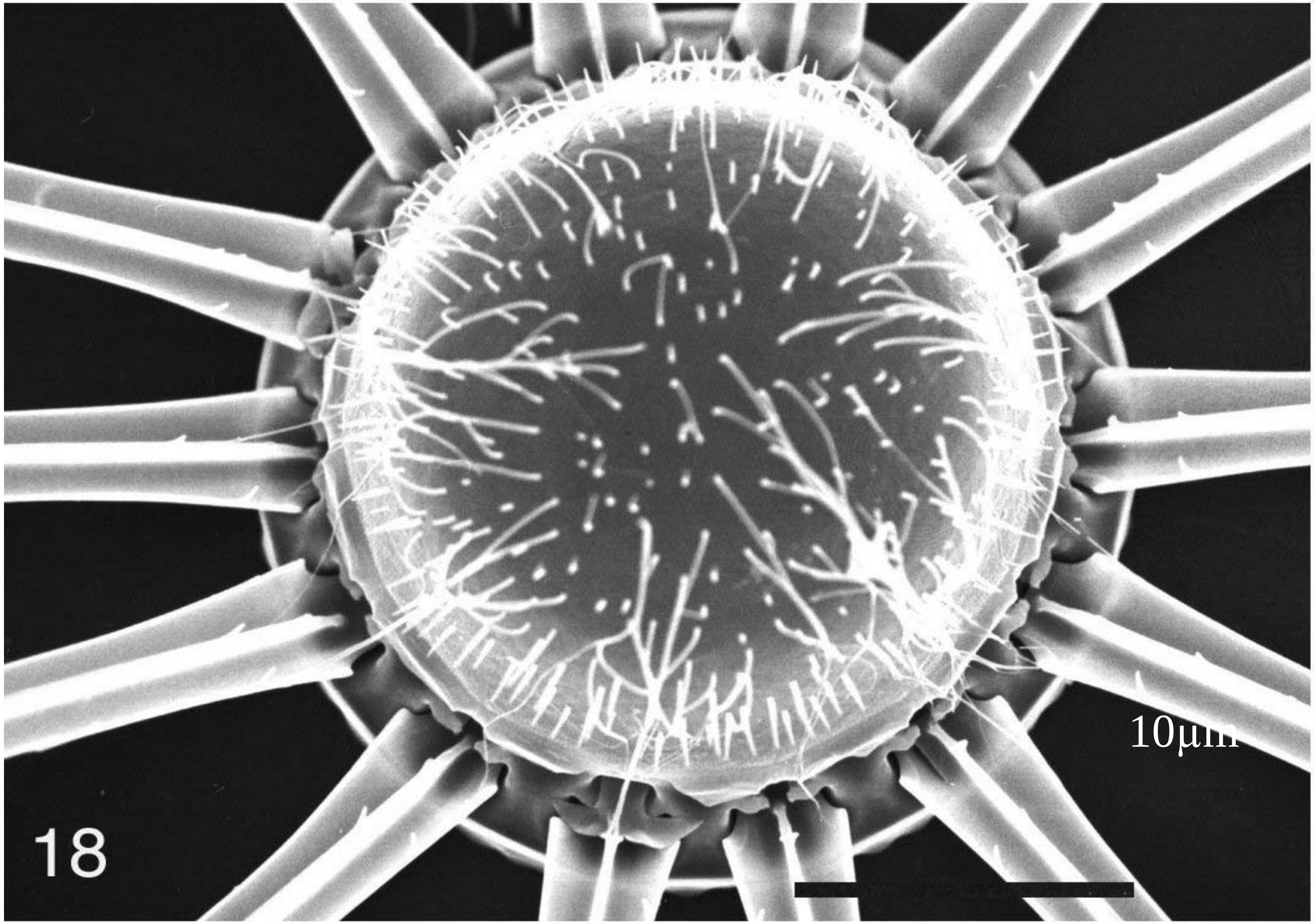




Corethron



Corethron



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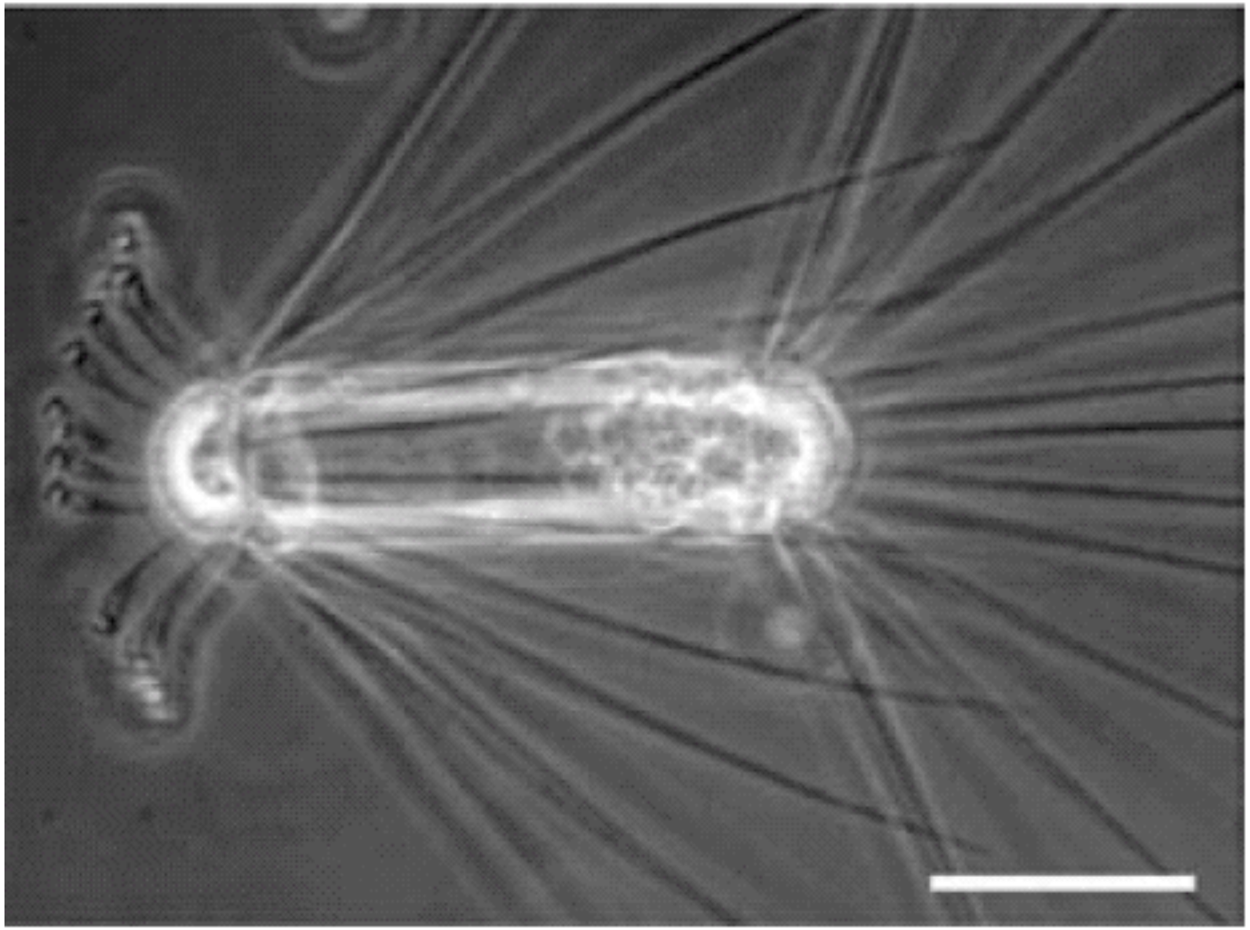
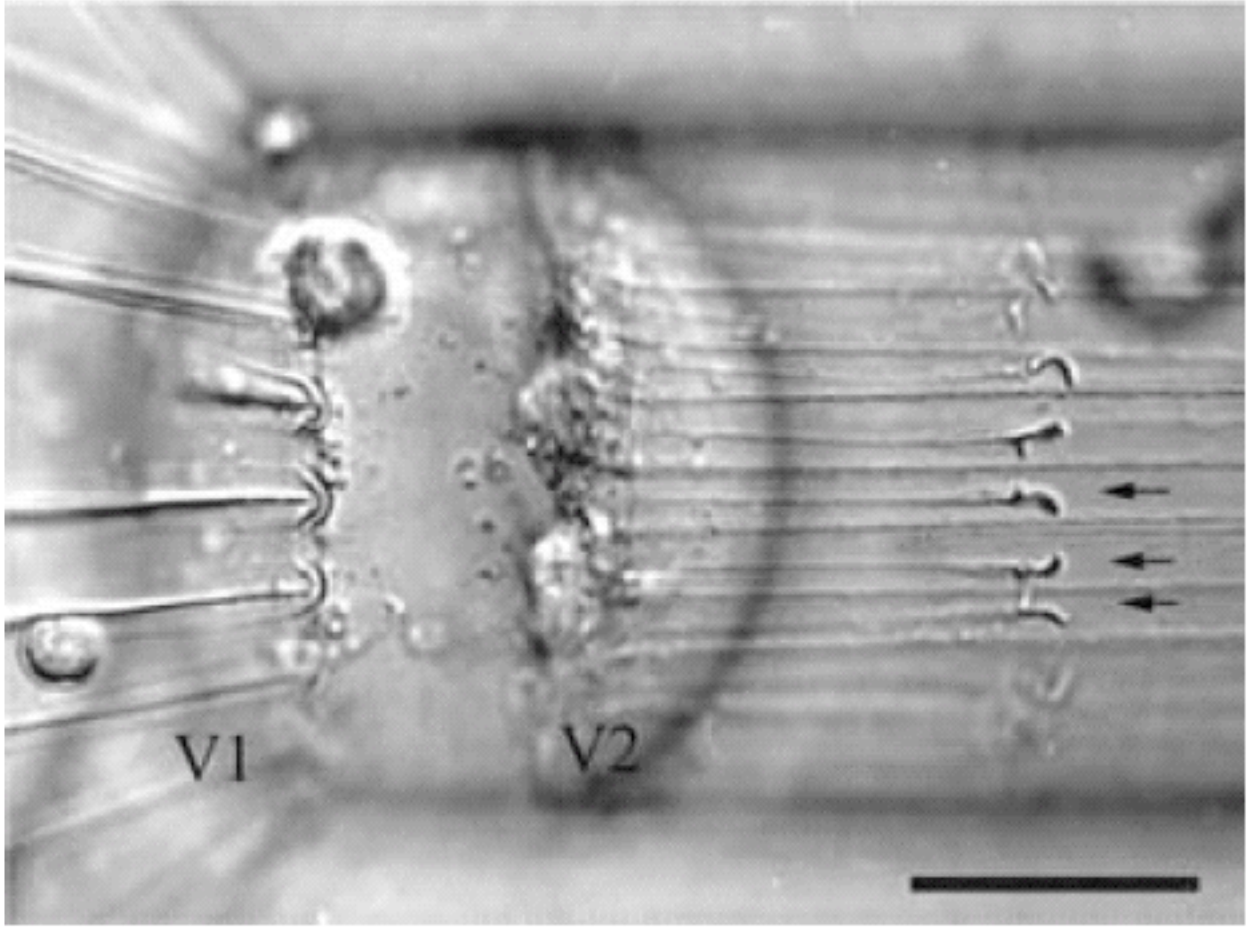


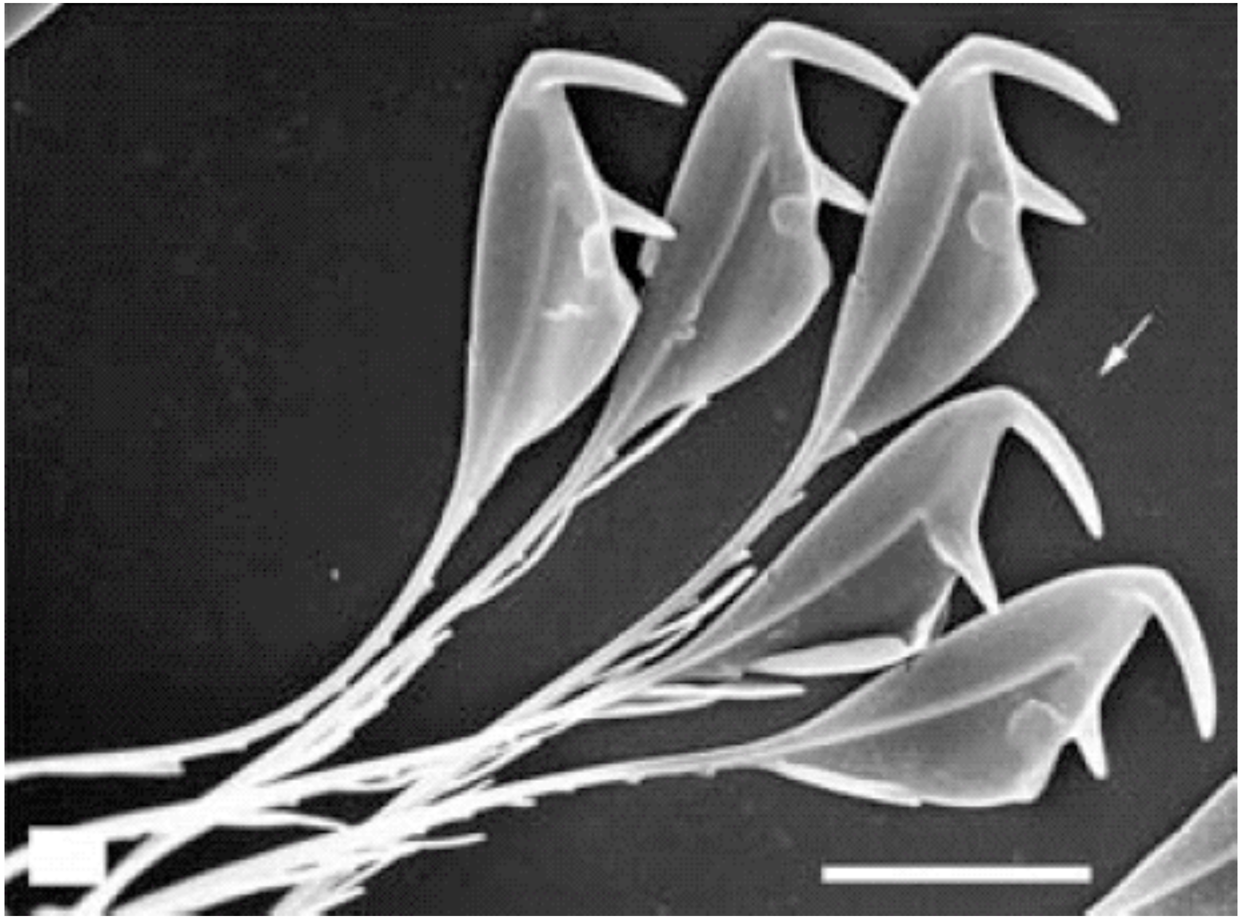
scale bar 50 μm

Corethron



scale bar 20 μm

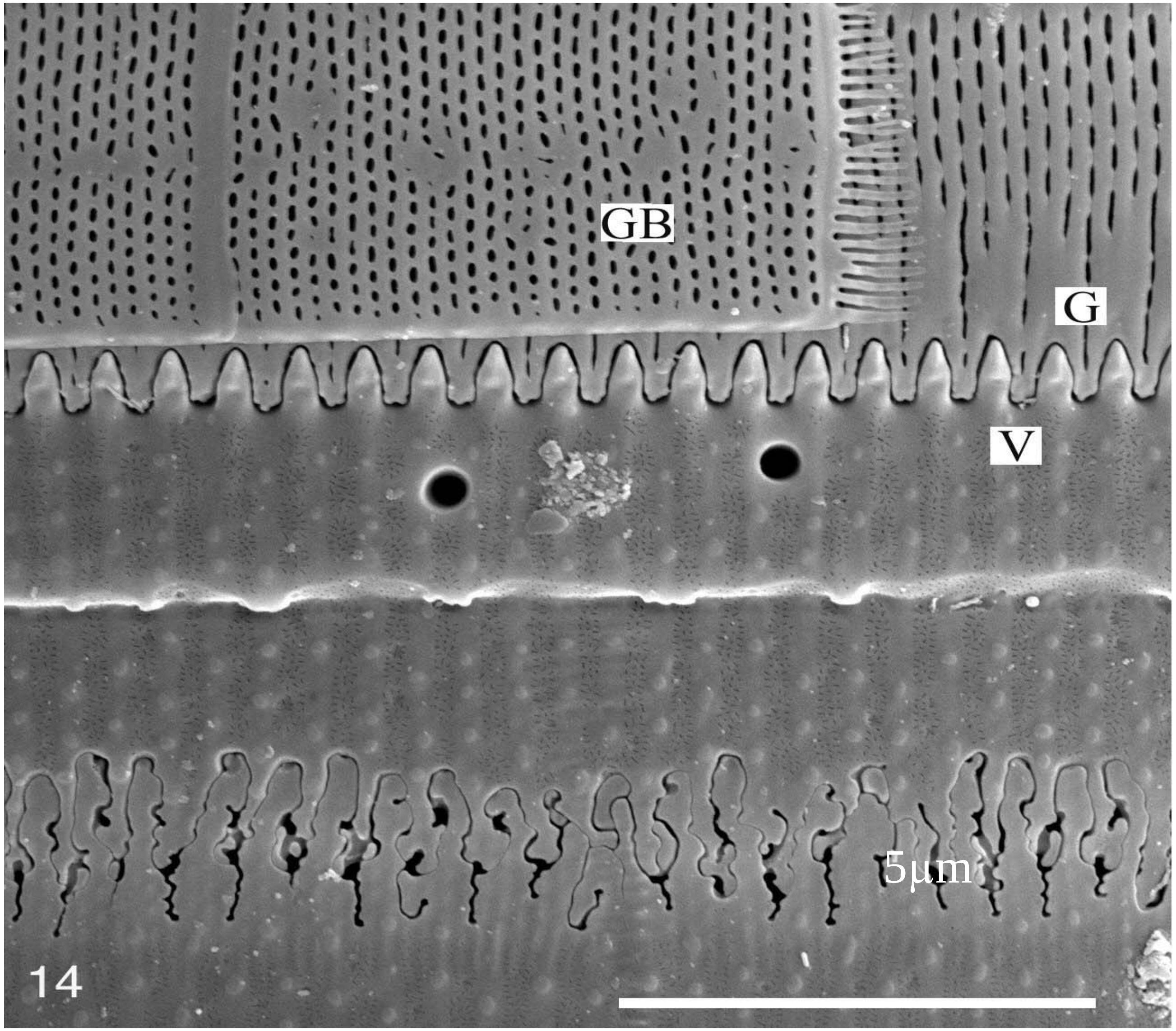
Corethron



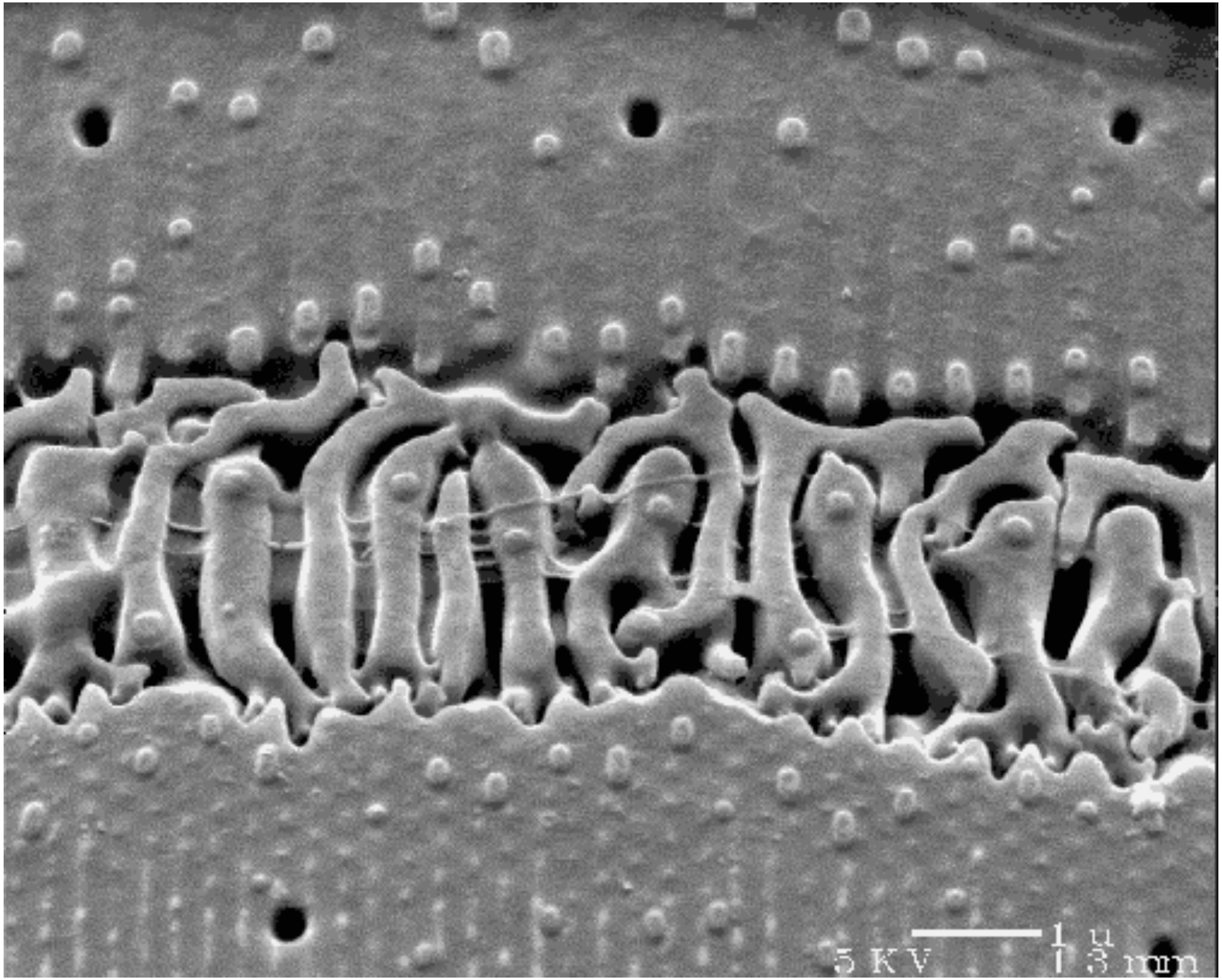
scale bar 10 μm

Gebeshuber I.C. and Crawford R.M. *”Micro-mechanics in biogenic hydrated silica - hinges and interlocking devices in diatoms*, J. Eng. Trib., to appear 12/2006.

Ellerbeckia

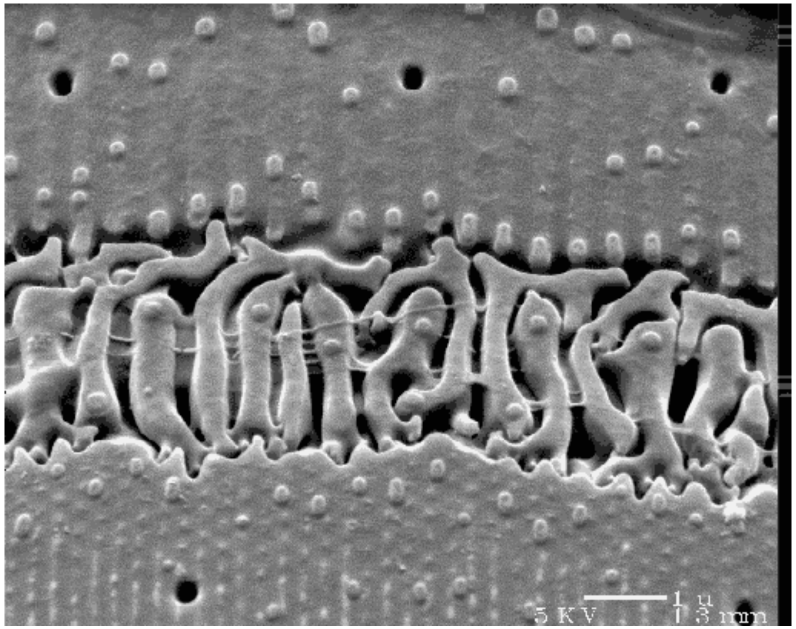


Ellerbeckia arenaria



ॐ भूर्भुवः स्वः
तत्सतिुर्वरेण्यं ।
भर्गो देवस्य धीमहि
धियो यो नः प्रचोदयात् ।।

Gayatri mantra,
written in Sanskrit



Ellerbeckia arenaria,
the rubberband diatom

Conclusions

- Current **man-made** adhesives and lubricants are **not perfect**.

- Man has only done research in this field for some hundreds of years. **Nature** has been producing lubricants and adhesives for **millions of years**.

- Biomicro- and -nanotribology, the investigation of micro- and nanoscale tribological principles in biological systems, may be a path for realizing simultaneously "**smart", dynamic, complex, environmentally friendly, self-healing, and multifunctional lubricants and adhesives**.

Outlook

- Relating structure to function in biomaterials can only be the beginning of promising developments.
- The **thermal and hydrolytic sensitivities** of biological materials **limit** their **applicability** in many important synthetic materials applications.
- **A real breakthrough requires an understanding of the basic building principles of living organisms** and a study of the chemical and physical properties at the interfaces, to control the form, size and compaction of objects.

Cooperation partners

- Paul Hansma Lab (Paul Hansma, Johannes Kindt, James Thompson, Mario Viani, Lia Pietrasanta, Ami Chand), Galen Stucky, Dan Morse, UC Santa Barbara, California
- Dick Crawford, AWI Bremerhaven, Germany
- Dick Gordon, University of Manitoba, Canada

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UNIVERSITY OF MANITOBA

AC²T research