Grain Alignment in Chiton Ocelli Lenses

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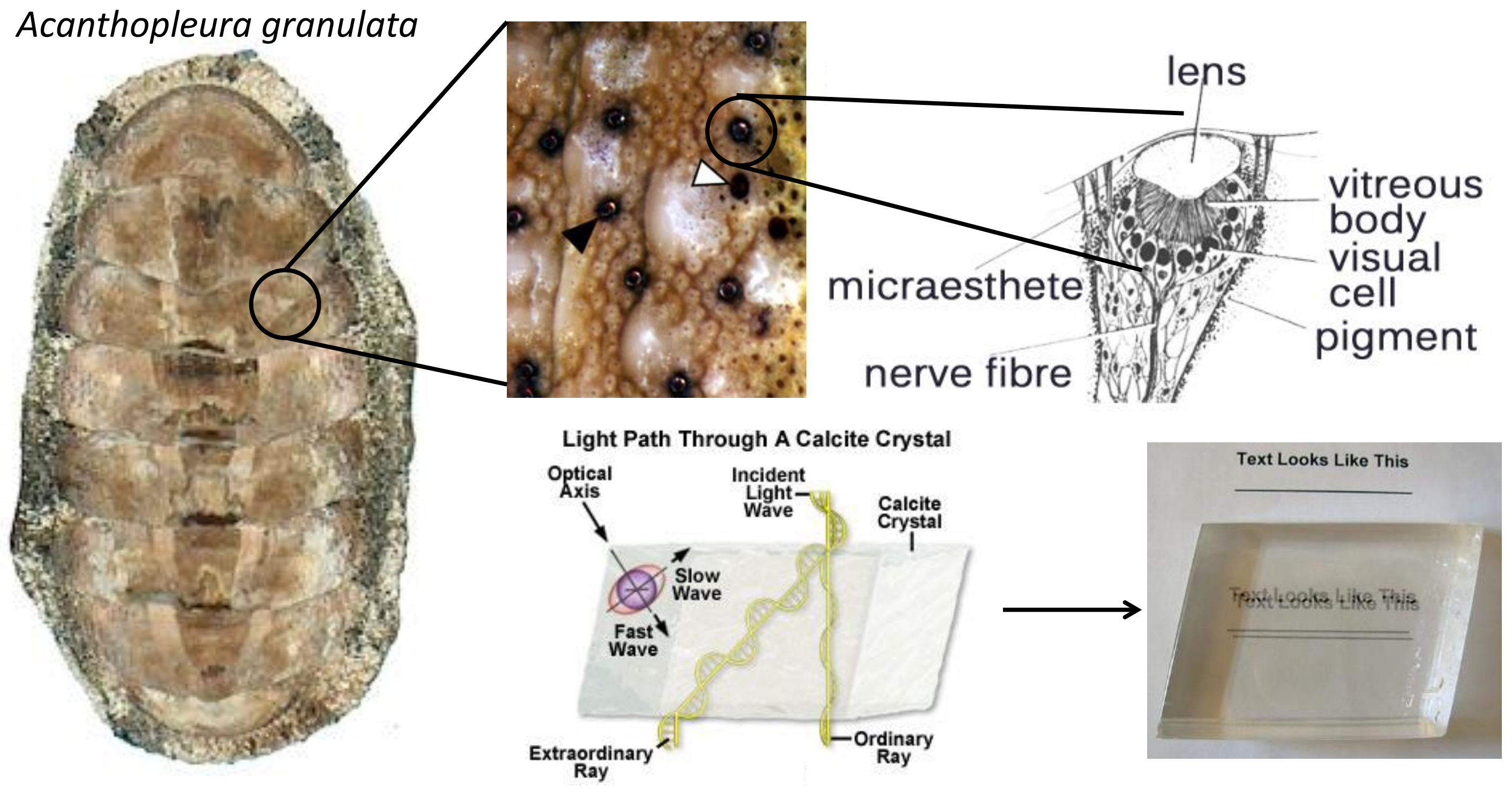
Do chitons have double vision?

Organisms form inorganic materials using structural and chemical controls. This process, called **biomineralization**, is important to biology and materials science. Chitons, a diverse group of mollusks, produce multiple biominerals in their teeth, shell, and ocelli, which are eyes. These ocelli are unique because their lenses are mineralized. Only two other species have mineralized lenses – trilobites and brittlestars.

Ocelli lenses are made of aragonite, which is birefringent, which means that light rays entering the material split into two paths, producing two images. This suggests that chitons may have double vision. Speiser, et. al., propose that because chitons live in tidal zones, the birefringence could enable chitons to adapt their vision to see clearly in water and in air[1]. This would eliminate the impact of double vision, since the chiton would simultaneously receive a focused image and an unfocused image.

However, this model assumes that the lens is a single crystal. In reality, the lens is made of smaller crystals, or grains. To fully understand the optical properties of the lens, we must know the orientation of the grains. Light rays refract at different angles through aragonite, depending on how the unit cell is oriented. **If the lens behaves like a single crystal, it will have better optical properties**. If it behaves like a polycrystalline crystal, it will scatter light and produce a blurry, jumbled image.

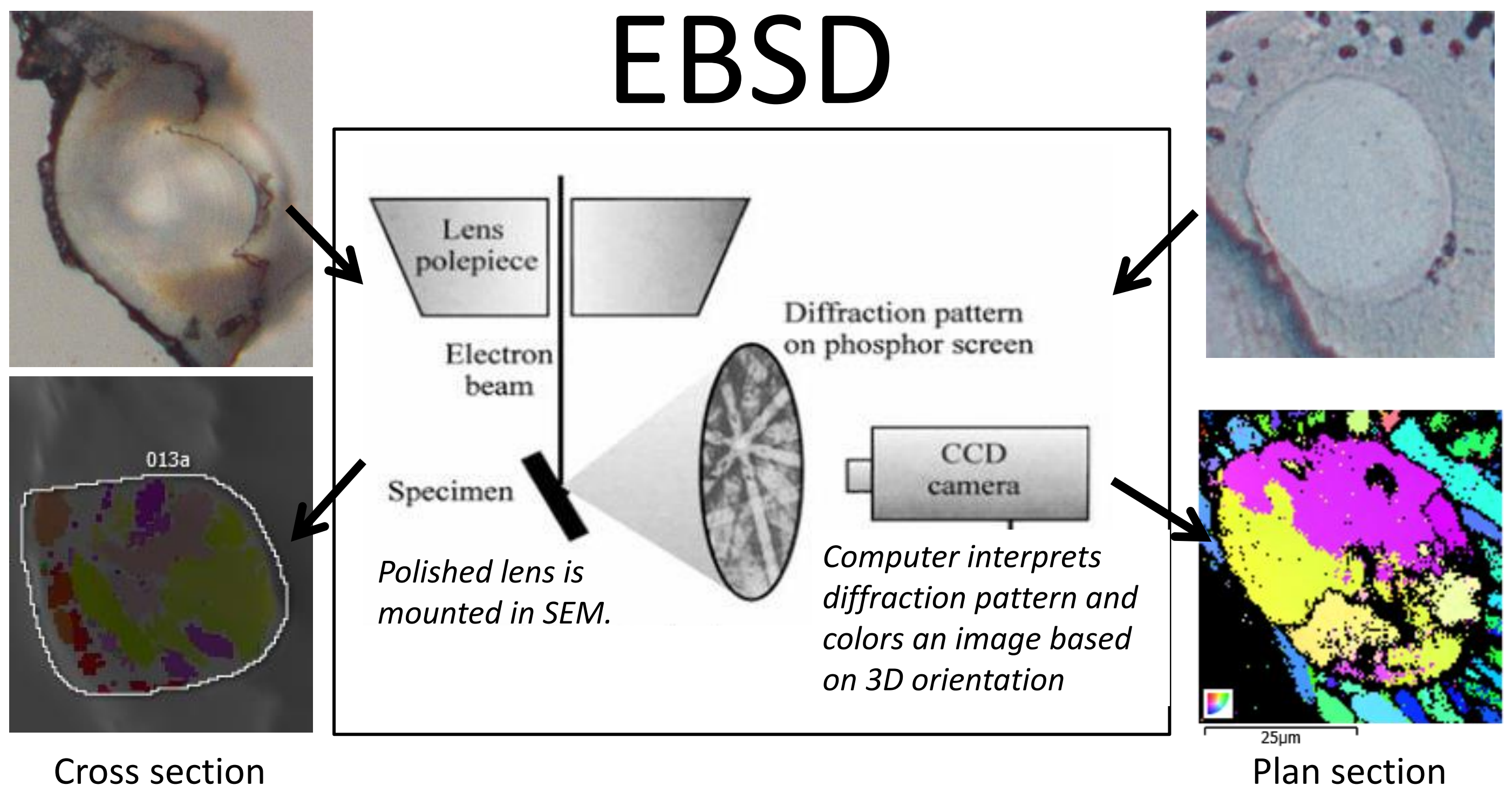


Chitons are recognizable by their multi-segmented shells. A close view of the shell reveals black spots, which are ocelli. A diagram of one ocellus of Acanthopleura japonica is shown[2]. The lens is made of birefringent aragonite. Light rays split into two when they enter a birefringent material, producing two simultaneous images.

Methods

24 ocelli were collected from the shell, embedded in epoxy, and polished to reveal cross sections and plan sections. These sections were mounted in a scanning electron microscope and mapped using electron backscatter diffraction. EBSD creates a pixel-by-pixel map of grain orientation.

Analysis of EBSD data was performed using Wolfram Mathematica 9 and HKL software. Ray tracing simulations were conducted using an algorithm described by Chang and Shieh[3].



Polished lens is mounted in SEM.

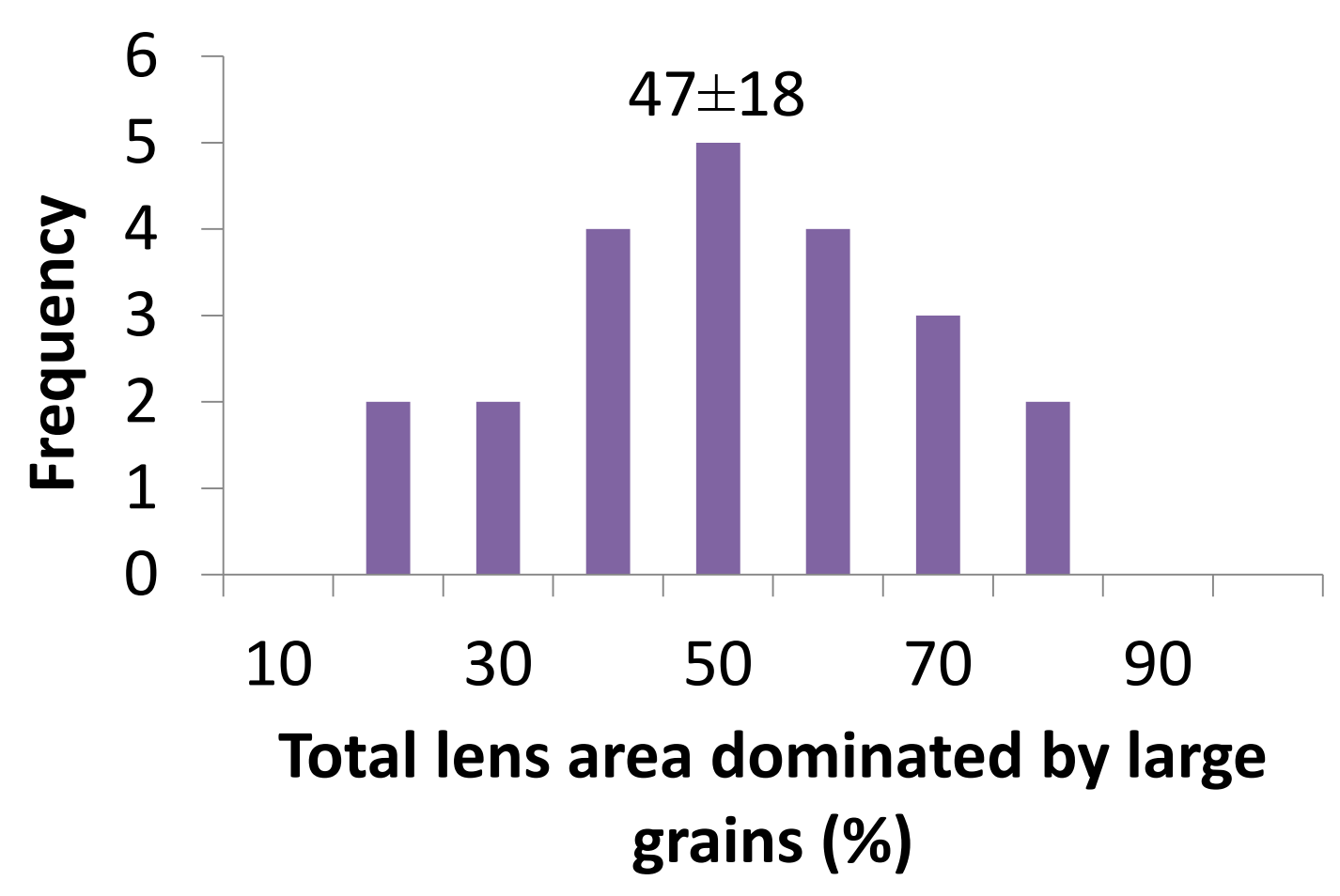
Computer interprets diffraction pattern and colors an image based on 3D orientation

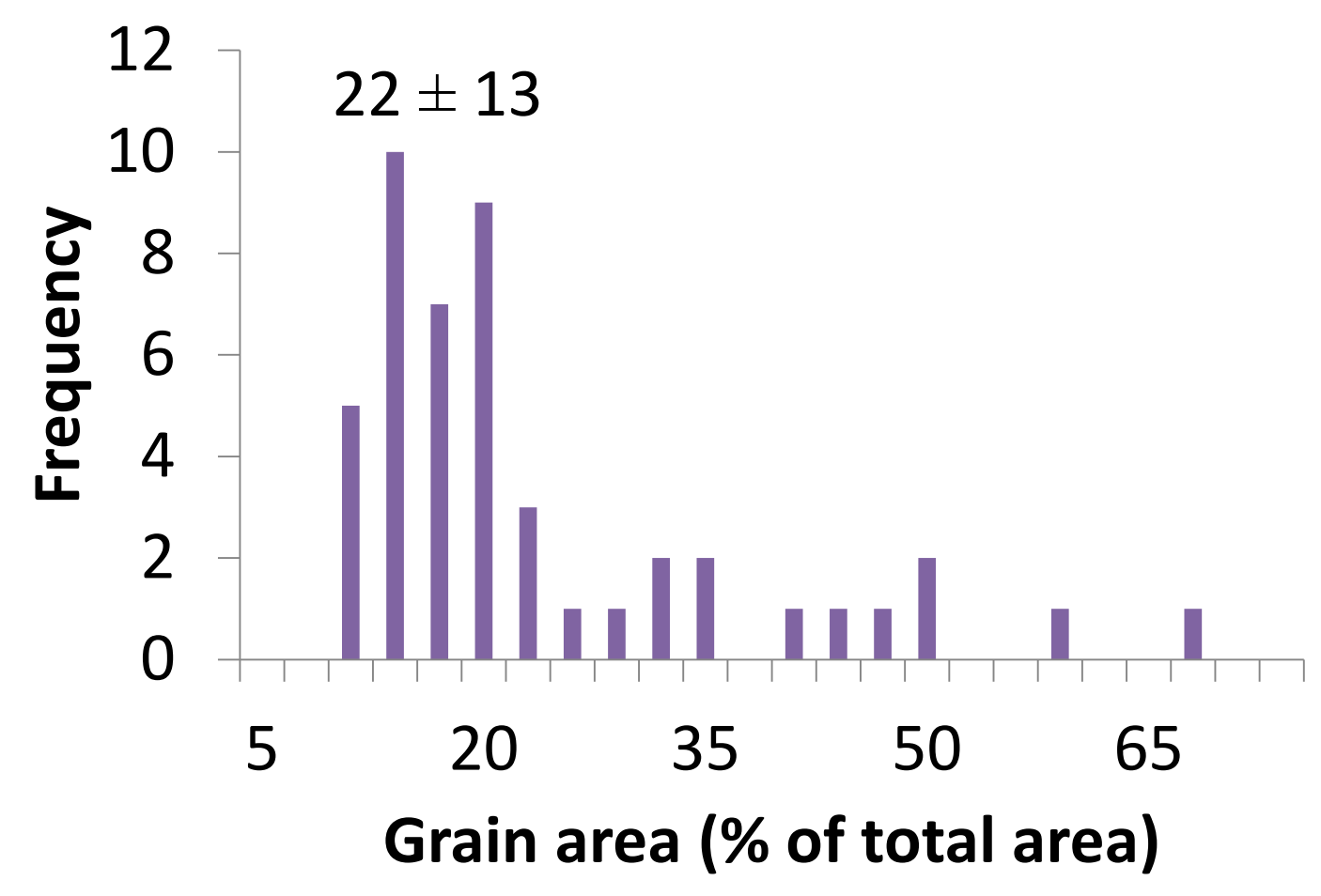
Cross section

Plan section

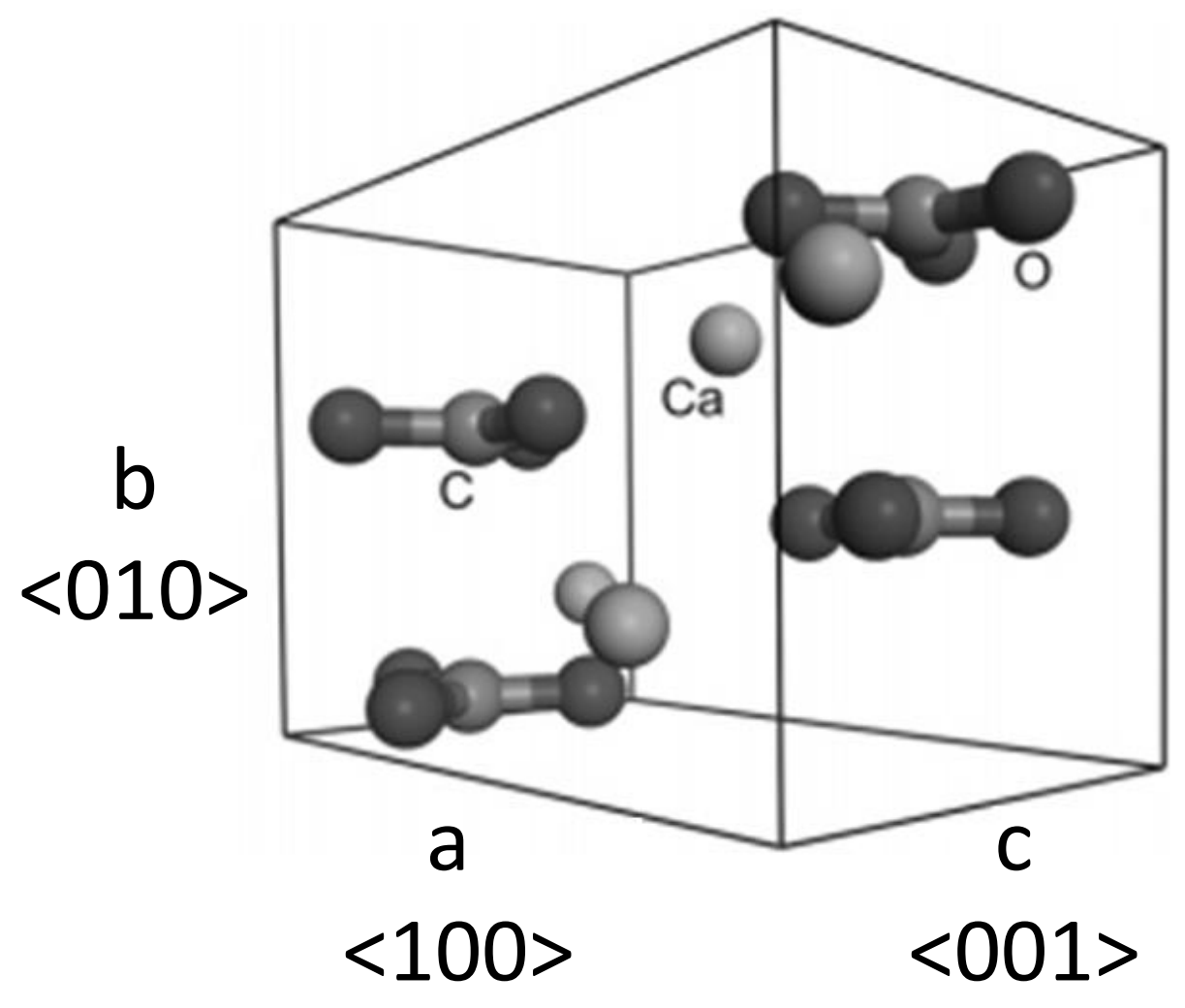
Ocelli have large grains

Most sections were dominated by fewer than four grains. Having fewer, larger grains gives the lens more single crystalline character.





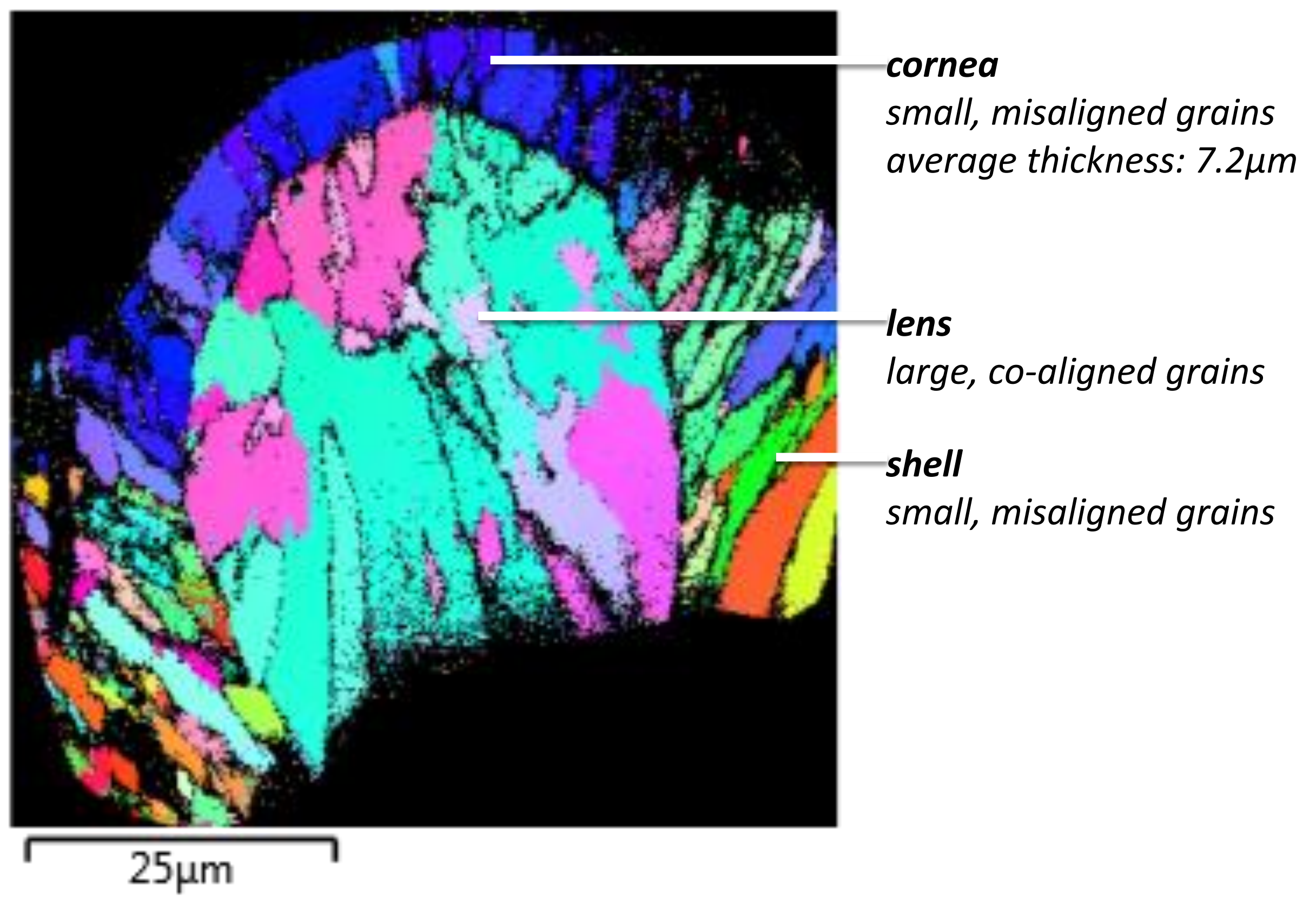
Refractive index	Axis	Value
n_α	c	1.530
n_β	a	1.681
n_γ	b	1.686



Above: Refractive indices of aragonite
Right: Aragonite unit cell

Grains are aligned

The position of the **c** axis is consistent within each lens, while positions of **a** and **b** axes vary. Because the refractive indices of the **a** and **b** axes are similar, alignment of **c** axes allows the polycrystalline lens to have similar optical properties to a single crystal.

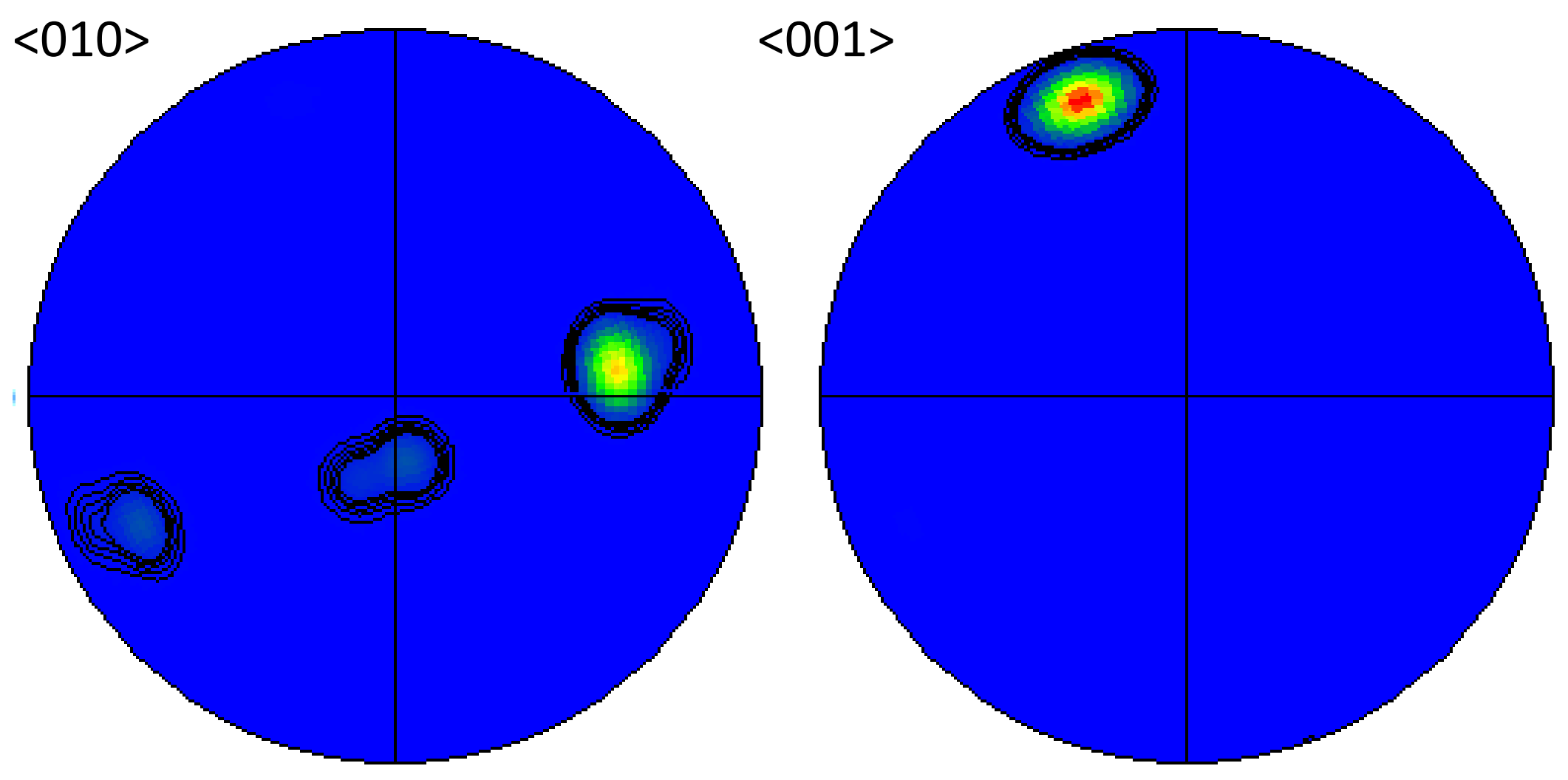


cornea
small, misaligned grains
average thickness: 7.2µm

lens
large, co-aligned grains

shell
small, misaligned grains

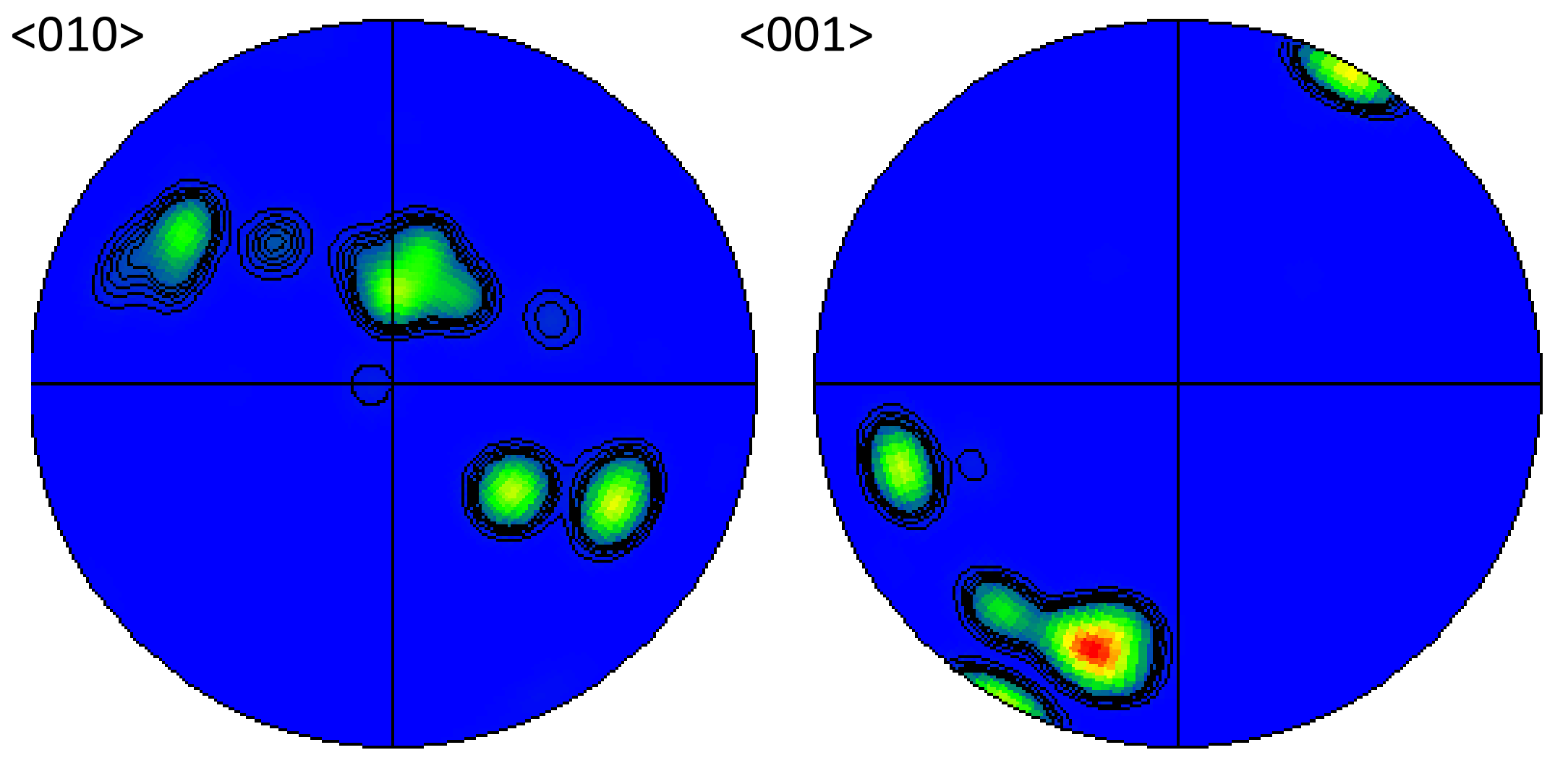
lens



***a** and **b** axes have many clusters and fall along a ring*

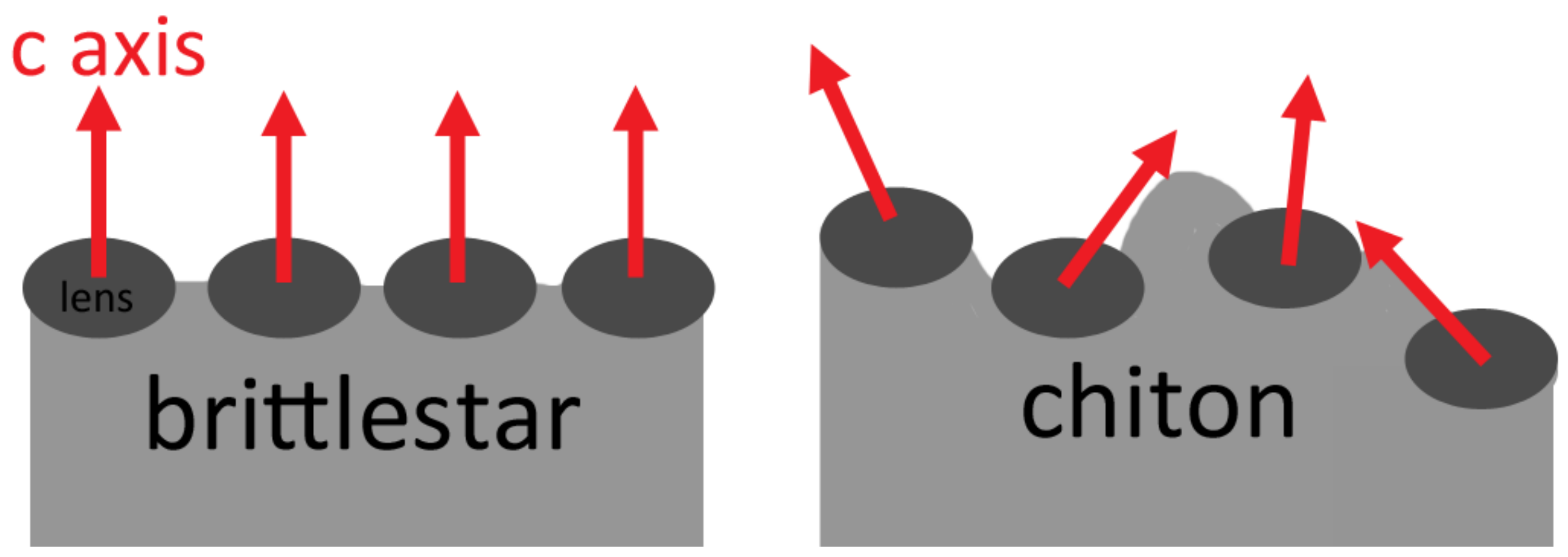
***c** axis has one cluster and is consistent across the lens*

cornea



***a** and **b** axes have many clusters and are scattered*

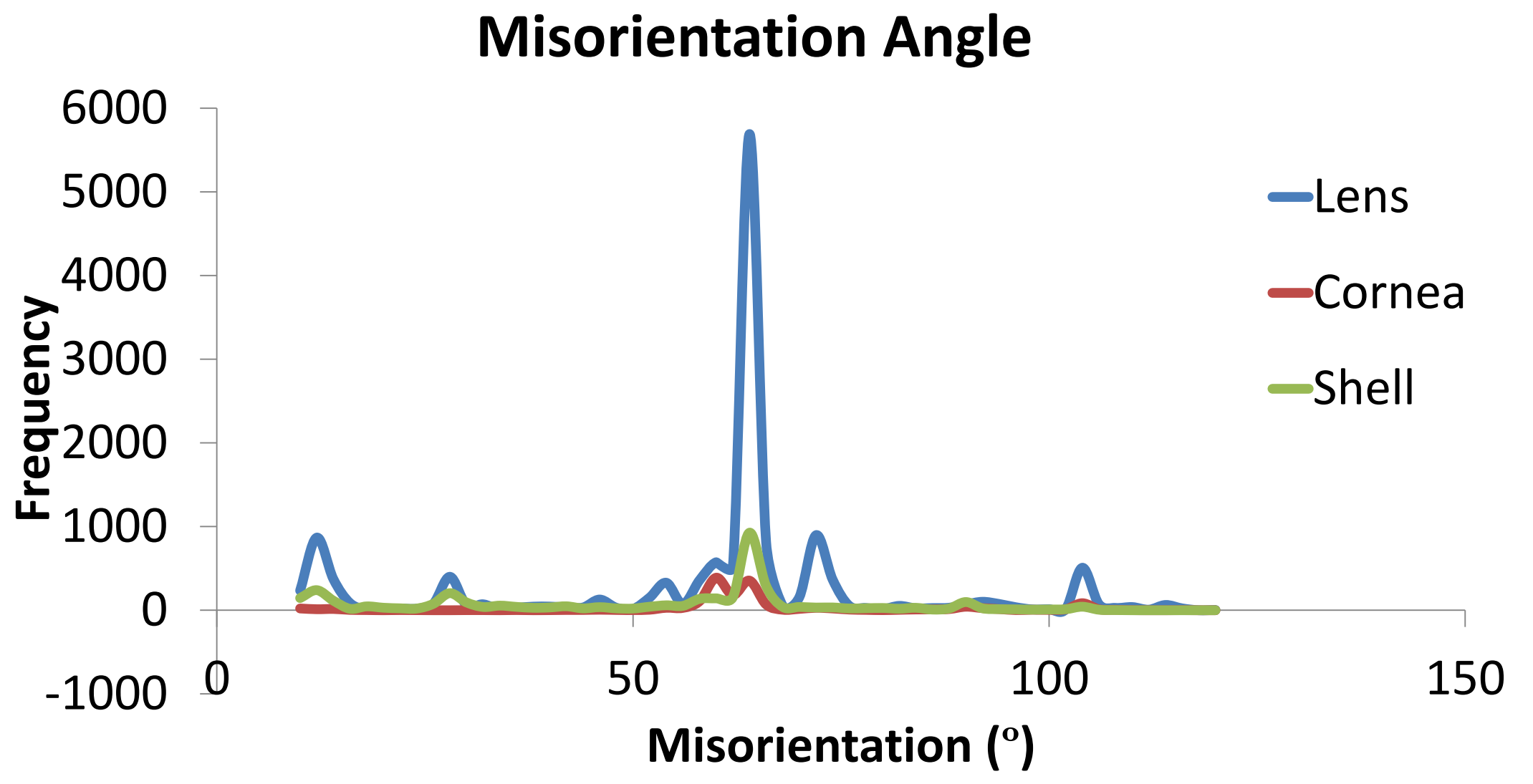
***c** axis has a few clusters and is not aligned*



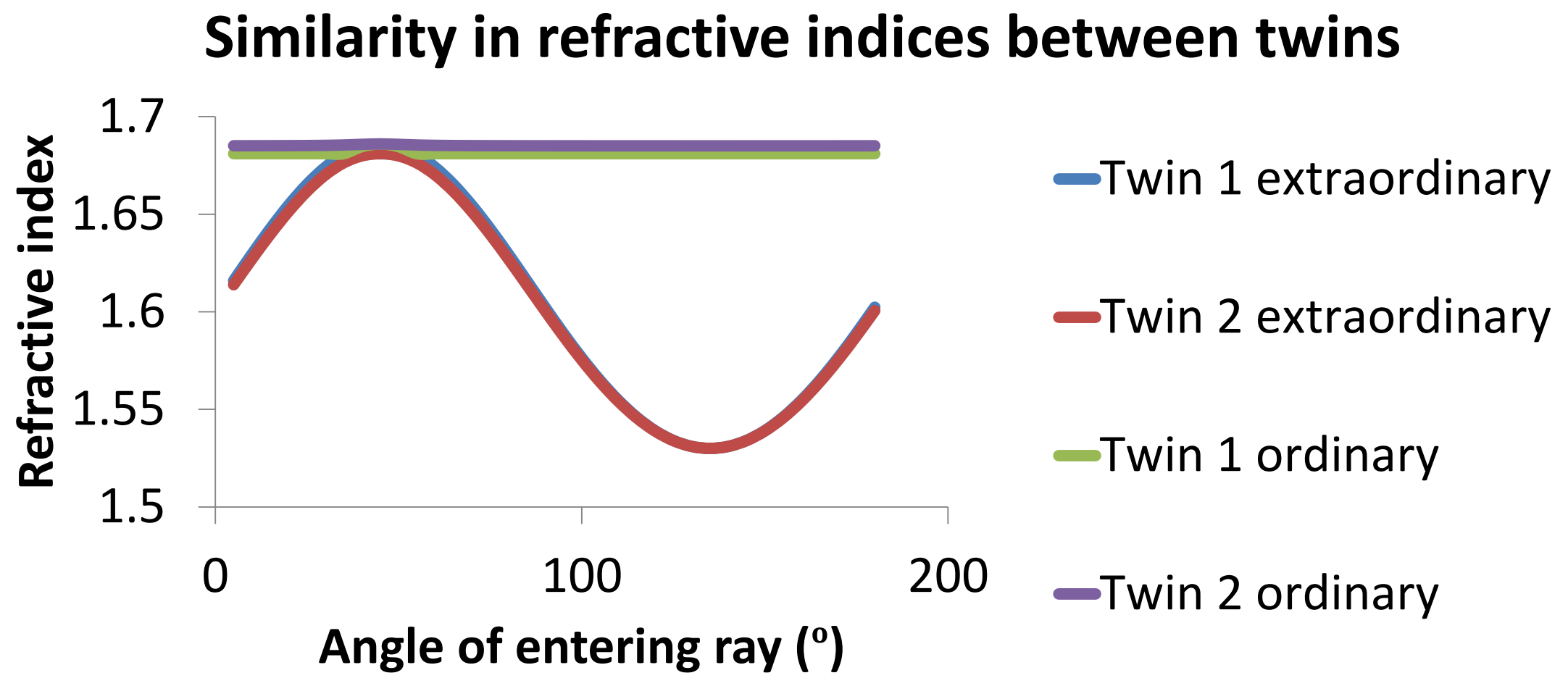
*Brittlestar and trilobite lenses have consistent orientations of **c** axes[4]. In chitons, absolute orientation of **c** axes relative to the shell varies from lens to lens.*

Misorientation follows a pattern

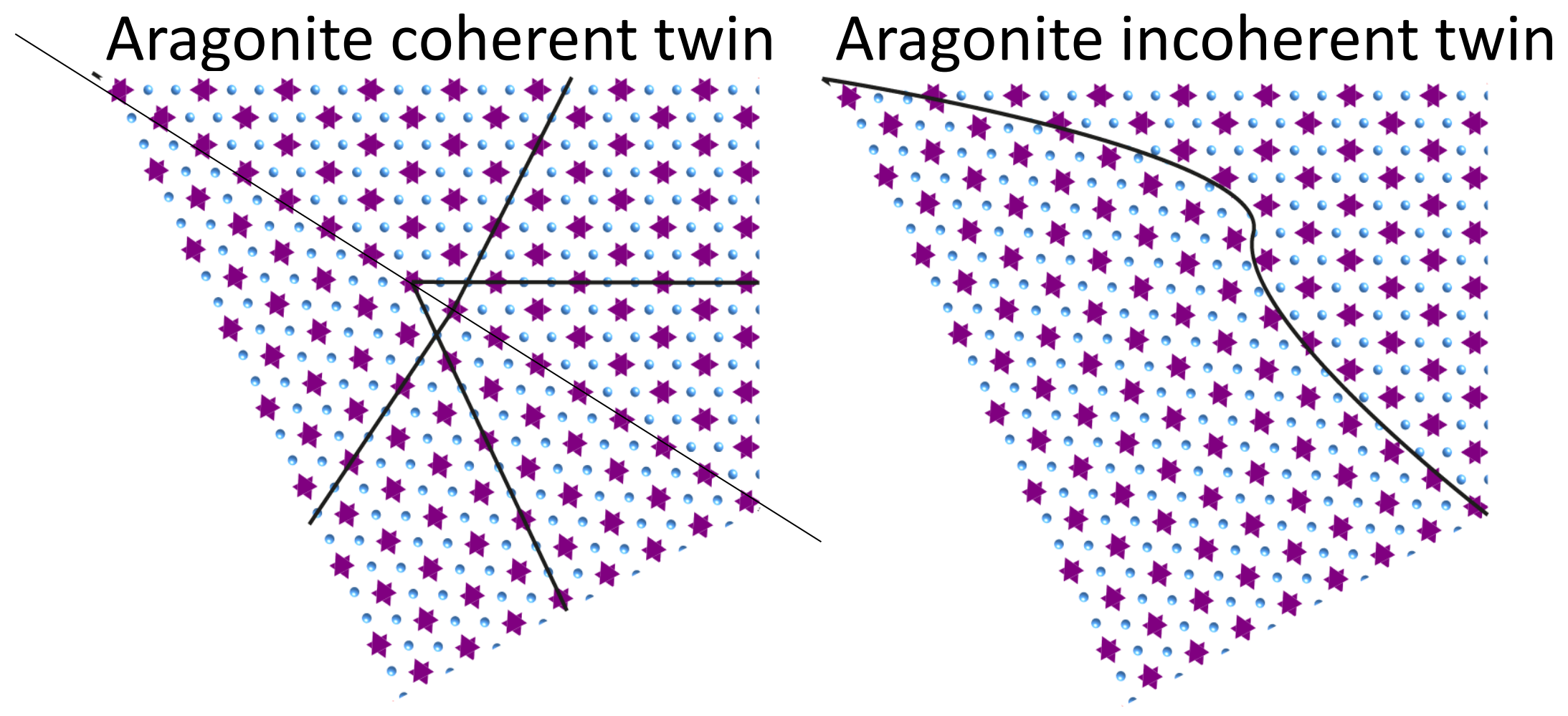
Misorientation, or the difference in orientation between neighboring grains, indicates that the orientation of the **a** and **b** axes may not be random. Measured misorientation angles and axes are consistent with typical biogenic aragonite twinning patterns, so lenses may be composed of incoherent twins.



*Grains are rotated by an average of 64°, maintaining a fixed **c** axis*



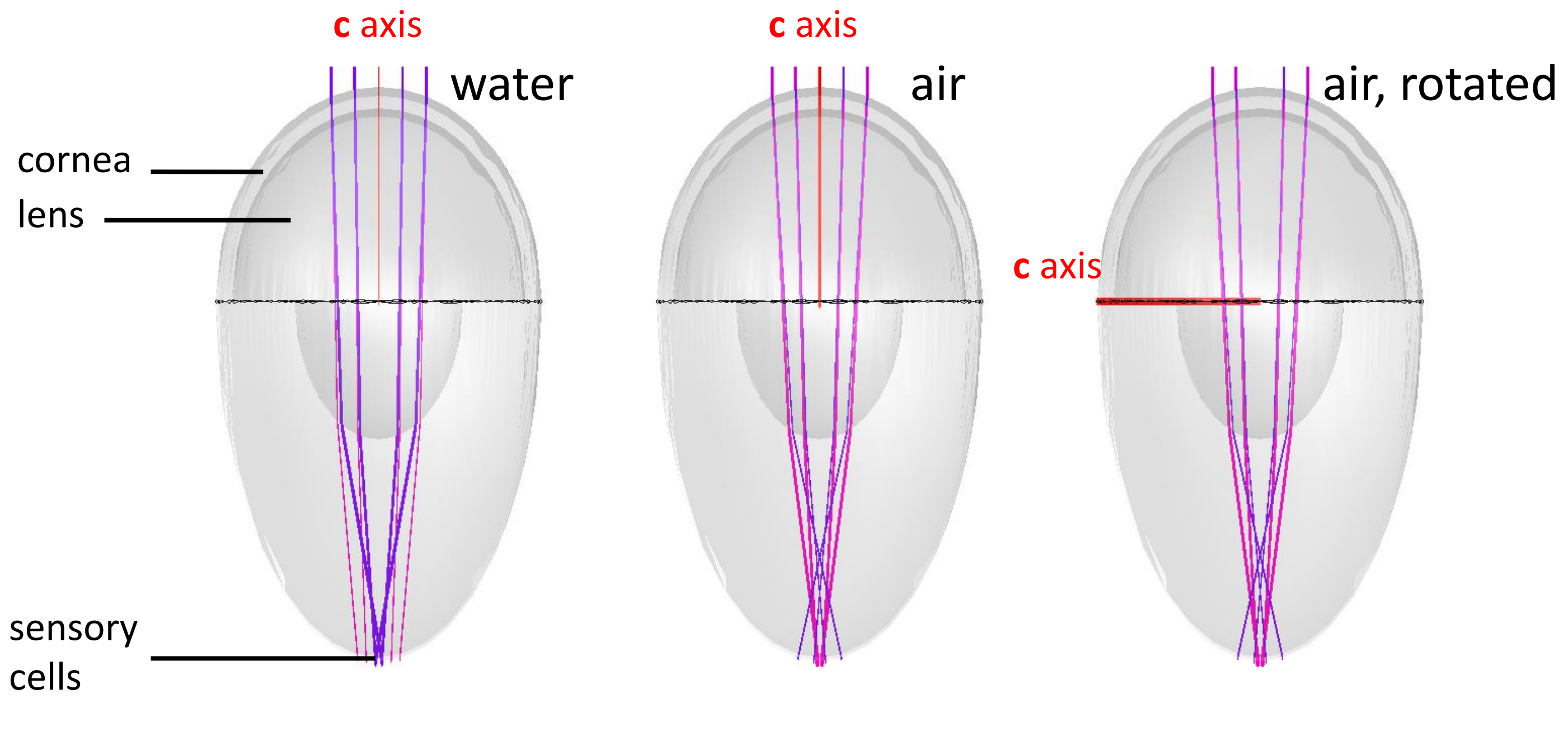
Refractive indices of twin ordinary and extraordinary rays have a maximum difference of .004, so twinning allows the lens to imitate the optical properties of a single crystal.



Grain boundaries in lenses are curved, so twins in lenses would be incoherent.

Does orientation matter?

To further understand the impact of orientation on optical properties, we can simulate the path of light through a single-crystalline lens. This model supports the theory that chitons can resolve clear images in air and water. Varying the orientation of the crystal does not make a large impact on focal length, and adding a cornea with a different orientation likewise makes no visible impact.



Single crystal lens. In water, blue rays are focused on the sensory cells. In air, red rays are focused on sensory cells.

Conclusion

The tight alignment of **c** axes in the polycrystalline lenses of ocelli allows the chiton to minimize scattering of light and mimic the optical properties of a single crystal. The effect of the birefringence of aragonite on the image-forming capabilities of the chiton is still unconfirmed. While preliminary simulations have shown that orientation will make little difference to the focal lengths of the lens, there is something to be said about the controlled microstructure of the lens.

Future work will explore grain boundaries. Many grain boundaries resemble twin boundaries in all respects except for their curved shape. These possible curved twins may elucidate how the chiton forms lenses.

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This research was sponsored by the Chemistry of Life Processes CAURS Fellowship. The study resulting in this presentation was also assisted by a grant from the Undergraduate Research Grant Program which is administered by Northwestern University's Office of the Provost. However, the conclusions, opinions, and other statements in this presentation are the author's and not necessarily those of the sponsoring institution.
This work made use of the EPIC facility (NUANCE Center-Northwestern University), which has received support from the MRSEC program (NSF DMR-1121262) at the Materials Research Center, The Nanoscale Science and Engineering Center (EEC-0118025/003), both programs of the National Science Foundation; the State of Illinois; and Northwestern University. This work made use of the OMM Facility supported by the MRSEC program of the National Science Foundation (DMR-1121262) at the Materials Research Center of Northwestern University.