

Bioinspiration from the Distinctive Armored Carapace of the Boxfish

Steven E. Naleway*, Wen Yang, Michael M. Porter, Marc A. Meyers, Joanna McKittrick

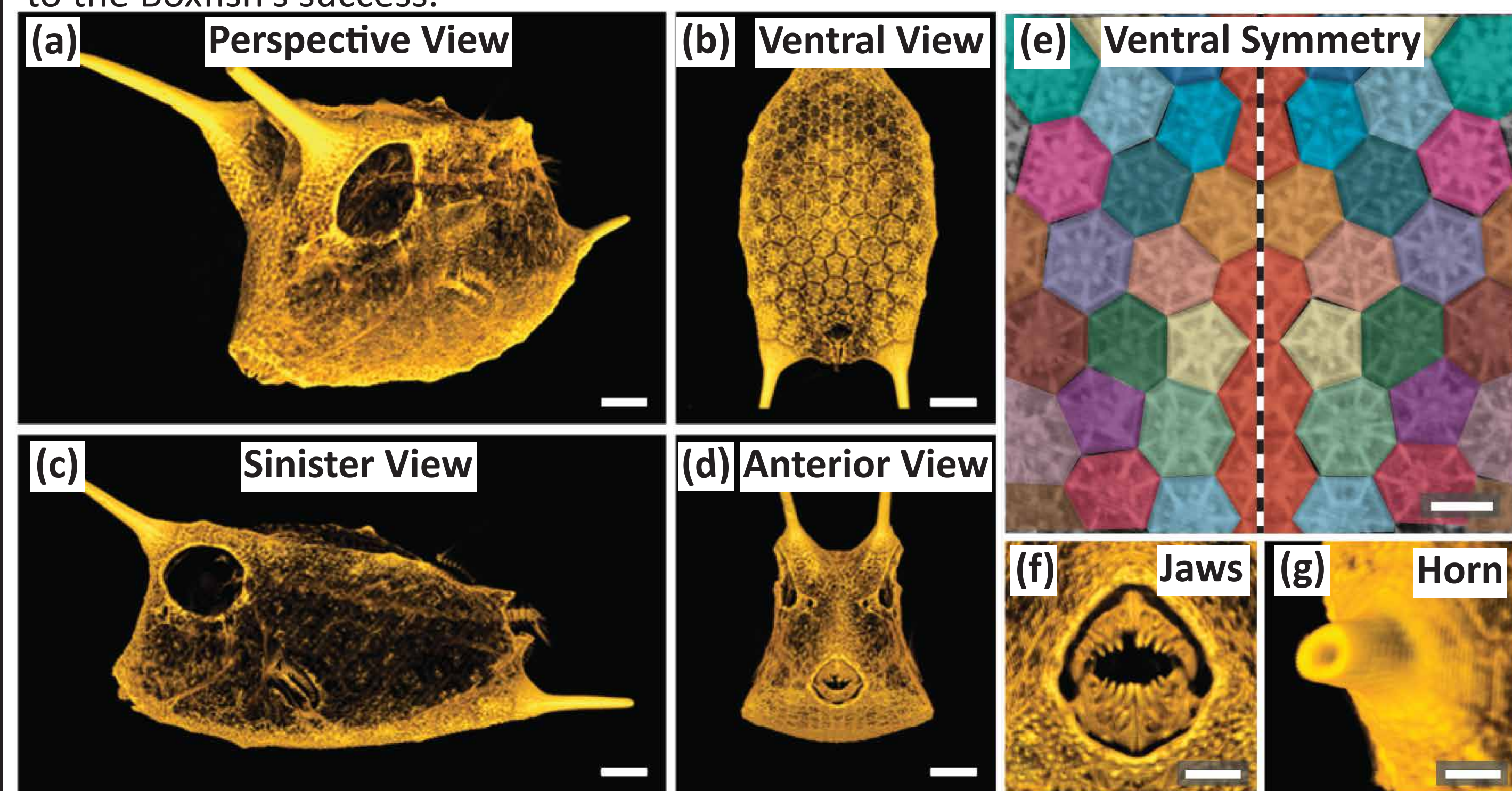
* Materials Science and Engineering Program
 Department of Mechanical and Aerospace Engineering
 University of California, San Diego

Lactoria cornuta

Lactoria cornuta (commonly called the Boxfish or Longhorned Cowfish) is a modern member of the Tetradontiformes. It is known for its rigid scute (plate) covered carapace as well as its distinctive horns. Its slow but self-correcting swimming technique has been investigated for its potential in bioinspired swimming robotics. This slow swimming necessitates the formation of a solid protective carapace. As the majority of their predators are unable to engulf a mature Boxfish, protection from the piercing attacks of teeth are paramount to the Boxfish's success.



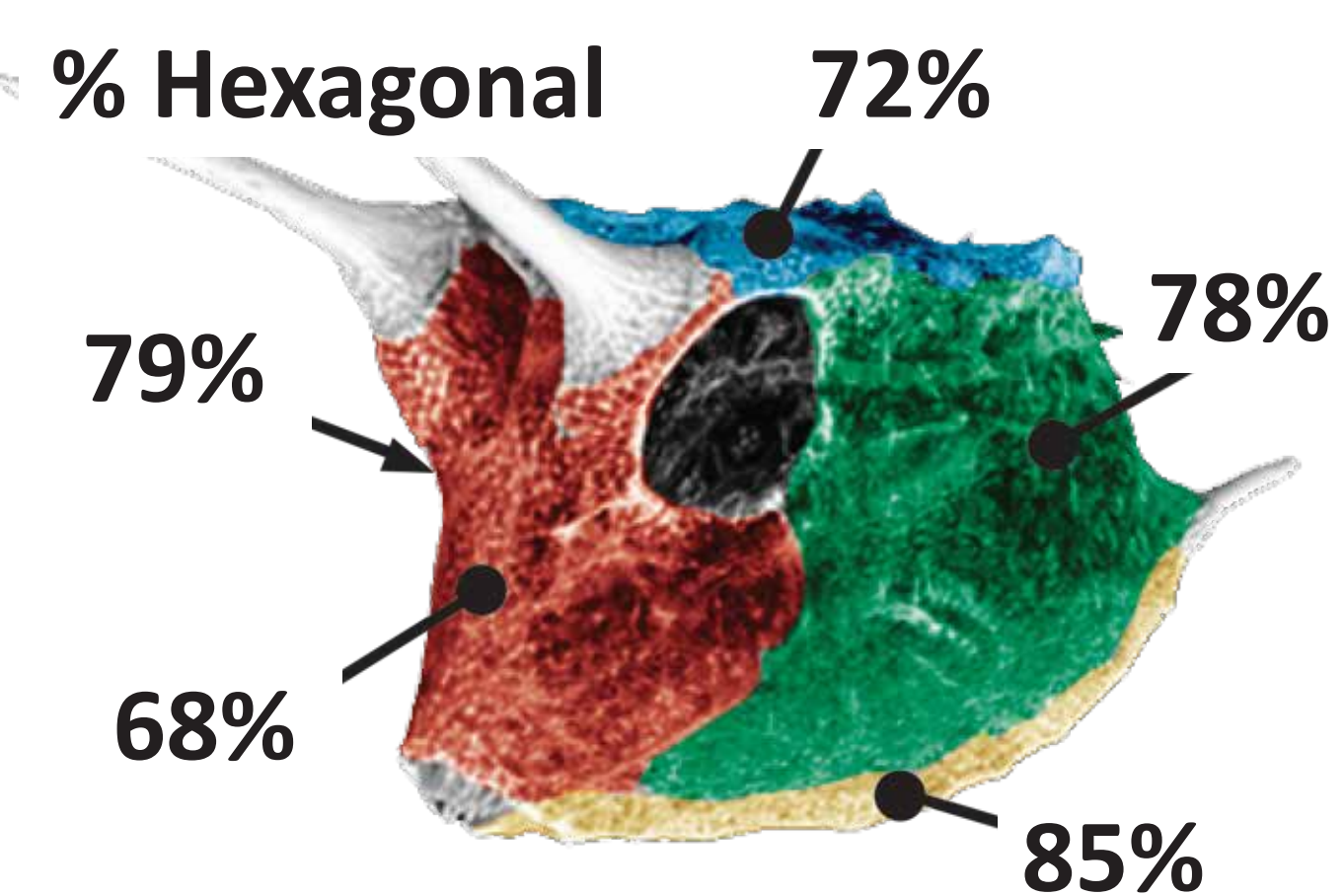
Live Lactoria cornuta.
 Taken from www.wikipedia.org



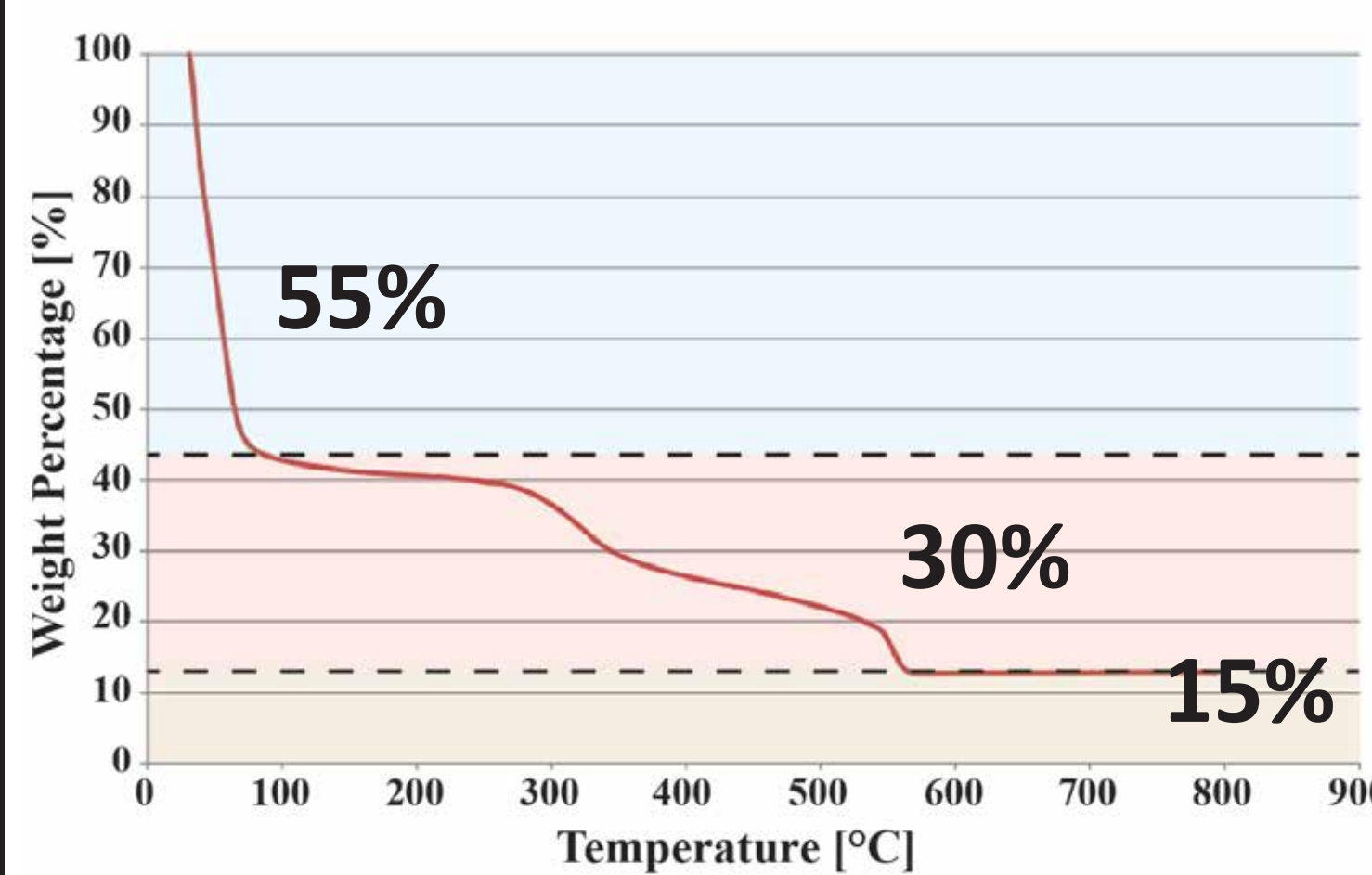
Micro-CT images of the boxfish. Scale bars: (a-d) 5 mm, (e) 2 mm, (f) 2 mm, (g) 1 mm.

Carapace

The carapace of the boxfish is made up of composite plates called scutes. The majority of scutes are hexagonal in shape (78%) with the minority square (4%), pentagonal (15%) and heptagonal (3%). The minority scutes are employed to accommodate the irregular surface of the boxfish. The more regular surfaces (ventral) have a larger proportion of hexagonal scutes than the irregular surfaces (dorsal and anterior).



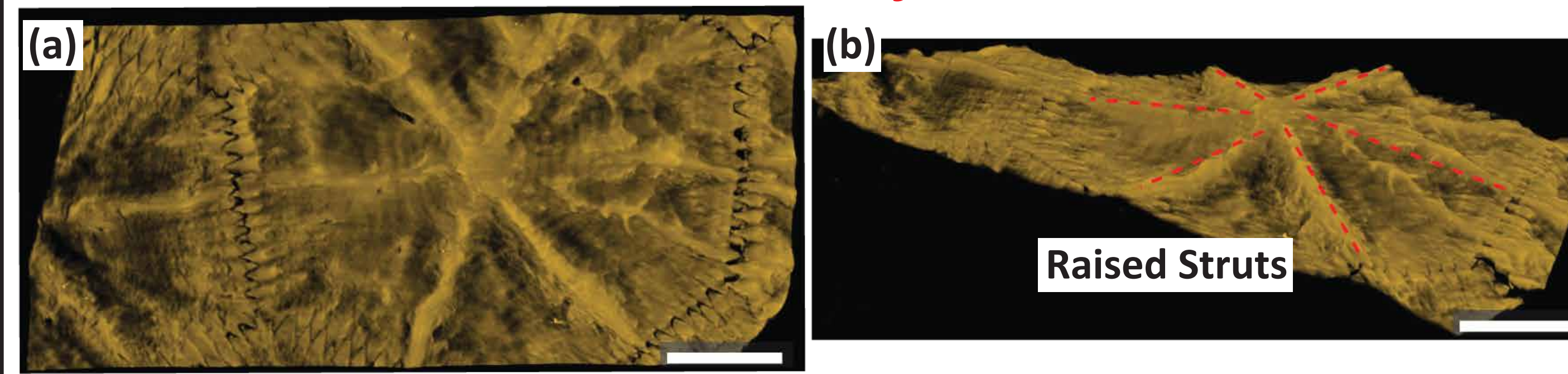
The individual scutes are made up of 55 wt.% water, 30 wt.% organic components (e.g. protein), and 15 wt.% mineral. While the high water content is reasonable for an aquatic creature, the ratio of organics to mineral (2 : 1) is quite different from those observed for other armored organisms such as the seahorse (1 : 1.48) [1], armadillo (1 : 3.1) [2], conch shells (1 : 19) [3], and alligator (1 : 1.86) [4]. This suggests that the boxfish employs the stiff mineral component of its dermal armor in a different way from most organisms with dermal armor.



Weight % vs. Temperature generated by Thermogravimetric Analysis (TGA) for a single boxfish scute. Averaged over six (N = 6) samples the relative weight percentages (reported as Average(Stdev)) were found to be; Water = 55.1(5.5) wt.%, Organic 30.0(3.4) wt.%, Mineral 14.9(3.5) wt.%.

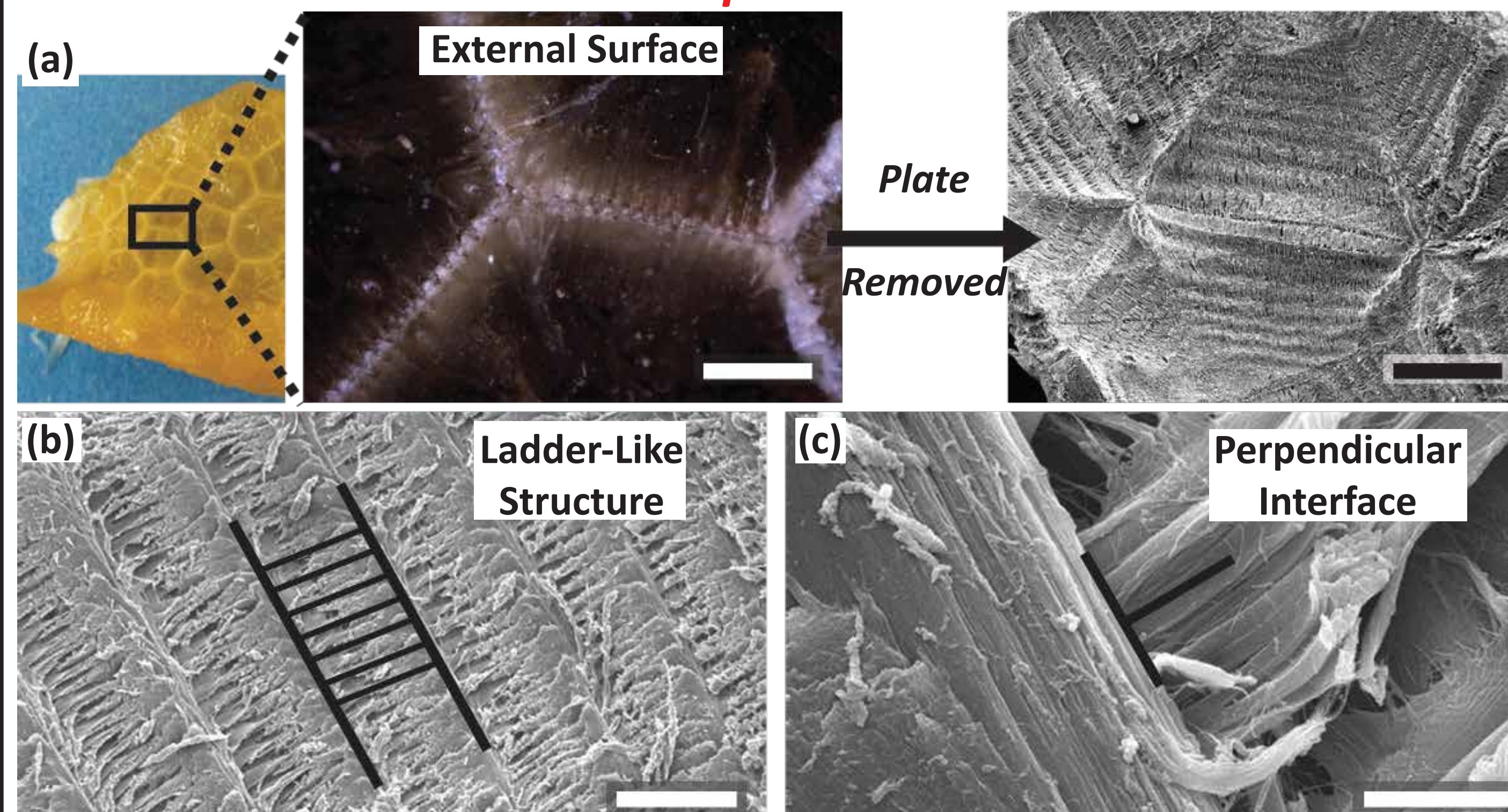
Structural Characterization

Mineral Surface



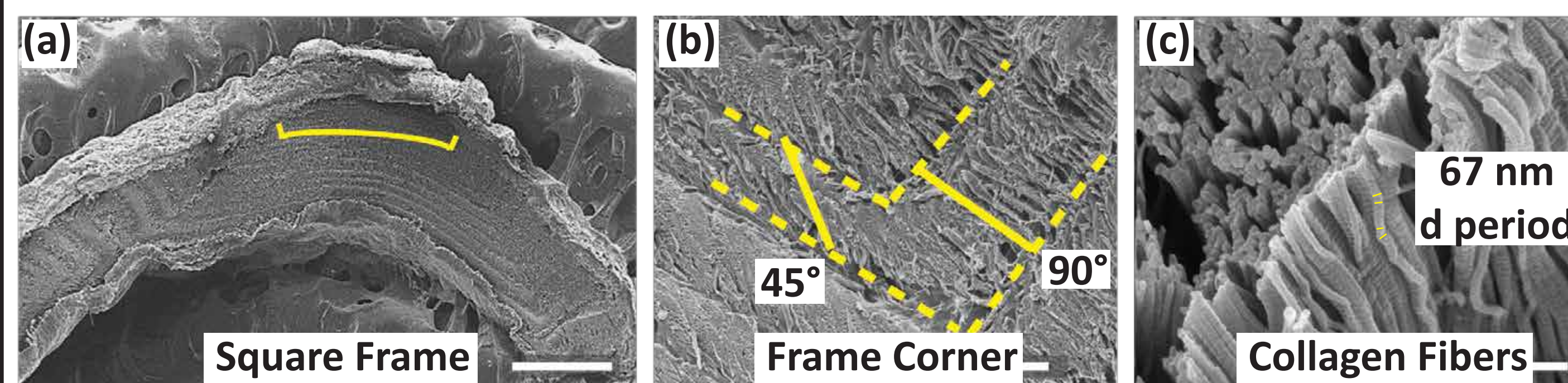
High resolution micro-CT images of the boxfish scute. Scale bars: (a) 500 μm, (b) 500 μm.

Top View



Structural characterization of the scutes from the top view. Scale bars: (a) 500 μm, (b) 100 μm, (c) 5 μm.

Side View



Structural characterization of cross-section of the scutes using SEM. Scale bars: (a) 500 μm, (b) 500 μm, (c) 500 nm. Note that scute is curved as an artifact of the sample preparation process.

Diagram

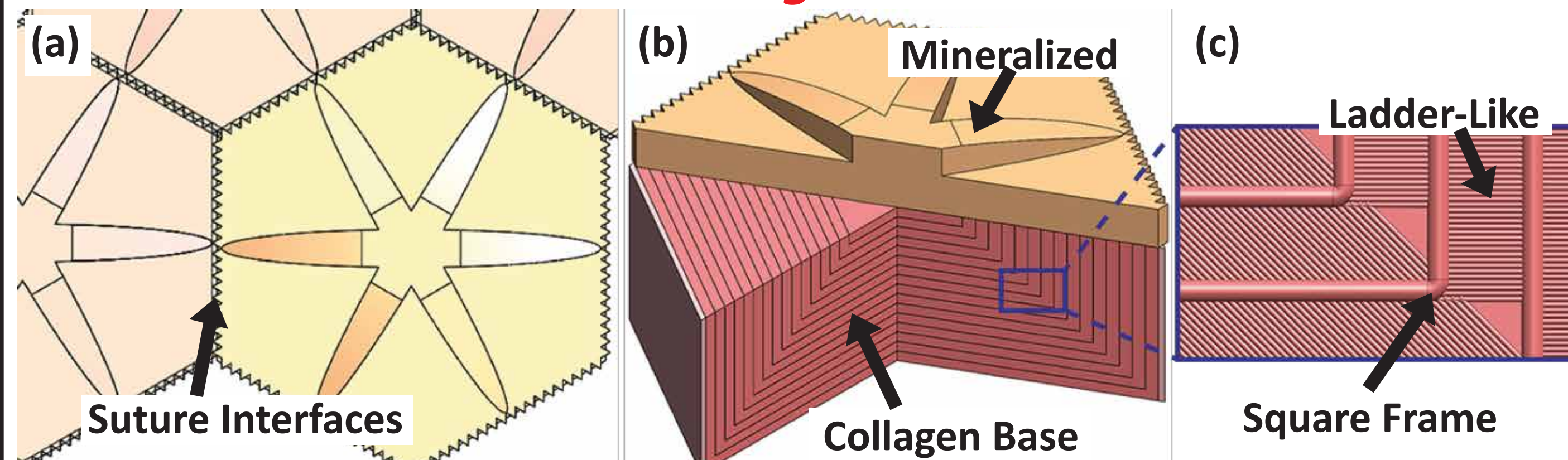
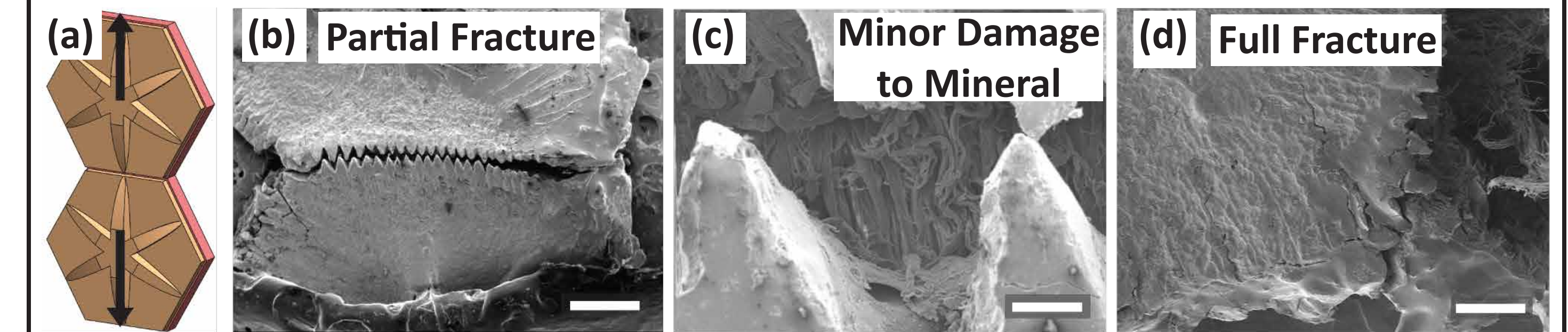


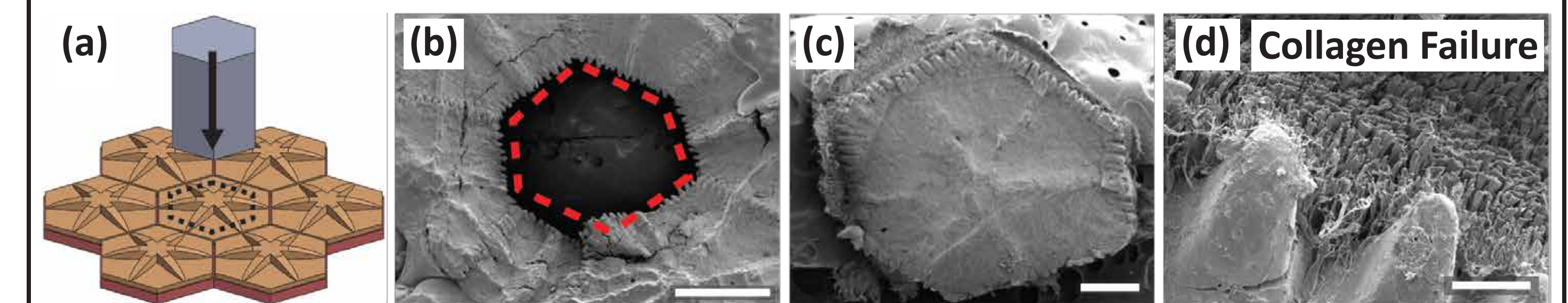
Diagram of the scute displaying the characteristic features: (a) from the top, suture interfaces and raised struts; (b) from the side, a mineralized plate and collagen base with fibers oriented in a square frame; (c) within the collagen base, ladder like perpendicular fiber orientations that become angled in order to accommodate the corners of the square frame.

Fracture

Both tension and punch tests showed the majority of deformation occurring within the collagen fibers with the mineralized scutes and sutures resisting fragmentation. This allows for the active stressed area to be increased in the event of a piercing attack.

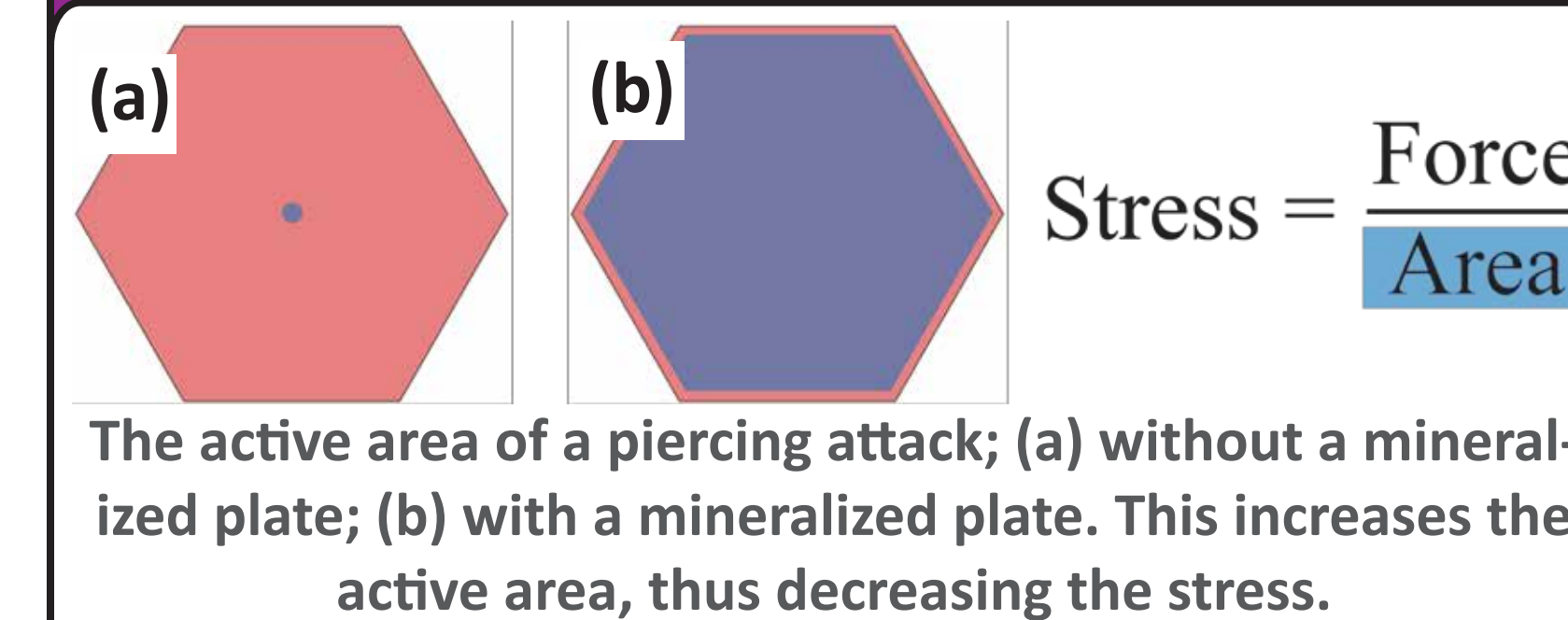


Fracture results of tension testing visualized through SEM imagery. Scale bars: (b) 500 μm, (c) 20 μm, (d) 200 μm.



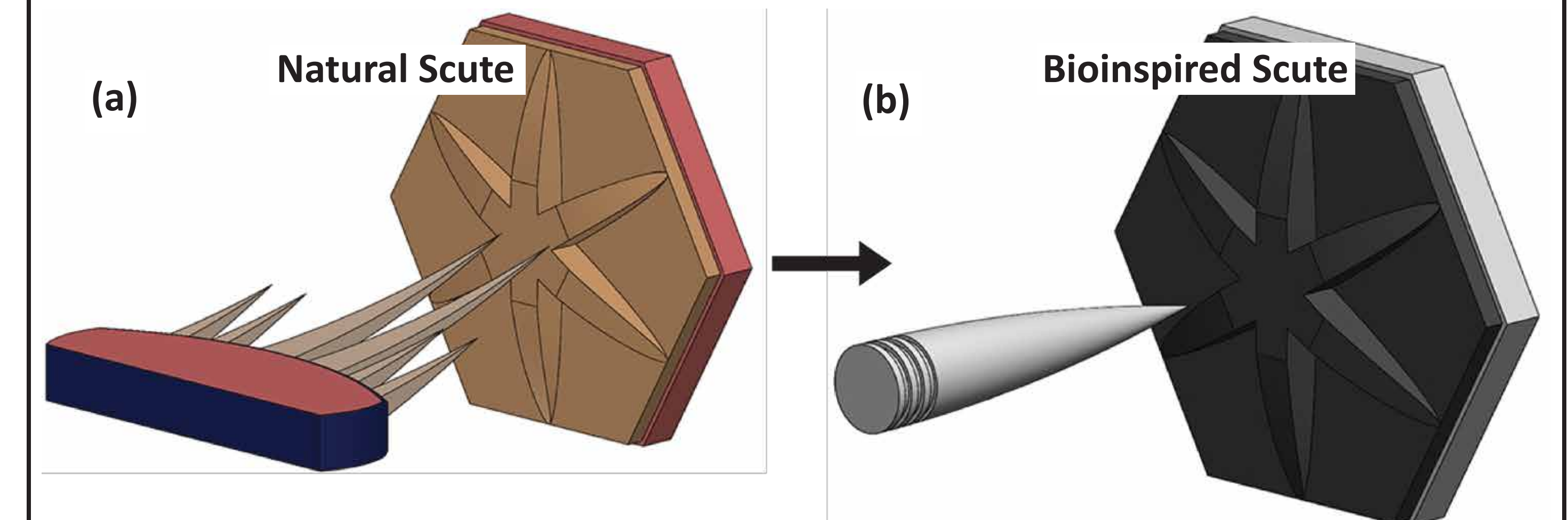
Fracture results of punch testing visualized through SEM imagery. Scale bars: (b) 1 mm, (c) 500 μm, (d) 50 μm.

Bioinspiration



The active area of a piercing attack; (a) without a mineralized plate; (b) with a mineralized plate. This increases the active area, thus decreasing the stress.

As can be seen from the presented fracture modes, the scutes act to increase the active area by avoiding fragmentation when strained. The increase in active area reduces the effective stress imposed on the body of the boxfish.



Bioinspired design based off of the boxfish scutes; (a) The boxfish scute, comprised of collagen and hydroxyapatite under assault from the piercing attack of fish teeth; (b) A bioinspired scute, comprised of stiff plate (e.g. steel) and a highly tough base (e.g. Kevlar) under assault from the piercing attack of a projectile.

These same mechanisms can be employed to fabricate bioinspired defensive systems. The majority of current dangers involve piercing attacks (e.g. projectiles) similar to the dangers that face the boxfish. The gradient structure of the boxfish scutes can be replaced by modern materials. The stiff surface plate can be fabricated with steel and the tough base can be fabricated with Kevlar or a carbon fiber laminate composite. The raised struts of the scute design serve to effectively spread the stress across the entire surface, further increasing the overall strength of the material.

Boxfish Inspired Protective Vest



Special thanks to: Phil Hastings and H.J. Walker of the Scripps Institute of Oceanography, UC San Diego, for providing the boxfish specimens, Ali Bahadur of Bruker Biospin, Billerica, MA for the high resolution micro-CT images, Ryan Anderson of CallIT2, UCSD, for help in SEM, Esther Cory and Robert Sah of the Department of Bioengineering, UCSD, for guided analysis of the micro-CT scans, Olivia Greave and Kyungah Seo of the Department of Mechanical and Aerospace Engineering, UCSD, for help with the TGA, and James Tyler of the Smithsonian for helpful discussions on boxfish and tetradontiformes.