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14. ABSTRACT
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**RPPR Final Report**  
as of 08-May-2019

Agency Code:

Proposal Number: 70052LSRIP

**Agreement Number: W911NF-17-1-0152**

**INVESTIGATOR(S):**

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**Report Date:** 13-Jun-2018

Date Received: 02-Mar-2019

**Final Report** for Period Beginning 14-Apr-2017 and Ending 13-Mar-2018

**Title:** Procurement of a Correlative Raman Microscope for in-situ SEM Imaging of Chemical-Structural Components in Biological Composites

**Begin Performance Period:** 14-Apr-2017

**End Performance Period:** 13-Mar-2018

**Report Term:** 0-Other

Submitted By: David Kisailus

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**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:**

**STEM Participants:**

**Major Goals:** We have acquired a Correlative Raman Microscope that is coupled with a scanning electron microscope, a TESCAN MIRA3 GMU Field Emission SEM equipped with a dual Energy Dispersive Spectrometer/STEM system with large area mapping capabilities. This Raman instrument provides high-resolution 3D reconstruction and concurrent elemental (via EDS) and molecular (chemical) mapping of large samples including biological, biomimetic and traditional composites as well as thin film semiconducting materials. It will greatly enhance the PI's contribution to ARO (W911NF-15-1-0306) and MURI projects (FA9550-15-1-0009) on the investigation of the presence and effects of chemical (organic and inorganic) as well as structural elements on not only the controlled synthesis of inorganic constituents, but also on strengthening and toughening in impact and abrasion resistant biological composites. This integrated system will provide the PI, fellow researchers, and students with unprecedented opportunities for research and will enhance undergraduate students' interest and understanding in materials science by facilitating research opportunities. This support will contribute to the PI's unique program, which conducts both experimental research on synthesis-structure-property relationships in biological and biomimetic composites and on biologically inspired synthesis of nanostructural materials – an area of extreme relevance to the DoD applications.

**Accomplishments:** We have just installed this instrument due to the fact that it had to be installed with the SEM in the Czech Republic. We have just started acquiring data on ARO and AFOSR funded projects. In addition, 4 of my group members have now been trained.

**Training Opportunities:** Through the acquisition of this Raman, we will enable the training and education of post-doctoral researchers, graduate and undergraduate students. Personnel that have been trained on this instrument include: Dr. Wei Huang (post-doctoral researcher), Jesus Rivera (Ph.D. student, Hispanic minority), Luz Cruz (Ph. D. student, female, Hispanic minority), Ramya Mohan (Ph.D. student).

**Results Dissemination:** Please see uploaded report.

**Honors and Awards:** Please see uploaded report.

**Protocol Activity Status:**

**Technology Transfer:** Please see uploaded report.

**RPPR Final Report**  
as of 08-May-2019

**PARTICIPANTS:**

**Participant Type:** PD/PI

**Participant:** David Kisailus

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

**Participant Type:** Postdoctoral (scholar, fellow or other postdoctoral position)

**Participant:** Wei Huang

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Jesus Rivera

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Luz Cruz

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Ramya Mohan

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

**RPPR Final Report**  
as of 08-May-2019

**Final Report (2018/2019)**  
**Procurement of a Correlative Raman Microscope for in-situ SEM Imaging of Chemical-  
Structural Components in Biological Composites**  
**Agreement # W911NF-17-1-0152**

PI: David Kisailus, UC Riverside

**Agency:** Army Research Office

**Program Manager:** Dr. Stephanie McElhinny, Biochemistry, Life Sciences Division

**Abstract**

We have acquired a Correlative Raman Microscope that is coupled with a scanning electron microscope, a TESCAN MIRA3 GMU Field Emission SEM equipped with a dual Energy Dispersive Spectrometer/STEM system with large area mapping capabilities. This Raman instrument (called “Raman Imaging and Scanning Electron” or RISE microscopy) couples confocal Raman with scanning electron microscopy. It will provide high-resolution 3D reconstruction and concurrent elemental (via EDS) and molecular (chemical) mapping of large samples including biological, biomimetic and traditional composites as well as thin film semiconducting materials. The equipment will greatly enhance the PI’s contribution to ARO (W911NF-15-1-0306) and MURI projects (FA9550-15-1-0009) on the investigation of the presence and effects of chemical (organic and inorganic) as well as structural elements on not only the controlled synthesis of inorganic constituents, but also on strengthening and toughening in impact and abrasion resistant biological composites. Additional projects are being created that investigate structure-property relationships of nanomaterials to develop energy conversion and storage systems. The impact and abrasion resistant structures, their mimics as well as nanostructures for energy conversion and storage all have utility for DoD missions.

This integrated system will provide the PI, fellow researchers, and students with unprecedented opportunities for research and will enhance undergraduate students’ interest and understanding in materials science by facilitating research opportunities. This support will contribute to the PI’s unique program, which conducts both experimental research on synthesis-structure-property relationships in biological and biomimetic composites and on biologically inspired synthesis of nanostructural materials – an area of extreme relevance to the DoD applications.

The Raman microscope will enable us to make significant contributions in uncovering details about ultrastructural features of the various regions within these biological composites and will enable us to begin deriving new design strategies for the synthesis of impact and abrasion-resistant composites.

**Research objectives relevant to DoD**

The proposed instrumentation has greatly enhanced the quality of research and research-related

education currently funded by the DoD as well as established new research capabilities at the University of California, Riverside, for performing research potentially of interest to the DoD.

ARO's mission is to serve as the Army's premier extramural basic research agency in the engineering, physical, information and life sciences; developing and exploiting innovative advances to ensure the Nation's technological superiority. ARO enables its mission based on an aggressive basic science research program so that cutting-edge scientific discoveries and the general store of scientific knowledge will be optimally used to develop and improve weapons systems that establish land force dominance.

The Biochemistry program's main goals are to focus on fundamental studies in biochemistry, structural biology, cell biology, and biophysics that will facilitate the development of novel systems and processes to enhance Soldier protection and performance. The research areas include biomolecular self-assembly, molecular recognition, protein and nucleic acid structure- function relationships, enzymology, signal transduction, cell-cell communication, macromolecular structure, and synthetic biology. This program also supports basic research in structural studies of molecular and macromolecular organization for novel materials or surfaces. The Mechanical Behavior of Materials program seeks to establish the fundamental relationships between the structure of materials and their mechanical properties as influenced by composition, processing, environment, and loading conditions. The program emphasizes research to develop innovative new materials with unprecedented mechanical, and other complementary, properties. A primary research thrust area of this program to realize novel mechanisms of energy absorption and dissipation and identifying novel mechanisms for enhancing specific toughness, engineering and synthesizing new materials containing unique and specifically designed chemical and biological functionalities and activities while maintaining, and preferably enhancing, requisite mechanical properties. Finally, the Synthesis and Processing of Materials Program encourages basic research on innovative processing and synthesis of advanced high performance structural materials systems. The vision of the program is to discover and illuminate the scientific linkages between novel processing and resultant microstructures, which enable exceptional properties in structural materials. Research thrusts specific to this program include high specific-strength materials and hierarchical composites, the subject of the PI's current project with ARO. Since advances in this area are enabled by insights and scientific breakthroughs achieved through combinations of novel experimental tools, this instrumentation will help to achieve these goals.

In order to address the above ARO needs, the PI, a promoted at University of California, Riverside (UCR), a minority serving institution, initiated several projects that investigate structure-function relationships of high-performance composites as well as developed synthetic strategies towards biologically inspired composites.

Our research touches all three of these program's objectives by (1) performing structural studies of molecular and macromolecular organization for novel materials or surfaces, (2) uncovering novel mechanisms of energy absorption and dissipation and identifying novel mechanisms for enhancing specific toughness through ultrastructural analyses combined with mechanical testing of this composite, and (3) discovering scientific linkages between biological processes and resultant microstructures. We aim to establish synthesis-structure-function relationships in mineralized and biologically inspired composite materials by overlaying ultrastructure, chemical

and mechanical maps of regional features expanded on a global scale. This includes a detailed understanding of the underlying organic matrix, which is believed to exert control over the crystallization process that ultimately controls the function of the composite. We will interrelate these observations to identify dominant mechanisms at relevant scales and extract design strategies for mimetic syntheses of high performance materials.

Aiming to address the above ARO needs, the PI has initiated several projects in the past year that investigate structure-function relationships of high-performance composites as well as develop synthetic strategies towards biologically inspired composites and nanostructured materials. This includes the PI's previous and current research with ARO: Organic Matrix Templating and Function in an Ultrahard Biological Composite, award #W911NF12-1-0257 and Organic-mediated Mineral Transport and Force Transduction in an Ultrahard Biological Composite, award #W911NF-15-1-0306.

One major focus area of the Kisailus lab at UCR is to develop new structural materials that have high strength and durability, and are light-weight and damage-tolerant. Biomineralized tissues are used as model systems for the understanding of structure-function relationships that serve as templates for biologically inspired systems. These biological systems demonstrate the ability to control nano- and microstructural features that significantly improve mechanical performance of otherwise brittle materials. By investigating the structure-function relationships of these mineralized structures using modern chemical, morphological, and mechanical characterization techniques, we will develop the necessary synthetic tools for the design and fabrication of light-weight, ultrahard and tough composites that mimic the various design elements and performance properties present in the biological systems.

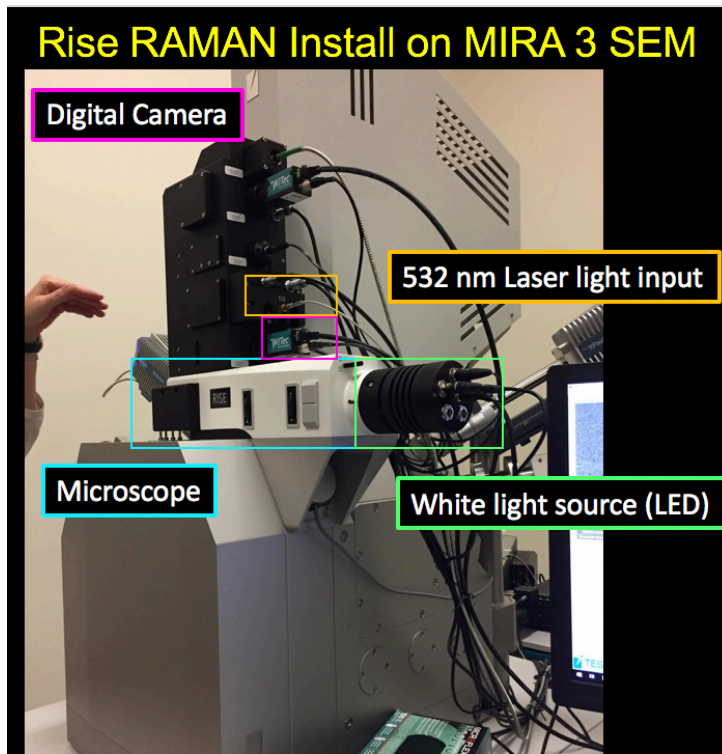
Much of our work relies the elucidation of the primary mechanisms of organic mediated templating and toughening within these unique composite materials through the following investigations:

1. A detailed study of the chemical and ultrastructural features of the fully mineralized composites with a complementary mechanical investigation (combined modeling and experimental) of the mineralized structures.
2. A thorough investigation of the underlying organic framework (structural and chemical) that provides templating for mineral growth as well as scaffolding for the composite.
3. Synthesis of biomimetic materials through in-vitro mineralization studies to understand organic-inorganic interactions and growth mechanisms, which provide architectural features that enhance performance and enable biomimetic syntheses.

The acquisition of the Raman microscope will enable us to significantly enhance our research capabilities towards all of these investigations by uncovering key elements in different composites that provide them with such remarkable ability to control interfacial elements which affects their performance. The installation of this Raman microscope has been delayed since it required the SEM Mira to be packaged and shipped to the Tescan company in the Czech Republic, where installation occurred. The Raman has now been in operation since February 2019.

### Acquisition and installation of the Raman microscope:

The following are overviews of projects that will benefit based on acquisition of the Raman microscope from Witec (Figure 1).



**Figure 1.** Rise Raman installed into MIRA 3 SEM.

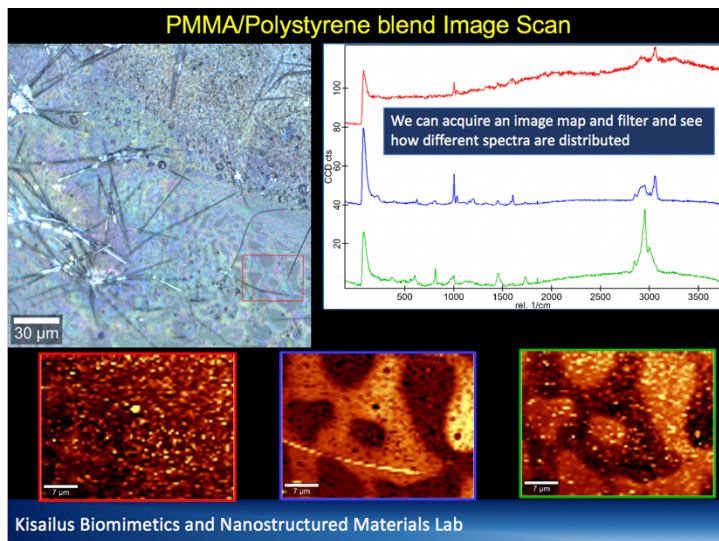
Numerous ongoing research projects in the Kisailus lab are investigating structure-function relationships in a wide range of self-sharpening, abrasion-resistant, and impact tolerant biological structures.

Current major research projects that would significantly benefit from this set of instruments focus on investigating structure-function relationships in three distinct types of impact tolerant biological composites; the exoskeletons from the terrestrial diabolical iron clad beetle and a flying beetle from Japan, the dactyl clubs of stomatopod crustaceans, and the ultrahard, mineralized teeth, as well as their supporting styli, in Chitons. Many additional projects that need RAMAN

microscope analyses have been initiated as part of the PI's MURI grant and beyond.

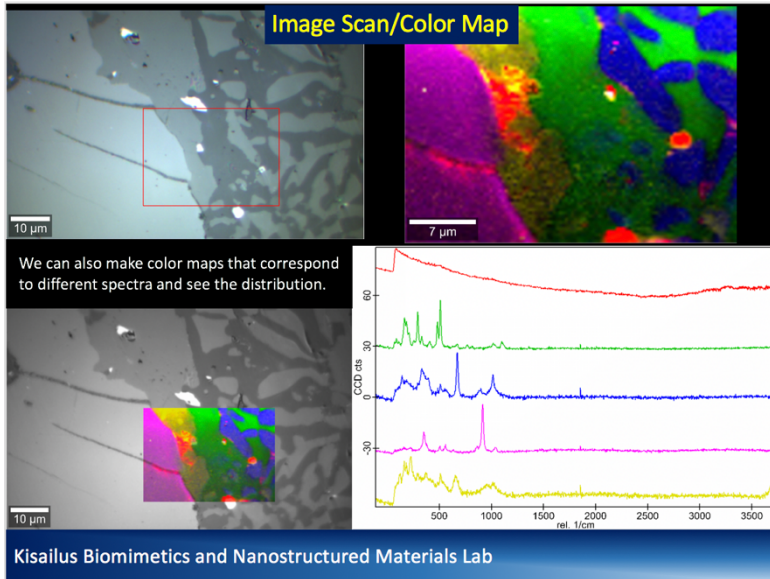
Initiated through the analysis of biologically-based composite materials, the results obtained from these studies will provide bio-mimetic / inspired tools for the design and fabrication of ultra-hard, abrasion and impact resistant materials.

Initial data collected by the Raman system after installation was very promising. We utilized block co-polymer films to test the effectiveness of the RISE Raman system. Figure 2 clearly shows the distribution of different domains of the PMMA-Polystyrene blends.



**Figure 2.** Raman spectra collected from PMMA/Polystyrene films.

Specific peaks can be selected from the Raman spectra and then utilized to pin point where the domains are located (Figure 3).



**Figure 3.** False colored maps of Raman spectra highlighting specific polymer domains.

**Project 1: ARO-funded “Organic Matrix Templating and Function in an Ultrahard Biological Composite” and “Organic-mediated Mineral Transport and Force Transduction in an Ultrahard Biological Composite”**

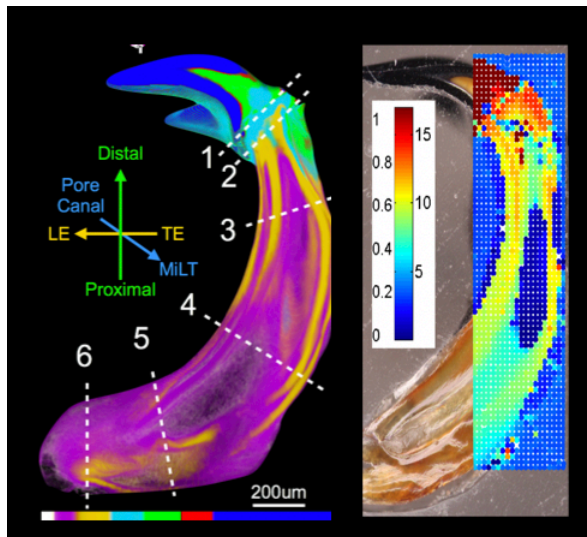
Now that we have the Raman system installed and operational, we will start investigating specific regions of the

non-mineralized, partially mineralized and fully mineralized radular teeth, as well as the supporting styli, from the Chiton.

The chitons (Mollusca, Polyplacophora) are an ancient group of mollusks with a fossil record dating back nearly half a billion years. Despite their long and successful history and their ecological importance in rocky coastal habitats they are a comparatively small group with about 650 modern species. Chitons are flattened and usually elongated mollusks that are protected dorsally by a shell consisting of eight overlapping plates. The foot is broad and powerful, well adapted for clinging tightly to the hard surfaces on which the animal grazes for algae. Like most other groups of mollusks, the chitons have a radula, a rasping, toothed conveyor belt-like structure, which is used for feeding. The composition and morphology of the radular teeth vary from group to group and depend on the dietary specifics and the mechanical properties of the substrates on which they feed.

CT and Nanomechanical analyses (Figure 4) of the tooth highlight that it the teeth are supported by a hollow tube-like stylus, and that the two mineral phases in the teeth (the magnetite veneer and the core of weakly crystalline hydrated iron phosphate) exhibit distinct mechanical properties.

The magnetite veneer has a modulus ranging from 90 to 125 GPa and a corresponding hardness ranging from 9 to 12 GPa. These values represent the highest modulus yet reported for a biomineral. The hardness is notably about 3 times higher than that of enamel and nacre, which exhibit indentation hardness and modulus of 3 - 4 GPa and 65 – 75 GPa, respectively, making this material exceptionally well suited for the continuous scraping activity of the radular teeth.

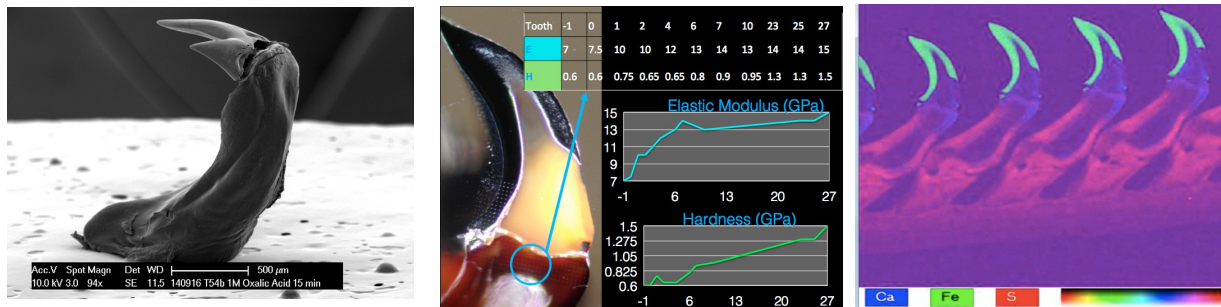


**Figure 4:** CT scan and nanomechanical testing of radular tooth and its supporting stylus.

Mechanical mapping of cross-sections through these two regions of the teeth reveals a distinct gradient in mechanical properties with the modulus of the leading edge of the tooth ca. 15% higher

than that on the trailing edge. This design strategy results in an uneven wear pattern along the scrapping edge of the tooth and establishes a self-sharpening condition, an observation consistent with radula structural studies on other species.

More recently, we initiated testing of the organic stylus, which supports the ultrahard magnetic teeth. At the macroscale, an ultrahard tooth is attached to softer and flexible stylus (Figure 5). From our preliminary studies, we find that the organic interface between this ultrahard tooth and flexible stylus undergoes some chemical and mechanical changes as a function of maturation (Figure 5, middle). We have also performed some initial elemental analyses of the stylus and have found large, but differing concentrations of sulfur within its leading and trailing edges (Figure 5, right).



**Figure 5.** SEM micrograph (left) of a fully mineralized tooth attached to its stylus. Nanoindentation modulus and hardness (middle), as a function of tooth number, at the organic interface between the tooth and stylus demonstrating significant increases with mineralization. Elemental mapping of Ca, Fe, S (right) of the longitudinal sections of teeth plus styli highlighting the presence of sulfur (red) along the leading and trailing edges of the stylus and likely enhancing stiffness of the organic.

Here, we will utilize our Raman microscope, in tandem with the SEM as well as the FTIR microscope and nanomechanical maps to correlate specific chemical features within the stylus and teeth with the observed graded stiffness.

More recently, we have observed specific proteins located within the fully mineralized teeth that suggest roles in biomineralization. In this study, a comprehensive transcriptome data from the radular tissue of *C. stelleri* has been developed for the first time. The constructed transcriptome data provides new insights into the genes highly expressed in radular tissue during teeth formation in *C. stelleri*. By using the transcriptome data, a proteome profile of mineralized cusp-specific proteins was determined. Those transcriptome and proteome data represent invaluable resources for the investigation of the magnetite biomineralization (including iron oxide nucleation, growth and phase transformation) in chitons. A novel mineralized cusp-specific protein, RTMP1, has a distinctive glycine and serine-rich region. The secondary structure of a glycine and serine-rich region was predicted to be disordered and thus might form a flexible structure like other biomineral proteins. It is possible that the extended conformation of RTMP1 might provide more mineral binding sites than tightly packed globular proteins. The WF-rich region in RTMP1 resembles a type-3 chitin binding domain of bacterial chitinase, which have  $\beta$ -sheets as well as aromatic and hydrophobic-rich sequences. Thus, similar to those bacterial chitinases, it is likely that RTMP1 binds to crystalline forms of chitin. A number of phosphorylated serines were inferred to reside in RTMP1. Of note, amino acid analysis of matrix proteins in the radula teeth of the chiton *Acanthopleura hirtosa* indicated that there were appreciable amounts of phosphorylated serines. In other biominerals, phosphorylation is often required for mineral-protein interaction. These results support the idea that the extracellularly secreted RTMP1, which is likely to be phosphorylated, may interact with chitin and promote iron oxide nucleation on chitin fibers.

We will utilize this combination of Raman and FTIR mapping to identify specific functional groups and correlate their role with respect to mineralization. The high resolution of this new microscope, and the fact that we can concurrently map elements and observe structure will be extremely valuable.

**Project 2: AFOSR funded “MURI: Convergent Evolution to Engineering: Multiscale Structures and Mechanics in Damage Tolerant Functional Bio-composite and Biomimetic Materials”.**

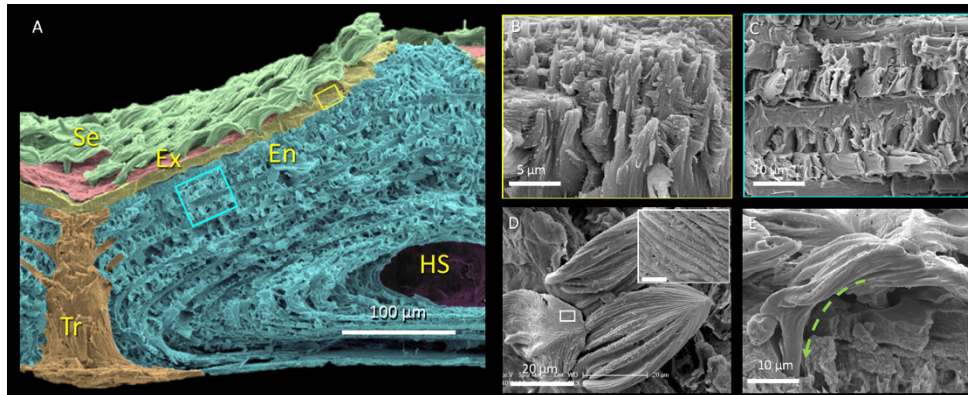
The PI and his collaborators from Purdue, UC Berkeley, Northwestern, and UCSD have initiated this work through AFOSR (Program Manager: Aura Gimm) for the development of ultra-tough, impact resistant composites. The project involves investigating multiple organisms to determine new design concepts for light-weight, tough, strong and impact resistant materials. The involvement of a new start-up company, Helicoid, will provide a pathway to eventual commercialization of the technologies in products of value to the DOD. The following shows one example of structure that will be investigated utilizing the Raman microscope.

**BEETLE:** The goal of this project is to elucidate the toughening mechanisms of the exoskeleton from the terrestrial diabolical iron clad beetle (Figure 6), a non-mineralized biological composite, and apply the lessons learned from these studies toward the fabrication of synthetic high- performance composites.



**Figure 6. The terrestrial diabolical iron clad beetle (*Phloeodes diabolicus*).**

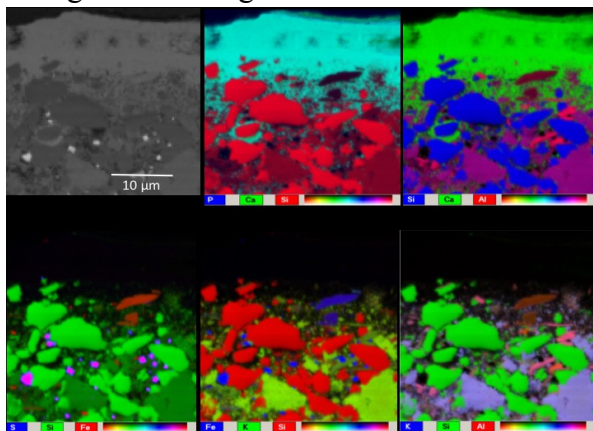
A major component of this research will be the ultrastructural analysis of the exoskeleton of this extremely impact and crush resistant beetle and compare it with other beetles designed for flying. We are now beginning to identify micro- and nano-scale morphological features that may contribute to the bulk mechanical properties (Figure 7). Utilizing the Raman within the SEM will provide structure-function relationships necessary for making next generation crush resistant materials.



**Figure 7.** Cross section of elytra highlighting complex microstructure. A) False colored SEM micrograph of fractured cross section of elytra, highlighting leaflike setae (Se, green), epicuticle (red), Exocuticle (Ex, yellow), Endocuticle (En, blue), Trabecula (Tr, orange) and Hemolymph space (HS, purple). B) SEM micrograph of fractured exocuticle (yellow box in A), highlighting through-ply thickness fibers. C) SEM micrograph of endocuticle (blue box in A), revealing pseudo-helicoidal fiber orientation. D) SEM micrographs highlighting leaf like structures (setae). Inset, detailed surface features of setae: textured ridges with nanometer spacing that likely facilitate water collection through capillary action. Scalebar 500 nm. E) SEM of the base of the setae revealing pathway to the pore canals.

**Project 3: ARO-funded “Adaptive Mechanisms and Substrate Interactions of Microbial Communities in Dry Extremes.”** The goal of this project is to elucidate microbe-mineral interactions in rock-inhabiting microbial communities and how these interactions impact the assembly, adaptations, and activities of communities in extreme environments. These microorganisms live in extreme conditions, often the only biotic component of the ecosystem, and find refuge inside rocks as a survival strategy. As such, these endolithic habitats provide a unique system to study processes at the biotic-abiotic interface under extreme environmental stresses.

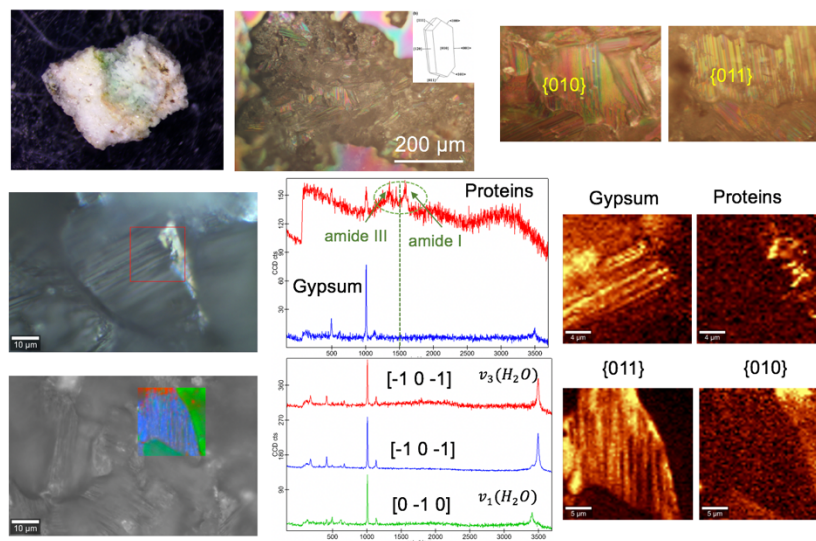
As part of this study, rocky substrates (Figure 8) as well as microbes on their surfaces will be subjected to analyses via different techniques including (i) optical and high-resolution electron microscopy, (ii) atomic force microscopy, and (iii) diffraction methods. Optical microscopy as well as scanning and transmission electron microscopy of regional sections will help provide higher-resolution details of the nano and microstructure to uncover mm -  $\mu\text{m}$  scale details of surfaces as well as organisms living on their surfaces.



**Figure 8.** SEM analysis of rocky substrate consisting of various elements. Upper left, Back scatter SEM micrograph; EDS maps are blends of selected elements such as P, Ca, Si (upper middle); Fe, K, Si (lower middle).

Understanding microbe community population distribution as a function of rock grain composition, size and texture, may reveal unique regional conditions critical for their *survival*. Beyond local surface roughness, Raman will be used to investigate the presence of microbe-rock boundaries within the system. In fact, our initial analysis using this new system has already been utilized to identify specific crystallographic facets upon which microbes are colonizing.

### Raman spectroscopy of Gypsum



**Figure 9.** SEM analysis of rocky substrate consisting of various elements. Upper left, Back scatter SEM micrograph.

This project supports the objectives of the ARO program and the DOD because it utilizes natural systems to bridge biology and materials science and engineering to create new technological capabilities for multifunctional systems that can survive in extreme environments.

## Supported Personnel and Collaborations: Training, Education, and Outreach Achievements

Besides providing scientific knowledge on multiple projects, acquisition of the Raman microscope will enable training, education, and outreach.

Through the acquisition of this Raman, we will enable the training and education of post-doctoral researchers, graduate and undergraduate students. Personnel that have been trained on this instrument include: Dr. Wei Huang (post-doctoral researcher), Jesus Rivera (Ph.D. student, Hispanic minority), Luz Cruz (Ph.D. student, female, Hispanic minority), Ramya Mohan (Ph.D. student). In addition to training and education, this equipment will enable our lab to collaborate with multiple PIs around the world.

Finally, through the procurement of this instrument, the data we will acquire will lead to outreach events at the Riverside Metropolitan Museum. During this event, undergraduates working in the Biomimetics and Nanostructured Materials Lab will present their research to a public audience.

The program for this event is shown below (Figure 10):

The flyer is titled "Design by Nature" and is for an event on Saturday, June 11, 2011, from 1-4 pm, free for all ages. It features a central image of a mantis shrimp with anatomical labels: Arm, Mouth, Podia, Ambulacral, and ov. Ovary with ova. A detailed diagram of the mantis shrimp's leg is shown on the right, with labels for Ambulacral (ossicle) and ov. Ambulacral (ossicle). The flyer includes a list of presentations such as "Teeth Harder Than Steel" and "Bullet Proof Armor Made from Sea Shells". It also mentions the Riverside Metropolitan Museum and the UCR Bourns College of Engineering. Logos for UCR, Riverside Metropolitan Museum, and supporting organizations like the National Science Foundation and the Air Force Office of Scientific Research are at the bottom.

**Design by Nature**  
Saturday, June 11, 2011  
1- 4 pm | Free | All Ages

Plants and animals always seem to construct the right tools for survival, and they do it with environmentally friendly mechanisms and materials.

- What can we learn from them to make our own tools better and more in tune with the environment?
- Join UC-Riverside Bourns College of Engineering Professor David Kisailus and his students as they share lessons learned from nature about the design of the next generation of engineering products.

Live specimens of the animals that inspire research will be on hand for your own observations!

**Riverside Metropolitan Museum**  
Information: (951) 826-5273

**UCR**  
Bourns College of Engineering  
www.engr.ucr.edu/david

**RIVERSIDE METROPOLITAN MUSEUM**  
3500 Mission Inn Ave., Riverside, CA 92501 (951) 826-5273 | www.riversidemca.gov/museum

**Mantis Shrimp**  
Mantis shrimp are an ancient group of marine tropical and subtropical crustaceans dating back to more than 400 million years. To the casual observer, stomatopods resemble heavily armored caterpillars. Yet, these feisty sea creatures have a pair of hard fists or clubs that can punch through the hardest seashells. They can deliver high speed strikes faster than a 0.22 bullet without breaking its own fist because it is very tough. Studying these club-like weapons and other structures from the sea have revealed some of Nature's secrets, which can be used to produce nearly indestructible materials for body armor, aircraft, vehicles, and more.

**Presentations**

- Teeth Harder Than Steel  
Brian Wieden, Leslie Wood, Glangqian Wang, David Kisailus
- Bullet Proof Armor Made from Sea Shells  
Mohammed Alam, Christopher Salinas, David Kisailus
- How "Boxing Shrimp" Can Help Protect Soldiers  
Steven Herrera, Garrett Milliron, David Kisailus
- Solar Cell Nanomaterials Made from Enzymes?  
Chhay Sun, John Johnson, David Kisailus
- Biologically-Inspired Production of Lithium Ion Batteries  
Kai-Kim Ngzyer, Jianxin Zhu, David Kisailus
- Colorful Paints to Make Hydrogen Fuels  
Elizabeth Hartman, Megan Langdon, Shermin Arabi, David Kisailus
- Using Sunscreens for the Next Generation of Solar Cells  
Ana Bawlus, Wenjing Hou, David Kisailus
- Biologically-Inspired Production of Nanostructured Materials for Clean Water  
Alexander Dudchenko, Nichole Kinsinger, David Kisailus
- Biologically-Inspired Production of Nanostructured Materials for Solar Cells  
Luka Turalich, Nichole Kinsinger, David Kisailus
- Not Your Grandma's Jewelry: Amino Acids for Nanostructured Platinum in Fuel Cells  
Christiah Contreras, David Kisailus

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National Science Foundation  
and the Air Force Office of Scientific Research

Figure 10. Design by Nature flyer for Kisailus Lab's outreach.

**Publications:**

As we have just acquired this instrument, we anticipate at least six manuscripts to be prepared this year, with 1 to be submitted in May 2019.

**Interactions/Transitions:**

We have established relationships with many industries: Airbus, Boeing, Centeye. Other new collaborations include those with:

Dimitri Deheyn (Scripps)

Nigel Hughes (UCR)

Atsushi Arakaki (TUAT)

Eric Schaible (ALS/LBNL)

Mikhail Zhernenkov (BNL)

Russell Varley (Deakin U)

Tiffany Walsh (Deakin U)

Lou Hector (GM)

Josh Orlicki, David Grey (ARL)

Darren Curtis (OSD, Adv. Manuf. Div.)

*Very importantly, my students and I are now in an active collaboration with Josh Orlicki and David Grey from ARL. The results from Raman examination of various impact resistant organisms have led to a new body of work to make coatings on impact resistant composites.*

**Conclusions:** The acquisition of this system has not only greatly enhanced our capability to carry out research activities related to biocomposite structure-function, but has also benefited the PI's and other researchers' overall capabilities in materials research. By understanding structure- function relationships and developing synthesis strategies to biomimetic composite materials, which have proved to be important for DoD applications, we have aligned our research activities with multiple DoD missions.