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Robert M. S. Schofield, *et al.*

Science **301**, 1049a (2003);
DOI: 10.1126/science.1089289

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TECHNICAL COMMENT

Comment on "High Abrasion Resistance with Sparse Mineralization: Copper Biomineral in Worm Jaws"

Lichtenegger *et al*. (*1*) demonstrated the fascinating occurrence of a copper biomineral in a worm jaw, but did not show, as they claimed, that this mineral has a structural role. Lichtenegger *et al*. based that conclusion on an apparent correlation between slight variations in mechanical properties and the measured chlorine content of the tested regions (the identified mineral, atacamite, contains copper and chlorine). The unjustified assumption is that all of the chlorine in the regions tested for the correlation in figure 5, E and F, of (*1*) is bound in the mineral and so serves as an indicator of the mineral content.

The problem with that assumption is that the very different copper, chlorine, and electron density maps [figure 1B, C, and D in (*1*)] indicate that significant portions of both chlorine and copper are not bound in the identified mineral. For example, the chlorine content appears to be as high in the upper-left-hand area of the section in figure 1C of (*1*), where the copper and electron densities are low, as it is in the more central (and presumably mineralized) regions, where the copper and electron densities are high.

It is important to distinguish which copper and chlorine compounds are correlated with mechanical properties, because it may be the unidentified nondiffracting copper and/or chlorine compounds that are predominantly responsible for mechanical properties, in a manner similar to the nondiffracting zinc and/or chlorine compounds that are associated with hardening in nereid worm jaws and the mandibles, claws, and other cuticular "tools" of many arthropods (*2*, *3*).

Unfortunately, the study by Lichtenegger *et al*. (*1*) does not even establish a correlation between unspecified copper and chlorine compounds and the sample's mechanical properties. First, the Oliver and Pharr method (*4*) used in (*1*) for measuring mechanical properties is designed for homogeneous specimens on noncompliant supports. Since the indent depth is not measured directly but is determined from the extension of the indenting probe, the resulting hardness value will be artificially low if the probe overextends because the specimen deforms due to poor support or because of softer subsurface tissue or voids such as pore and poison canals. If a well-supported specimen deforms less near the tip because there are no subsurface voids, the tip may appear harder. On ant mandibles, hardness values from the Oliver and Pharr method were inconsistent (and clearly inaccurate) for similar specimens, while hardness values from indent depths measured using atomic force microscopy were consistent (*3*). The results for the single specimen in the Lichtenegger *et al*. study (*1*) are suspect unless the authors show that the Oliver and Pharr method is applicable to their nonstandard specimen and unless they also demonstrate repeatability.

Second, both absolute and relative mechanical properties change as specimens dry: We have found that two regions of an ant mandible that are about equal in hardness in fresh specimens may differ by about a factor of two in dried specimens. For example, the hardness of tooth and off-tooth regions of a fresh ant (*Atta sexdens*) mandible from an enclosing adult measured 0.23 and 0.20 GPa, respectively; after air drying, these hardness values for the same mandible were 0.61 and 0.35 GPa (*3*). The conclusions of Lichtenegger *et al*. (*1*) are based on small (<35%) variations in hardness and modulus of elasticity on a dried specimen of a jaw that is, in nature, wet.

Third, Lichtenegger *et al*. (*1*) have not demonstrated the accuracy of the approximation used to compare the abrasion resistance of nonuniform biological composites. Without such a demonstration, the claim that the tested glycerid jaw is more resistant to abrasion than vertebrate dentin is only speculation.

Finally, Lichtenegger *et al*. (*1*) did not report finding the copper mineral at the surface of the jaw, where abrasion resistance would have biological relevance.

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1 November 2002; accepted 24 July 2003

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