Mineral minimization in nature’s alternative teeth

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Contrary to conventional wisdom, mineralization is not the only strategy evolved for the formation of hard, stiff materials. Indeed, the sclerotized mouthparts of marine invertebrates exhibit Young’s modulus and hardness approaching 10 and 1 GPa, respectively, with little to no help from mineralization. Based on biochemical analyses, three of these mouthparts, the jaws of glycerid and nereid polychaetes and a squid beak, reveal a largely organic composition dominated by glycine- and histidine-rich proteins. Despite the well-known metal ion binding by the imidazole side-chain of histidine and the suggestion that this interaction provides mechanical support in nereid jaws, there is at present no universal molecular explanation for the relationship of histidine to mechanical properties in these sclerotized structures.

Keywords: histidine-rich proteins; sclerotins; polychaete jaws; squid beak; zinc; copper

1. INTRODUCTION

Impact and wear resistant structures evolved by living organisms encompass some of the most ingenious and fearsome adaptations in hard tissue biology. Scorpion stingers, hydroid nematocysts, snapping claws, fangs, beaks, hooves, ovipositors and antlers represent just a few (Brown 1975). Ostensibly, these structures can be divided into two groups—those with mineral and those without. This is, of course, a naive classification because the boundary between the two is not an abrupt one. Rather, the proportion of mineral and organic phases is an evolutionarily adjustable continuum, and nature undoubtedly possesses examples for every step between all mineral and all organic. Highly mineralized (greater than 50%) impact structures, particularly teeth, have been extensively studied in structural, chemical, mechanical and clinical detail. However, much less is known about the more diverse non- or slightly mineralized structures. Indeed, given the widely held view that mechanical robustness is imparted by the presence of hard minerals, non-mineralized structures have typically been dismissed—at least as bio-inspired design paradigms for hard, abrasion resistant materials. One chink in the ‘armor’ occurred when Lichtenegger et al. (2002) reported that the abrasion resistance of Glycera jaws was tantamount to that of tooth enamel, yet with only a tenth as much mineral. This was followed by another report that hardness and stiffness in the completely non-mineralized jaw of Nereis approach those of tooth dentin (Lichtenegger et al. 2003). Thus, a new research hypothesis is emerging: that factors other than mineral content can endow biological materials with stiffness, hardness and abrasion resistance. The practical significance of this cannot be emphasized enough.

In this review, we describe some of the recent advances in the biochemical, structural and mechanical characterization of three impact structures: jaws from two marine polychaetes (Glycera dibranchiata and Nereis species) and the beak of the jumbo squid (Dosidicus gigas). Of these, only the Glycera jaws contain a small amount of mineral, Nereis jaws contain Zn ions but no mineral, and Dosidicus beak has no detectable inorganic content. These systems are of interest not only for their functional prowess, but also because they serve as possible models for a new generation of bio-inspired, mechanically robust materials. Extensive improvements in the repertory of nanocharacterization are providing an ever clearer view of the remarkable chemistry and construction of these materials. This overview is devoted to a brief description of two intimately intertwined topics: the unusual properties of these largely organic sclerotized structures and the evolving technologies available for their characterization.
2. CURRENT STRATEGIES FOR MATERIALS CHARACTERIZATION

2.1. Mechanical

Obtaining accurate mechanical property data for biological materials is complicated by several factors. (i) Sample volumes are typically very small. Polychaete jaws, for example, are only about 1–5 mm in size. (ii) Variations in mechanical properties over small length-scales (10–100 µm) are not uncommon. In such cases, macroscopic measurements are, at best, representative of average properties and can only be correlated with average compositions and structural characteristics. (iii) Even when available in large sizes, most biological samples come in complex shapes. Consequently, testing of samples with well-defined geometries, as done for engineering materials, is rarely possible.

Some of these difficulties have been mitigated by recent advances in low-load instrumented nanoindenters. Nanoindentation enables probing of mechanical properties at small length-scales (approx. 1 µm) and is the preferred method for characterizing hard tissues (Pharr 1998; Fisher-Cripps 2002; Oliver & Pharr 2004). The instruments employ high-resolution actuators and transducers to continuously control and monitor loads and displacements on a rigid tip as it penetrates into the surface of a material. Typical measurement resolutions are 100 nN for force and 1 nm for displacement (Fisher-Cripps 2002).

Given the low displacements and forces obtained during nanoindentation, the surfaces of the test specimens must be extremely flat and smooth to ensure accurate measurements. A useful strategy for preparing surfaces with minimal roughness is ultramicrotomy. Just as in the preparation of thin sections for transmission electron microscopy (TEM), the test sample is embedded in a hard resin and the surface is cut or shaved with successively finer glass or diamond knives. The freshly exposed finished surface is then tested. Alternatively, in larger samples (greater than or equal to a few millimetre square), surfaces can be prepared by lapidary polishing. In this case, the sample is embedded in an epoxy resin and subsequently polished with abrasive media of progressively finer grit, typically down to about 0.02 µm.

Nanoindentation is most commonly used to measure the hardness, H, and the Young modulus, E. Both are readily obtained from a single indentation test (Oliver & Pharr 1992). Furthermore, by performing a series of indentation tests at prescribed locations on the specimen surface, mechanical property maps can be generated and correlated to local structure and composition. Additionally, to assess the effects of hydration on mechanical properties, fluid cells can be used to test samples that are fully submerged in a liquid environment (Broomell et al. 2006).

Abrasion resistance can also be probed directly using the most recent generations of nanoindenters. For this purpose, two-dimensional transducers are employed to scratch the surface, typically with a spherico-conical indenter tip, while simultaneously measuring the penetration depth as well as both normal and tangential forces (Pontin et al. submitted). The results are frequently cast in terms of a (nominal) friction coefficient, defined as the ratio of normal to tangential force. Similarly, wear resistance can be assessed by passing the same indenter repetitively over a prescribed region of the surface. The resulting wear depth is measured in situ using a piezoelectric scanner affixed to the transducer.

Like hardness and elastic modulus, fracture toughness \( K_c \) is a critical property in the assessment of structural biomaterials. It is used to characterize a material’s resistance to crack propagation, owing to either a global applied force (such as that induced in a jaw during capture of prey) or localized forces that exist at asperity contacts. Indeed, optimizing wear and abrasion resistance requires a balanced combination of \( H \), \( E \) and \( K_c \) (Hornbogen 1975; Adachi et al. 1997; Budinski 1997). Indentation methods have been used extensively to measure toughness in hard, brittle materials such as ceramics and glasses, but the measurements are predicated on the formation of well-defined cracks, emanating from the edges of the indenter. The critical load to initiate such cracks from the tip of a sharp indenter is proportional to the quantity \( K_c^2 / H^3 \) (Lawn 1993). Owing to the combination of low toughness and high hardness characteristic of ceramics and glasses, the crack initiation loads are only moderately high: typically in the range of 0.1–1 N for a Vickers indenter. In contrast, in biological materials, the low hardness leads to exceedingly large critical loads: typically \( 10^2 – 10^6 \) times that for ceramics. Not only are these loads virtually impossible to achieve with current instruments, but also they would lead to indent sizes that dwarf the sample dimensions if applied. Consequently, indentation methods are not a viable option for measuring toughness of most biological materials. Instead, standard (macroscopic) engineering tests on notched test specimens must be performed. The paucity of insect cuticles and other sclerotized structures with adequate dimensions for toughness measurements has led to a rather thin database in comparison to other biological materials (Vincent 2002; Vincent & Wegst 2004).

2.2. Structural characterization

Neither scanning electron microscopy (SEM) nor TEM is new to the investigation of biological materials, but both have become indispensable, especially in combination with other types of analysis (figure 1). It is not uncommon, for example, to examine the same sectioned surface by TEM before and after nanoindentation, finally finishing with a chemical analysis such as backscattered electrons (BSE) or energy dispersive X-ray spectroscopy (EDS) for detection of heavy element and specific element distributions, respectively. Successive imaging and re-imaging of sample surfaces enables the compilation of topographical, mechanical and chemical datasets for the same material before and after specific treatments. This has proven especially revealing in the case of Nereis jaw sections before and after removal of Zn by chelation and is generally applicable to a wide variety of sample surfaces.

SEM is used most commonly to explore the topography of a sample surface. Information on the organization of various microstructural entities and
the micromechanisms of fracture can be obtained by examination of fracture surfaces produced at either ambient or low temperatures. Topography is effectively investigated by secondary electron imaging. In contrast, BSE imaging provides complementary information about the distributions of heavy (electron-dense) elements that frequently reinforce biological materials. Additionally, with the use of EDS and/or electron probe microscopy, maps of elemental distributions in the near-surface regions can be obtained. BSE imaging also lends itself to immunochemistry in that the binding of specific antibodies can be indirectly imaged when coupled to colloidal gold (Seto et al. 2004).

TEM is well suited for examining the fine structure of thin sections (typically 50–150 nm thick). Samples are fixed and embedded in resin or epoxy in order to preserve the natural structural order. Samples can be non-specifically stained with heavy-metal compounds such as uranyl acetate or osmium tetroxide to provide contrast for general morphological characterization. In addition, they can be labelled with specific antibodies, coupled to electron-dense colloidal gold, for example, to localize individual proteins or other molecules. Although compelling when it works, immunohistochemistry is often less than satisfactory in those materials where sclerotization involves biochemical changes that alter the original antigenic epitopes (Anderson & Waite 2000; Robinson et al. 2001). In SEM as in TEM, the biological materials subjected to electron beams emit X-rays, thus enabling determination of additional elemental and chemical information on a nanometer scale (Williams & Carter 1996). Sections of secretory granules (1 μm diameter), for example, have been subjected to EDS for detection of divalent metals (Vovelle & Grasset 1990; Foster et al. 1993); selected area electron diffraction of Glycera jaw thin sections has revealed higher-order structures such as crystalline fibres of a copper-based mineral (Lichtenegger et al. 2002).

Small-angle X-ray scattering (SAXS) has also been used to reveal and quantify fine-scale structural features and their spatial arrangements in hard biological tissues (Fratzl et al. 1997; Lichtenegger et al. 2003; Gupta et al. 2005). With the small diffraction angles (less than 1°) resolvable by SAXS, features at length-scales of 1–100 nm can be readily probed. In both Glycera and Nereis jaws, for example, SAXS measurements have been used to demonstrate that the atacamite and protein fibres, respectively, are parallel with the long axis of the jaw (Lichtenegger et al. 2003, 2005).

2.3. Compositional
2.3.1. Elemental analysis. Despite the variety of available techniques, the hierarchical and multidimensional organization of biomolecular materials provides endless surprises and challenges for investigators attempting to define the correlations between structure and composition (figure 1). EDS, secondary ion mass spectrometry (SIMS) and X-ray photoelectron spectroscopy (XPS) enable chemical analysis of a surface and each has different advantages and limitations. In EDS, the incident beam of electrons induces X-rays of characteristic energies to be emitted from the material sample (Williams & Carter 1996). We have applied this technique mostly to micromotted surfaces of biological materials. As previously noted, the main advantage to this approach is the convenience of elemental analysis following nanoindentation, so that hardness and stiffness can be correlated to specific element distributions. In addition, elements can be mapped over the entire sample or along line scans (Birkedal et al. 2006; Broomell et al. 2006).

SIMS and XPS are common methods for elemental analysis of solid samples (Briggs 1998; Ratner et al. 2004) and are useful for determining the compositions of surfaces and interfaces between dissimilar phases. In SIMS, an ion beam is rastered over a defined region of the sample surface, resulting in the generation of secondary ions from resident elements in the material (Briggs 1998; Ratner et al. 2004). This is a destructive process, leading to the formation of a crater, which deepens over time. Mass analysis of secondary ions liberated from the sample crater provides elemental depth profiles of surface regions up to 10–20 μm deep, enabling an assessment of the interrelationship of chemical composition and material ultrastructure (Khan et al. 2006).

XPS has a depth penetration of less than 100 Å and is thus ideal for characterizing the chemistry of the outermost surface. XPS is conceptually the opposite of EDS; interaction of X-rays with the sample surface induces emission of electrons with energies that are characteristic for each element (Moulder et al. 1995; Briggs 1998). In many cases, XPS can be used to deduce the bonding environments of elements detected in biological surfaces. For example, halides can be easily distinguished from organohalogens in Nereis jaws (Khan et al. 2006). As a rule, sample spectra need to be accumulated quickly to avoid artefacts. Otherwise, during lengthy beam exposures, sample decomposition can be substantial. In Nereis jaws, for example, following 60 min of beam exposure, C–X bonds (X being I, Br or Cl) begin to decompose into multiple chemical environments (R. K. Khan 2005, unpublished data).
Although current technology can provide much information about line and depth profiles of elemental composition, information about the distribution of larger functionalities is somewhat more limited. Phenolic groups, such as those in bromo- and iodo-tyrosines in _Nereis_ jaws, are readily distinguishable by the influence of phenolic environments on the halogens in XPS (Khan _et al._ 2006), but unhalogenated functionalities like the phenol, imidazole and catechol of tyrosine, histidine and 3,4-dihydroxyphenylalanine (DOPA), respectively, are not. At one time, laser Raman microprobe spectroscopy was expected to fill this void in biological samples (Dong _et al._ 2003; Takeuchi 2003), but the high intrinsic fluorescence of many scleritized materials including polychaete jaws has prevented its widespread use.

Investigators increasingly subject whole or sectioned biological samples to synchrotron X-ray analysis. These instruments have a positional resolution of 5 μm and are frequently equipped with a variety of characterization tools including X-ray fluorescence, absorption (XAS) and diffraction (Lichtenegger _et al._ 2005). When transition metals are present, XAS can provide exceptional insights about metal bonding environments by excitation of K-edge electrons. Two applications of XAS, namely X-ray absorption near edge structure (XANES) and more particularly extended X-ray absorption fine structure (EXAFS), often allow a confident reconstruction of the ligand environment around the metal nucleus (Holm _et al._ 1996). EXAFS, which measures the oscillating photoelectron energy of BSE, is less sensitive than XANES but informative about the scattering groups (e.g. ligands) and bond lengths. In the case of the XANES and EXAFS spectra for a _Nereis_ jaw tip, an extensive bio-inorganic database (Protein Data Bank) was searched to reveal the best fit; this was found to be the Zn insulin hexamer with three imidazoles and one chloride ligand for each Zn$^{+2}$ nucleus (Lichtenegger _et al._ 2003).

### 2.3.2. Protein analysis

Biochemical characterization of macromolecules from scleritized materials has always been daunting. It remains so despite a dramatic increase in the sensitivity of various methodologies. Although difficulties are usually attributed to ‘cross-linking’ of component molecules, this remains more anecdotal than proven. Many silks, for example, resist characterization despite the absence of cross-links. Techniques employed in the characterization of protein from biological materials include bulk amino acid analysis and peptide mapping in combination with N-terminal (Edman) sequencing (Wilson & Walker 2000; figure 1). Composition analysis allows for qualitative and quantitative characterization of standard amino acids from intact structures or fractions purified from extracts. Quantitative data are useful for assessing the mass percentage of protein in the intact structure, whereas qualitative data provide molar ratios of constitutive residues (excluding asparagine and glutamine). Although no sequence information is given by this technique, composition analysis can, in some cases, provide clues into the nature of a protein component. Characteristic molar ratios between specific amino acids often provide evidence of sequence repeats, such as glycine, proline and hydroxyproline in collagen-like domains, and glycine, alanine and serine in silks. In principle, post-translational modifications can also be identified by comparison with known standards, if available, although corroboration by additional techniques (such as tandem mass spectrometry) is necessary.

Direct sequence determination is achieved by N-terminal sequencing (Edman degradation). Traditionally, complete (or near complete) sequences are obtained by splicing together overlapping peptide sequences generated from multiple digests of purified protein. This often requires the isolation of significant quantities of protein, a rare luxury in scleroproteins. The same processing events, which confer ideal functional properties _in vivo_ (insolubility, hardness, resistance to environmental insult, etc.), often render the component proteins intractable to chemical or enzymatic extraction in the laboratory. Additionally, variations in primary sequence within a ‘purified’ fraction can prevent isolation of enough homogenous sample for a thorough sequencing regimen. Even when a sufficient quantity of material can be purified, traditional Edman degradation is not always informative when unstable post-translational modifications such as phosphoserine dihydroxyproline, γ-carboxyglutamate, sulfoxyproline and others occur (Wold & Moldave eds 1984). Thus, in many cases, the biochemist can only glean small stretches of sequence information of a few peptides from a large protein or complex. This is akin to trying to describe the picture on a jigsaw puzzle from a few miscellaneous pieces. In such cases, molecular biology offers the only recourse for solutions.

Recombinant DNA technology has been a great boon for the characterization of proteins from biological materials. Using well-established techniques, such as polymerase chain reaction with degenerate oligonucleotides, sequence obtained from a small peptide—as few as 6–10 residues—is often sufficient to clone the gene encoding the protein from its associated tissue, thereby allowing the deduction of the full-length protein sequence. This greatly facilitates the analysis of materials with poorly extractable components. Additionally, as these techniques select for any genes (in a given collection of cDNA) that encode the particular sequence, one can often identify variants at the genetic level or, even, proteins with similar sequence motifs (and possibly functions) from closely related organisms.

Although such methodology has greatly facilitated identification of proteins in hopelessly insoluble sclero-proteins (Koch _et al._ 1998; Anderson & Waite 2000), it does have significant limitations. As primary sequences are deduced from recombinant DNA, all information reflects only unprocessed precursors. Any modifications present in the native molecule (e.g. hydroxylation, deamidation, cross-linking, halogenation, etc.) cannot be identified. Such modifications can be characterized, however, by comparing deduced sequences to those obtained using modern proteomics techniques (i.e. tandem mass spectrometry; Taylor _et al._ 1994).
Comparison of peptide masses ‘expected’ from predicted sequences to those ‘observed’ from purified peptides occasionally enables identification and localization of modifications in the native molecule.

3. CASE STUDIES

3.1. Squid beaks: chitin-containing composites

Cephalopods are equipped with robust beaks with which they grasp and tear apart food. Comprehensive nomenclature and description of cephalopod beaks can be found in Clarke (1986), whereas a detailed study of the mandibular action has been described in Kear (1994). Given their large size (1–3 cm), Dosidicus gigas beaks (figure 2a,b) lend themselves to a battery of mechanical tests not possible with smaller structures. The dominant microstructural characteristic revealed by optical and scanning electron microscopy is the lamellar organization of the constituents: the lamellae are oriented predominantly towards the tip of the beak and perpendicular to the external beak surface. Figure 2c is a low magnification image by light microscopy of a fracture surface illustrating this layered structure. The sample was dissected from the external part of the upper beak and the plane of the fracture surface is orthogonal to the axis in the near-surface layer is about 50 µm thick (figure 2c).

Structural features at the nanometer scale have been identified by SAXS. The measurements reveal the presence of fibres (likely chitin) with characteristic dimensions ranging from 5 to 35 nm. They also indicate that the fibres are preferentially oriented along the beak axis in the near-tip regions.

Proteins comprise 40–45% of the dry weight of the beak, as determined by quantitative amino acid analysis. X-ray and EDS studies have confirmed that the beak is devoid of metal ions, minerals and halogens. Chitin has been detected by analysis for amines and chitin, which are not detectable by any of the analytical methods used. Chitin appears to provide a residual scaffold for the beak: when whole beaks are degraded in a H2O2/NaOH solution, the hard tissue becomes very soft, featuring a hydrogel-like texture (figure 3), but its overall shape is preserved. Subsequent analysis shows that the degraded structure contains only chitin, whereas pigments and proteins are removed.

A prominent feature of matrix proteins in Dosidicus beak is the relative abundance of Gly and His at 25 and 10 mol%, respectively. This composition is strikingly resonant with sclerotized insect cuticles (Andersen et al. 1995; Economou et al. 2005) as well as the polychaete jaws described later. In insect cuticles, it has been postulated that the covalent bonds between chitin and scleroproteins are mediated through His residues (Schaefer et al. 1987; Kerwin et al. 1999b) and that the enrichment of His in the C-terminal region of cuticular proteins plays an active role in sclerotization (Andersen et al. 1995).

Whether they act by dehydration or cross-linking or both, low molecular weight catechols are another prerequisite of sclerotization in insect cuticles. Catechols are present in Dosidicus beaks in the form of peptide-bound DOPA, a post-translational modification of tyrosine. Preliminary analysis of the beak indicates at least two extractable proteins that contain significant levels of both His and DOPA. DOPA-containing proteins are reminiscent of sclerotization in other molluscan structures, notably byssus (Waite 1990). Oxidation of DOPA to quinone in the beak could contribute to beak pigmentation and intermolecular cross-linking, but this remains to be demonstrated.

Typical profiles of Young’s modulus and hardness along a longitudinal section of a beak are shown in figure 4. Although some variation occurs from beak to beak, fairly uniform values are measured on a single specimen. Property gradients like those found in polychaete jaws (Waite et al. 2004) have not been detected in the hard regions of the beaks. Typical properties of dry beaks are \( E = 7\,–\,9\) GPa and \( H = 0.6\,–\,0.8\) GPa. These values are similar to those of Nereis jaws at Zn contents of 1–2% and are at least twice those of the stiffest and hardest engineering polymers with comparable densities. However, they are significantly lower than those of Glycera jaws at the highest mineral content (figure 5). Hydration lowers these property values by about 1/3 to \( E \approx 5\) GPa and \( H \approx 0.4\) GPa. The fracture toughness \( K_c \) measured on macroscopic fracture specimens are \( 3.2 \pm 1.5 \) and \( 3.5\,\pm\,1.1\) MPa m\(^{1/2}\) in dry and wet conditions, respectively. Interestingly, despite having a hardness well above that of the hardest engineering polymers, the jaws exhibit a fracture toughness which is comparable to that of the toughest polymers (Kausch et al. 2001). This is an unusual combination, in light of the usual trade-offs between toughness and hardness in most engineering materials. Additionally, although the database remains thin, the only known biological structural material that exhibits higher toughness is antler (Zioupos et al. 1996; figure 5).

Using the preceding property values, an initial assessment can be made of the abrasion resistance of the beaks. For soft materials (encompassing most engineering polymers and metals as well as the squid beaks), abrasive damage occurs only when the local stress beneath a contact exceeds the material yield strength. The pertinent material property group that characterizes resistance to plastic deformation during contact with a blunt abrasive body can be ascertained from Hertzian contact mechanics (Johnson 1985).
resulting critical load for yield initiation is proportional to the material property group $H^3/E^2$. Comparative assessments of abrasion resistance are made by plotting $H$ versus $E$ for materials of interest. When plotted logarithmically, data lying on a straight line of slope $2/3$ represent materials with equivalent performance, i.e. with the same value of the property group and hence the same load for yield initiation. Figure 6 shows such a plot with data for common engineering polymers as well as that for the squid beak. Also shown in the figure is a family of lines of constant $H^3/E^2$: each one corresponding to dentin (lowest line), polyamide (the best of the engineering polymers) and enamel (top line). The plot reveals that the value of $H^3/E^2$ for the squid beak is higher than that for dentin and comparable to those of the best engineering polymers. A more critical assessment awaits the outcome of direct abrasion measurements.

3.2. Nereis jaws: composite of protein and metal ions

Nereid polychaetes are armed with a pair of reversible fang-like jaws that are used for grasping food and...
The jaws of *Nereis virens* are complex with respect to architecture and composition. Structurally, they approximate fibre-reinforced composites with bundles of fibres arranged parallel to the contour of the jaw’s long axis (Figure 7c). SAXS analysis indicates that the fibres are themselves arrays of tightly packed fibrils, each with a diameter of roughly 50–100 nm (Lichtenegger et al. 2003). The jaw is encased within an amorphous coating (3–10 μm thick) of unknown composition (Figure 7b).

*Nereis* jaws contain protein, metal ions and the halogens Br, Cl and I; each differentially distributed throughout the structure (Lichtenegger et al. 2003; Birkedal et al. 2006; Khan et al. 2006). The distributions of Br, I and Cl were explored near the jaw tip using SIMS from the surface to a depth of about 10 μm and found to be deficient in the first 1–2 μm (Figure 7d).

Protein is the most abundant constituent, comprising between 70 and 90% of the total mass. Since estimating the proportion of protein is done by amino acid analysis, all post-translational modifications resulting in derivatives not recognized or detected by the analyser would lower the estimated percentage by weight. Amino acid content is biased towards glycine and histidine (36 and 19 mol%, respectively, in whole jaws; Broomell et al. 2006), whereas, as revealed by analysis of small jaw sections, important differences in the content of some residues exist. Figure 8 demonstrates that histidine concentration increases towards the tip and toothed-edge of the jaw (Birkedal et al. 2006). The opposite trend is observed for alanine; levels increase towards the jaw base. Concentrations of other predominant amino acids (tyrosine and aspartate) do not vary within the jaw. These results suggest that the jaw is made up of at least two, but probably more, proteins with distinct compositions and distribution.
profiles. Extractable protein accounts for only 0.1% of the total jaw mass. The major protein extractable from the jaw has a mass of about 35 kDa and a composition in which both glycine and histidine approach 30 mol% (Broomell & Waite in preparation). This is likely to predominate at the tip.

Recent evidence suggests considerable post-translational modification of nereid jaw proteins. Halogenation of both tyrosine and histidine are prevalent, but DOPA and aryl coupling products, e.g. di- and trityrosines, are also detectable (Birkedal et al. 2006). The biochemical reactions responsible for these modifications in the jaws have not yet been determined. Both halogenation and cross-linking of tyrosine residues are often mediated by peroxidase activity, which has been histochemically detected in situ (Edelhoch & Lippoldt 1962; C. Broomell, unpublished data). It is possible that either modification is a byproduct of the other (i.e. intentional cross-linking results in inadvertent halogenation or vice versa). However, the distinct distribution of each halogen suggests that jaw protein modification involves multiple specific processes. Although the functional consequences of such activity are unclear, a multi-step modification process may be advantageous for two main reasons: (i) mechanical/chemical properties can be changed at the regional level without having to change the general protein expression profile and (ii) properties can be modulated later in development (i.e. after jaw material is deposited), perhaps assisting with remodelling or repair. Establishment of halogenation at the jaw periphery, for example, could diminish susceptibility to degradation by chemical or microbial attack (Myneni 2002).

Non-mineral Zn accounts for roughly 2% of the total jaw mass (Bryan & Gibbs 1979a). Results of X-ray absorption spectroscopy suggest a single metal coordination environment with each Zn ion bound by three histidine residues and a chloride ion thereby resembling the coordination environment in the Zn insulin hexamer (Lichtenegger et al. 2003). Since early studies on the composition of Nereis jaws were conducted on specimens from polluted estuaries in the UK, it was initially proposed that the jaws might serve as a metal-sink, sequestering toxic levels of Zn absorbed from the sediment away from the living tissue (Bryan & Gibbs 1979b). Further observations demonstrated that Zn levels in jaws were high, regardless of environmental context, leading to the hypothesis that metals might contribute to their mechanical properties. Several lines of evidence support this hypothesis. Zn levels increase (approaching 10%) towards the tip and toothed-edges of the jaw—both regions that need to be hard in vivo. Both hardness and modulus increase with Zn content in jaws (Lichtenegger et al. 2003). Most importantly, removal of Zn by chelation with EDTA causes a nearly 80% reduction in both H and E (Broomell et al. 2006). Both properties are almost completely restored following reintroduction of Zn into the jaw matrix (figure 9). Taken together, these data support the view that Zn is an essential ingredient for endowing the Nereis jaw with its mechanical robustness.

A comparison of H and E for Nereis jaw tips with other biomaterials and polymers is shown in figures 5 and 6. As for the squid beak, the expected abrasion resistance, characterized by $H^{2}/E^{2}$, is higher than that for dentin and comparable to that of the best engineering polymers.
3.3. Glycera jaws: composite of protein, melanin, mineral and metal ions

The four fangs comprising the jaw of the marine worm Glycera are instruments that serve the dual purpose of grasping and injection. The fangs are hollow, like a syringe, with one major and several accessory apertures for release of venom (figure 10a; Michel 1970; Meunier et al. 2002). The jaws consist of melanin, protein, atacamite mineral (Cu₂Cl(OH)₃) and Cu ions (Gibbs & Bryan 1979; Lichtenegger et al. 2002, 2005; Moses et al. in press). Melanin comprises about 40% of the jaws by dry weight. Moreover, it exists as a contiguous phase throughout the jaw and is arranged in sheets approximately 200 nm thick, oriented perpendicular to the long axis of the jaw (Moses et al. submitted; figure 10a). Protein comprises 40–45% of the jaws by dry weight. Although the protein is distributed throughout the jaws, the His content is elevated near the jaw tips, where it approaches 25 mol%. A high degree of chemical and physical intimacy between the His-rich domains of the protein and the melanin is suggested by the fact that, following exhaustive hydrolytic removal of all proteins, the remaining microstructure still retains the essential features of the pristine jaw (Moses et al. in press). Atacamite mineral accounts for less than 10% of the jaws by dry weight. The mineral is arranged as fine fibres, located near the outer surfaces of the jaw tip and oriented parallel to the outer surface (Lichtenegger et al. 2002). Distinct from atacamite, Cu ions also appear to be localized to the near-surface layers in the jaw tips (figure 10b; Lichtenegger et al. 2005).

Given the relatively sparse mineralization, the high stiffness of Glycera jaws suggests a densely cross-linked structure. Assuming that Cu ions play a role analogous to that of Zn in Nereis jaws, we have been keen to measure the mechanical consequences of Cu removal. Unfortunately, typical chelate-based metal ion depletion strategies do not dislodge Cu ions from Glycera jaws. While EDTA treatments for 3 days typically suffice to demineralize bone and teeth and remove Zn from Nereis jaws, EDTA treatment of Glycera jaws for as long as 2 weeks does not remove detectable levels of Cu (Moses et al. 2006; figure 10c). It is unlikely that the affinity of Cu binding to His-rich domains would exceed that of Cu–EDTA (Dawson et al. 1986), but the extreme stability of the Cu–melanin complex is well known (Szpoganicz et al. 2002). At present, we propose that at least some of the Cu connects the melanin to which it is tightly bound and the His-rich domains to which it is less tightly coordinated. It does not seem probable that Cu cross-links melanin polymers in the jaws because the melanin component was still stiff after the metal (and everything else) had been removed by extended hydrolysis in strong acid. The remarkable cohesion within the melanin of the jaw has been attributed to π–π interactions in the interior and H-bonding along the edges of stacked, highly aromatic sheets of polyhydroxyindoles (Stark et al. 2005). Whether the high aromaticity or degree of cross-linking mitigates the mechanical response of jaws to hydration is not known; although the hardness and modulus of human dentin exhibit 50% reductions when hydrated, the corresponding property changes in Glycera jaws are only about 20% (Ho et al. 2004; Moses et al. 2006).

Nanoindentation tests indicate that the highest values of H (0.8–0.9 GPa) and E (9–10 GPa) are obtained in regions with high Cu and Cl content (figure 11). The implication is that atacamite fibres...
and Cu ions near the jaw tip play a significant structural role (Moses et al. 2006). This hypothesis is further supported by the observation that these ions are most abundant in the near-surface regions of the jaw tips; precisely where the abrasive forces will be highest during penetration into prey and hence the mechanical properties will be most crucial. Additionally, nanoindentation tests performed on the acid-resistant melanin relics of Glycera jaws indicate that both the hardness and the modulus of the melanin alone are approximately one-half of those of the pristine structure (Moses et al. 2006). The retention of the jaw shape following exhaustive hydrolysis suggests that the hydrolysed constituents (including minerals, metal ions and proteins) intercalate and interpenetrate a contiguous melanin scaffold (Moses et al. submitted). The implications of these arrangements for mechanical robustness have yet to be ascertained.

Based on property measurements under both wet and dry conditions, Glycera jaws exhibit similar mechanical characteristics to those of the Nereis jaws (figures 5 and 6). Hence, their abrasion resistance is expected to be similar as well.

4. CONCLUSIONS

The hardened mouthparts of two polychaete worms and a squid share similar mechanical properties and protein compositions rich in glycine and histidine. The histidine content—ranging from 12 to 25 mol%—is elevated well above the protein average of 2% (Creighton 1993), thus suggesting a role crucial in function. Histidine serves many pivotal roles in protein function including catalysis (histidine containing triads and metal prostheses), metal storage and detoxification (histidine ligands), and pH-dependent triggers of conformational change (histidine ionization). While it is probable that histidine-rich proteins have been adaptively co-opted by these organisms to optimize some aspect of jaw performance, there does not appear to be a single underlying mechanism for accomplishing this end.

In Nereis, a major matrix protein with histidine levels at 30 mol% appears to be a polydentate ligand for Zn$^2+$. Both hardness and stiffness are greatly reduced by the removal of Zn$^2+$ and restored by re-exposure to Zn$^2+$. Zn$^2+$ is thus a reversible cross-linker, in contrast to the dityrosines also present in the structure. Despite the abundance of histidine in Dosidicus beak proteins, no metals are present. The sclerotization of beak may parallel histidine-rich insect cuticles, where histidyl side chains are proposed to be nucleophiles of catechol-derived quinones that lead to covalent cross-links (Kerwin et al. 1999a). While plausible, this hypothesis remains largely unproven. Strong hydrogen bonding between histidine and polyphenols is also possible (Wróblewski et al. 2001). Like insect cuticles, squid beak contains both catechols (in the form of peptidyl-DOPA) and chitin (Hunt & Nixon 1981).

The picture is even more complex in the jaws of Glycera, where histidine-rich proteins coexist with melanin, mineral and Cu ions (figure 12). The contribution of Cu ions to hardness and stiffness is difficult to ascertain, since no known chelator is strong enough to dislodge the Cu. Moreover, even after exhaustive acid hydrolysis has removed all the protein, mineral and metal ions, the remaining melanin retains over 50% of the hardness and stiffness of pristine jaws.

This review of structure–property relationships has focused on compositional structure, particularly with regard to histidine content. Fibre orientation is also of tremendous importance to fracture toughness in biocomposites (Neville 1993; Currey 2002). Of the three materials covered, only Dosidicus beak was large enough to allow toughness measurements and the observed magnitude of these is quite consistent with the laminate construction (figure 2) that is reminiscent of stiff insect cuticles, e.g. locust femur (Neville 1993). Indeed, preferential fibre orientation is evident in all three structures from the tightly bundled fibres of Nereis jaws to the neatly stacked lamellae in both Glycera and Dosidicus jaws (figures 2, 7 and 10). While in Nereis jaw the His-rich proteins may contribute to both the fibre and the matrix, in Glycera and Dosidicus the His-rich proteins appear to be dispersed between the melanin sheets and chitin fibres, respectively, which form the continuous network.
Figure 11. Hardness and modulus maps of the tip region of a *Glycera* jaw, measured while the sample was submerged in water. The regions of high hardness and modulus near the surface are rich in Cu and Cl. Adapted from Moses *et al.* (2006).

Figure 12. Glycine and histidine (HIS)-rich proteins appear to be unusually versatile for combining with minerals, metal ions and other organic polymers like chitin or melanin for construction of load-bearing sclerotized materials. Fibre orientation would add another level for controlling properties.

of the interrelationships between architecture at different scales and the nanomechanical properties of these materials remains to be done.

In summary, histidine plays as diverse a role in stabilizing the load-bearing biomacromolecules of *Nereis*, *Glycera* and *Dosidicus* as it does in proteins generally. Further exploration of the functional versatility of imidazoles in molecular scaffolds is expected to yield new insights into the mechanisms through which mechanical functionality is endowed in non-mineralized structures. Although it would be a mistake to assume that all load- and impact-bearing structures contain histidine-rich proteins, their occurrence in other load-bearing biomaterials is noteworthy. For instance, a histidine-rich protein, amelogenin, is the major organic component in tooth enamel (Paine *et al.* 2001), and spinaulin, with nearly 20 mol% histidine, dominates the ballistic nematocyst spines of *Hydra* (Koch *et al.* 1998).

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