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DECAY AND MINERALIZATION IN SOFT-TISSUE FOSSILIZATION

Introduction

The term 'soft tissue', as used here, incorporates all tissues that are not biomineralized in life. This includes a spectrum from decay resistant organic tissues, like the cuticles of animals and plants, to more labile tissues such as muscle, which are rapidly degraded. The former may resist decay long enough to become incorporated into the sedimentary record as organic materials. Preservation of the latter, on the other hand, requires replication by authigenic minerals at an early stage. Our understanding of both these processes has advanced significantly in the last few years.

Organic preservation

The preservation of macrofossils as organic remains generally has been attributed to the decay resistant properties of structural macromolecules such as ligno-cellulose, cutan and algaenan in plants, and chitin in animals. Evidence in support of this has been obtained through the analysis of fossils using flash pyrolysis in combination with gas chromatography and/or mass spectrometry. This has shown that certain plant fossils, for example, yield highly aliphatic biopolymers (*n*-alk-1-enes and *n*-alkanes) such as 'cutan' which are very similar to those in some of the tissues of their living counterparts. This is the basis for the model of 'selective preservation', i.e. taxa that originally contained a high content of aliphatic macromolecular material are major contributors to sedimentary organic matter, and are more likely to be represented as fossils (Tegelaar *et al.* 1991).

Some of the most common organic animal remains in the fossil record are arthropod cuticles. Younger fossil examples preserve traces of the more resistant elements of the original chitin-protein complex that made up the cuticle; the earliest traces yet discovered are Oligocene in age, from the 25 my old Enspel lacustrine deposit in Germany (Stankiewicz *et al.* 1997). Older fossil arthropods, however, are dramatically altered and often yield an aliphatic signature, which is similar to that of many plant fossils (Briggs *et al.* 1998). Insoluble aliphatic macromolecules are not known from the exoskeletons of modern arthropods so their preservation as organic fossils cannot be explained by selective preservation. The convergence in the macromolecular composition of plant and animal cuticles is difficult to explain based on their original constituents. The aliphatic composition of fossil arthropod cuticles must be the result of a diagenetic process, involving polymerization (see Briggs 1999). It is now evident that a similar process was involved in the preservation of some plant cuticles (Collinson *et al.* 1998).

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Authigenic mineralization

More decay resistant organic tissues can survive long enough to be transformed into aliphatic macromolecules, while retaining the morphological integrity which makes them identifiable as fossils. Labile tissues, like muscle, degrade rapidly and the information loss that this causes can only be prevented by mineralization. Phosphate minerals normally perform this function, but it can involve a range of other minerals including calcite, pyrite, silica, siderite and clay minerals. The precipitation of minerals is driven by microbial processes - surprisingly, perhaps, some decay is essential for preservation.

The fossilization of soft-bodied organisms commonly involves decay, replication by authigenic minerals, and the survival (and subsequent transformation by diagenesis) of some organic materials. This is illustrated by recent analyses of specimens from the Cambrian Burgess Shale of British Columbia (Orr *et al.* 1998). It has long been known that the Burgess Shale fossils are preserved, at least partly, as organic carbon. Less well known has been the role of the clays associated with the specimens. Elemental mapping allows the relative abundance of elements in different parts of the Burgess Shale fossils, and the surrounding matrix, to be determined. Such maps provide images which show the fossils standing out in contrast to the matrix. More importantly there is clear variation within specimens; the relative abundance of elements varies dramatically between different anatomical features. These differences reflect the composition of the clay minerals that replicated the decaying organism, which were controlled by contrasts in tissue chemistry. Delicate morphological details are clearly replicated in the elemental maps (Orr *et al.* 1998).

Much rarer than preservation in clay minerals is the extensive fossilization of soft tissues in pyrite. The best known example is the Devonian Hunsrück Slate (Bartels *et al.* 1998). A combination of rapid burial and sediment chemistry explains the pyritization (Briggs *et al.* 1996). Turbidity currents resulted in burial of the Hunsrück Slate organisms in a variety of orientations to bedding. Rapid setting of the clay-rich sediment eliminated most scavengers (Sutcliffe *et al.* 1999). The water column was oxygenated. The high concentration of iron was the critical factor. The new availability of *ca* $18m^3$ of Hunsrück Slate columns from Bundenbach, as well as 150m of core through the sequence, provides an opportunity to address a range of new questions on the mineralization of the fossils, and on the factors controlling pyritization in general. For the first time it will be possible to relate the mineralization of the fossils to their place in the sedimentary sequence. Systematic splitting and sampling will allow an investigation of the relationship between the pyritization of the fossils and: (1) depositional conditions, as evidenced by sedimentology and trace fossils; (2) sediment chemistry, particularly iron content; (3) oxygen levels, as revealed by framboid size; and (4) diagenetic processes. In the Jurassic of La Voulte-sur-Rhône, one of the small number of other localities where soft-tissue pyritization is known, pyrite is a diagenetic replacement after more rapidly formed apatite which replicated the soft tissues in the first instance (Wilby *et al.* 1996). The possibility that preservation of the soft tissues in the Hunsrück Slate also involved other minerals, possibly formed in sequence, remains to be investigated.

Conclusion

Soft-tissue fossilization relies on the microbial processes that cause decay and drive mineralization. Labile tissues are only preserved where authigenic mineralization occurs. Macromolecular material may be selectively preserved, but the long-term preservation of organic macrofossils involves diagenetic alteration.

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