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SOUPY SUBSTRATES AS MEDIA FOR EXCEPTIONAL FOSSIL PRESERVATION: A MODEL FOR THEIR OCCURRENCE

Exceptional preservation of fossils, including retention of articulated skeletons, preservation of soft tissues, stomach and intestinal contents, is usually attributed to rapid burial followed by very early diagenesis. For many conservation Lagerstätte net sedimentation rates appear to be very low (mm per thousand years) and evidence for episodically high rates of sedimentation, such as turbidites, is often lacking (Hudson & Martill, 1991). However, rapid burial may be achieved without high rates of sedimentation when sediment pore waters are under pressure (e.g. flux from buried aquifers) or when sediments contain more pore water than sediment (soup grounds). Such sediments may allow for the intrusion of carcasses descending from the nekton and is equivalent to rapid burial but will result in a distinct suite of taphonomic features. The sinking of carcasses into soupy substrates results in near instantaneous injection of the carcass into bacterially active diagenetic regimes, such as the sulphate reduction zone, resulting in extremely early diagenesis. Long term maintenance of soup grounds may also allow for limited concentration of carcasses over prolonged periods.

Petrographic analyses of lithologies considered to have been originally soup grounds can be achieved by examination of early diagenetic concretions. Such concretions often preserve the original fabric and together with the enclosed three-dimensional fossils, may reveal suites of minerals allowing diagenetic sequences to be mapped. For the Oxford Clay Formation, that part of the sequence yielding exceptionally preserved marine vertebrates was originally pelletised sediment with pellets ranging from a few tens of microns to several millimetres in diameter. Some pellets were composites representing loose aggregations of smaller agglutinated pellets. Thus the sediment had both inter and intra granular porosity. Pore fluid pressure may have been high due to an underlying aquifer (Kellaways Sand).

The accumulation of pelletal soup grounds depended on at least two factors. Firstly, high productivity was required for pellet production, possibly in the surface waters, (but probably also on the sea floor), and secondly relatively quiet conditions were required such that pellets were not destroyed by wave or current activity.

High productivity in surface waters is indicated by high TOC content (4-15%) and often occurs during marine transgressions when mineral nutrient input is high as coastal plain sediments are reworked (Pederson & Calvert 1990). Preservation of pelletal substrates

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does not occur however until waters reach a depth of approximately 100 metres. At this depth pellets survive most normal storm events and can accumulate below normal storm wave base. Input of pellets to the accumulation zone can be by direct descent from surface water but is more probably by lateral movement from shallow regions into deeper parts of the basin. As the marine transgression continues pelletal soup grounds become covered with normal calcareous clays.

Such pelletal deposits are unlikely to occur during regressive phases as nutrient input drops resulting in lower productivity, but even if they were generated, such sediments would be easily reworked as sea level falls. Thus high TOC pelletal soup ground conservation Lagerstätte (SGCL's) only occur in transgressive system tracts and are found in those parts of the section that represent the first sediments deposited below storm wave base. They are also likely to be diachronous over wide areas.

This model for the accumulation and stratigraphic occurrence of pelletal SGCL may be a predictive tool for identifying exceptional fossil deposits. Using postulated sea level curves for the Jurassic, it can be seen that there are five long term marine transgressions (Haq et al., 1987). Marine mudstones with high TOC and which are well-known for their well preserved fossil vertebrates occur just after the initiation of each marine transgression except one. These are the Blue Lias (Hettangian), the Posidonia Shales and Jet Rock (Toarcian), the Peterborough Member of the Oxford Clay (Callovian) and the Kimmeridge Clay (Kimmeridgian).

This simplistic model requires further scrutiny as there are a number of marine transgressions in the Mesozoic that appear to lack Lagerstätte where they would be predicted to be. Their absence may be due to local conditions, or to biological/ecological factors. For example, the marine transgression at the end of the Triassic in southern England certainly generated an organic rich mudrock (the Westbury Formation) but it is famous for a concentration Lagerstätte (the so-called Rhaetic Bone Bed); articulated material of high preservation quality has yet to be discovered in this formation.

Soup grounds compact by several orders of magnitude and as such criteria for their recognition may be difficult to discern. Where early diagenetic concretion formation has occurred, soup grounds can be recognised by: an abundance of fossils in concretions at high angles to bedding; by the deformation of sedimentary structures adjacent to the carcass and by the intrusion and leakage of sediment into the body cavity through natural openings and punctures of the body wall. When compaction has been intense such features may be difficult to recognise and many fossils that may have been at a high angle to bedding are rotated into a near horizontal position.

Failure to recognise soup grounds as a medium for exceptional preservation may in part be due to the somewhat polarised debate regarding the role of anoxia in bottom waters. In the Posidonia Shales of Germany debates over the position and depth of the O_2 minimum zone tended to ignore the relevance of substrate consistency as an important taphonomic agency (see Martill, 1993). Soup grounds can inhibit the establishment of benthic communities that require purchase for locomotion or burrowing. Thus, only animals able to 'swim' through sediment or able to spread their weight would be able to colonise such substrates. As few organisms appear to be able to do this, soup grounds have very low benthic diversity index. In addition, the limiting of benthos may result in the accumulation of nektonic organic matter due to lack of macrophages, resulting in black shale generation, perhaps without anoxic bottom water (only the pore water need be anoxic).

In the nodule bearing Romualdo Member of the Santana Formation evidence for the intrusion of sinking carcasses into the sediment is well known and easily demonstrated (Martill 1998). In highly compacted lithologies, such as the Middle Jurassic Oxford Clay evidence that substrates may have been soupy is more difficult to track down. The rare occurrence of ichthyosaurs with their rostra at a high angle to bedding and with differential preservation of the lower part of the carcass are the most convincing lines of evidence, but such specimens were rarely collected on slabs and most important taphonomic evidence was destroyed during collection. Such features are much better seen in the ichthyosaurs from the Posidonia Shales. Are soupy substrates of importance in lithographic limestones? The Crato Formation of Brazil yields an abundance of fossils, most of which lie in the plane of the bedding. It has suffered intense compaction, and early diagenesis appears to have been restricted to some early pyrite formation followed by later dolomitization. Evidence for deep penetration by the larger tetrapods has not been forthcoming and it is likely that the sediment was not soupy to any great depth. However, numerous insects are preserved three dimensionally and with limbs penetrating into the sediment, suggesting that the top few millimetres may have been soupy.

The Nova Olinda Member of the Crato Formation can be termed a plattenkalk, but is probably more akin to a laminated black shale than to a lithographic limestone *sensu stricto*. At present it is unclear if soupy substrates are involved in fossil burial in true lithographic limestones.

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