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Biological Signatures in the Rock Record

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We live in an age of unprecedented interest in life as a planetary phenomenon, fuelled both by strengthening research in Earth system science and by cautious optimism that questions of extraterrestrial biology may be tractable. In the guiding mantra of nascent astrobiology, life is born of planetary processes, is sustained by planetary processes, and, through time, can emerge as a set of planetary processes that is important in its own right. This perspective prompts us to believe that life may be distributed widely in the universe, arising wherever and whenever the right physical conditions obtain. It also suggests that where life thrives and persists, it will leave an interpretable signature in the rock record. On Earth, life has indeed left an unambiguous imprint in sedimentary rocks, permitting a reconstruction of biological history that is in fair concord with evolutionary and environmental inferences drawn from molecular phylogenies. Conventional palaeontology provides a rich record of unambiguously biological morphologies that range from mammal teeth to cyano-bacterial trichomes. Biogeochemistry adds biomarker molecules and biologically interpretable variations in isotopic abundances. Sedimentologists recognize the imprint of organisms in bio-turbation, biogenic minerals and sediments, and some (but not all) stromatolites. In all cases, the methodology of interpretation is the same. Morphological or chemical signatures are identified as biological if they display features known to be produced by living organisms, but not known as products of physical processes. Interpretation is based on insights from comparative biology, constrained by information on age and environment. Despite the success of palaeontology and geobiology, NASA contends that unambiguous bio-indicators have yet to be discovered. What they mean, of course, is that we have no assurance that biological signatures preserved in terrestrial rocks will prove general. At one level, this caution is admirable: while everyday experience suggests that the gulf between biology and the physical world is large, this impression arises because the biology most familiar to us is that of organisms found on distal branches of the tree of life. The problem of distinguishing biological from abiological lies at the other end of the tree, and in the earliest phases of biological diversification. Insofar as life originated by means of planetary processes, we must almost inevitably conclude that patterns formed by a planet's earliest biological entities will not easily be distinguished from physico-chemical patterns. On the other hand, paleontology and geobiology thrive precisely because terrestrial rocks are replete with unambiguous biological signatures. Early in Earth history, evolution fashioned morphologies than cannot be duplicated by physical processes, organic molecules of diagnostically biological composition, and isotopic signatures that taken in context permit confident biological interpretation. Building a more complete catalogue of terrestrial bio-signatures is a worthy goal, but it will not by itself solve the problem of bio-detection on other planets. The range of morphological and chemical patterns produced by contemporary organisms reflects four billion years of adaptation and extinction, and does not necessarily circumscribe the biological potential of organisms in other places or near the dawn of life. For this reason, our meter stick for evaluating potentially biological features of Martian or other extraterrestrial samples must be the limits on pattern generation by physical processes. Features found in rocks can be accepted as evidence of life only if they are incompatible with formation by physico-chemical processes. The ranges of morphological or chemical patterns generated by biological and non-biological processes overlap, so there will inevitably be an interpretational grey zone. At present, we don't know the limits of biological pattern formation; nor do we know the limits of abiological pattern formation. Until we do, the dimensions of the grey zone will remain uncertain.