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Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation

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ABSTRACT

The study of the role that fungi have played and are playing in fundamental geological processes can be termed 'geomycology' and this article seeks to emphasize the fundamental importance of fungi in several key areas. These include organic and inorganic transformations and element cycling, rock and mineral transformations, bioweathering, mycogenic mineral formation, fungal–clay interactions, metal–fungal interactions, and the significance of such processes in the environment and their relevance to areas of environmental biotechnology such as bioremediation. Fungi are intimately involved in biogeochemical transformations at local and global scales, and although such transformations occur in both aquatic and terrestrial habitats, it is the latter environment where fungi probably have the greatest influence. Within terrestrial aerobic ecosystems, fungi may exert an especially profound influence on biogeochemical processes, particularly when considering soil, rock and mineral surfaces, and the plant root–soil interface. The geochemical transformations that take place can influence plant productivity and the mobility of toxic elements and substances, and are therefore of considerable socio-economic relevance, including human health. Of special significance are the mutualistic symbioses, lichens and mycorrhizas. Some of the fungal transformations discussed have beneficial applications in environmental biotechnology, e.g. in metal leaching, recovery and detoxification, and xenobiotic and organic pollutant degradation. They may also result in adverse effects when these processes are associated with the degradation of foodstuffs, natural products, and building materials, including wood, stone and concrete. It is clear that a multidisciplinary approach is essential to understand fully all the phenomena encompassed within geomycology, and it is hoped that this review will serve to catalyse further research, as well as stimulate interest in an area of mycology of global significance.

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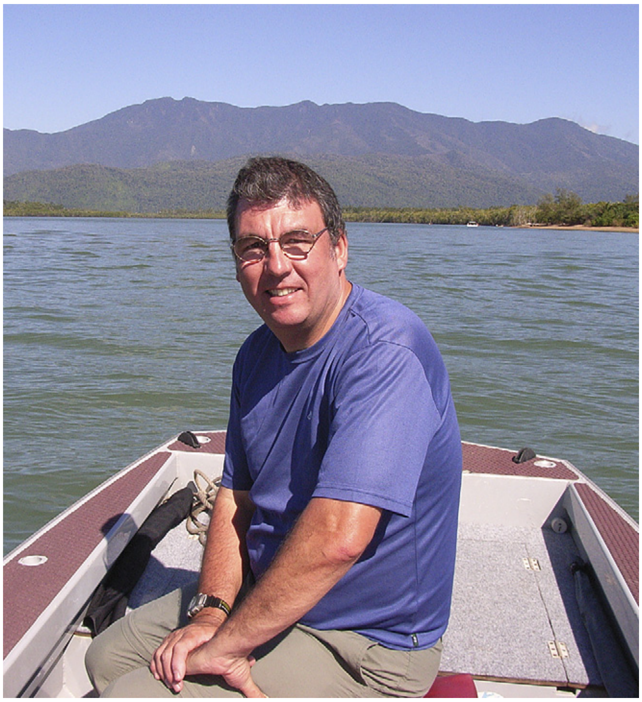

Fig 1 – Geoffrey Michael Gadd (President, British Mycological Society 2004–2006).

Introduction

Fungi are chemoheterotrophic organisms, ubiquitous in subaerial and subsoil environments, and important as decomposers, animal and plant mutualistic symbionts and pathogens, and spoilage organisms of natural and manufactured materials (Gadd 1993a, 1999, 2006; Burford *et al.* 2003a). They also have a role in the maintenance of soil structure, due to their filamentous branching growth habit and frequent exopolymer production. A fungal role in biogeochemical cycling of the elements (e.g. carbon, nitrogen, phosphorus, sulphur, metals) is obvious and interlinked with the ability to adopt a variety of growth, metabolic and morphological strategies, their adaptive capabilities to environmental extremes and, their mutualistic associations with animals, plants, algae and cyanobacteria (Burford *et al.* 2003a; Gadd 2004; Braissant *et al.* 2004; Fomina *et al.* 2005a). Fungal polymorphism and reproduction by spores underpin successful colonization of many different environments. Most fungi exhibit a filamentous growth habit, which provides the ability to adopt both explorative or exploitative growth strategies, and the formation of linear organs of aggregated hyphae for protected fungal translocation (Fomina *et al.* 2005a, 2005b). Some fungi are polymorphic, occurring as both filamentous mycelium and unicellular yeasts or yeast-like cells, as in black meristematic or microcolonial fungi colonizing rocks (Sterflinger 2000; Gorbushina *et al.* 2002a, 2002b, 2003). Fungi can also grow inside their own parental hyphae, utilizing dead parts of the colony under the protection of parental cell walls (Gorbushina *et al.* 2003). The ability of fungi to translocate nutrients through the mycelial network is another important feature for exploring heterogeneous environments (Lindahl & Olsson 2004; Jacobs *et al.* 2002a, 2002b, 2004; Boswell *et al.* 2002, 2003, 2006).

However, a broader appreciation of fungi as agents of biogeochemical change is lacking, and apart from obvious connections with the carbon cycle, they are frequently neglected within broader microbiological and geochemical research contexts. While the profound geochemical activities of bacteria and archaea receive considerable attention, especially in relation to carbon-limited and/or anaerobic environments (Gadd *et al.* 2005a), in aerobic environments fungi are of great importance, especially when considering rock surfaces, soil and the plant root–soil interface (Fig 2, Table 1) (Gadd 2005, 2006; Fomina *et al.* 2005a, 2005b; Gadd *et al.* 2005a, 2005b, 2006). For example, mycorrhizal fungi are associated with ~80 % of plant species, and are involved in major mineral transformations and redistributions of inorganic nutrients, e.g. essential metals and phosphate, as well as carbon flow (Paris *et al.* 1995; Hoffland *et al.* 2002; Fomina *et al.* 2004, 2005b). Free-living fungi have major roles in the decomposition of plant and other organic materials, including xenobiotics, as well as mineral solubilization (Gadd 2004). Lichens (a fungal growth form comprising a mutualistic symbiosis between an alga and/or cyanobacterium and a fungus) are one of the commonest members of the microbial consortia, inhabiting exposed rock substrates, and play fundamental roles in early stages of rock colonization and mineral soil formation. Fungi are also major biodeterioration agents of stone, wood, plaster, cement and other building materials, and it is now realized that they are important components of rock-inhabiting microbial communities with significant roles in mineral dissolution and secondary mineral formation (Hughes and Lawley 2003; Burford *et al.* 2003a, 2003b, 2006; Fomina *et al.* 2005a, 2005b). There is even some evidence that several fungi can dissolve minerals and mobilize metals at higher pH values, and over a wider redox range,

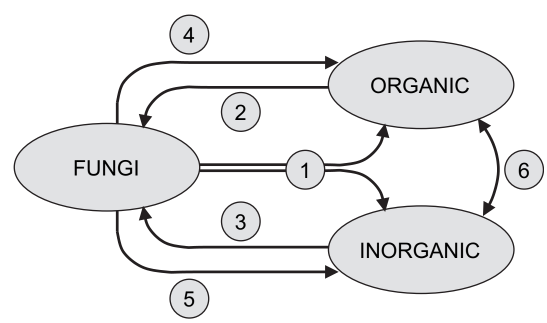

Fig 2 – Simple model of fungal action on naturally-occurring and/or anthropogenically-derived organic and inorganic substrates. (1) Organic and inorganic transformations mediated by enzymes and metabolites, e.g. protons (H^+), carbon dioxide (CO_2), and organic acids, and physicochemical changes occurring as a result of metabolism; (2) uptake, metabolism or degradation of organic substrates; (3) uptake, accumulation, sorption, metabolism of inorganic substrates; (4) production of organic metabolites, exopolymers, and biomass; (5) production of inorganic metabolites, secondary minerals and transformed metal(loid)s; and (6) chemical interactions between organic and inorganic substances, e.g. complexation and chelation (from Gadd 2004).