Weathering (Part 2)

Weathering is a key geomorphic process which shapes all natural landscapes; this is the second of two articles which describe the processes of weathering (the first (GNS News, June 2023) dealt with mechanical and chemical weathering) whilst this one focusses on biological weathering.

Biological weathering involves the decomposition of rock by physical and chemical processes resulting from the activities of plants, micro-organisms, and animals. Before turning to the role of plants and their associated micro-organisms in more detail, a brief summary of the kinds of physical bio-weathering achieved by some 'larger' organisms is in order:-

Fig. 1: The power of biological weathering. A: the birch tree has split the boulder, Altai Mts. (www.dreamstime.com/photos-images/tree-roots-split-boulder); B: Hawthorn tree has split the limestone outcrop, Cleeve Hill.

- Tree roots: seeds of trees can be deposited in cracks in rock outcrops or boulders by birds or by the wind, and as the plant grows, its trunk and/or its roots become bigger and bigger, and they can eventually split the rock (Figs. 1A, 1B).
- Marine molluscs: can bore holes into rock in the inter-tidal zone, and accelerate beach-rock erosion (Fig. 2).
- Trampling: by cattle and other large herbivores can compact the soil, and also cause erosion, especially at watering holes, due to bank collapse (Fig. 3).
- Stripping of vegetation: by sheep and goats for example. In arid climates, over-grazing is a major cause of 'desertification'. Man should also be included here: the effect of man's pursuit of ever more efficient agriculture has, from Neolithic times to the present,

Fig. 2: Molluscs in their burrows bored into the rock in the intertidal zone. (From Wikipedia)

Fig. 3: River bank trampled by cattle coming down to drink (Daylesford Brook).

resulted in forest clearance and ploughing, which leads to higher soil temperatures, soil erosion, and increased areas of rock exposed to weathering.

- Termites and ants in warm climates, and earthworms in temperate climates, have a huge beneficial effect in aerating and turning over the soil, but they can also render it more susceptible to erosion.

Plants and their associated 'micro-organisms': their impact on Earth history

There is strong evidence that micro-organism evolution has had a major impact on Earth's history, initially (and most dramatically) with the Great Oxidation Event (GOE, ~2.3 billion years ago), during which the earth's atmosphere changed from one that was almost devoid of oxygen to one that contained a low level (~5%) of free oxygen. This was caused by the evolution of oxygen-producing photosynthesis by cyanobacteria, and although this was not a weathering process *per se*, it was a trigger for the evolution of oxygen-metabolising plants and animals, and consequently for most biological weathering which has helped mould the Earth's surface since then. Most of the oxygen formed in the GOE was absorbed into the oceans, and resulted in the formation of massive iron-ore deposits known as the Banded Iron Formation (Fig. 4), found in W. Australia, N. America, Brazil, and S. Africa.

These deposits arose due to the soluble ferrous (Fe^{2+}) ions in the primordial ocean being oxidised to insoluble ferric (Fe^{3+}) ions as the atmosphere and oceans became oxygenated, and the wholesale deposition of these insoluble iron compounds on the bed of the primordial seas (Finlay et al (2020)).

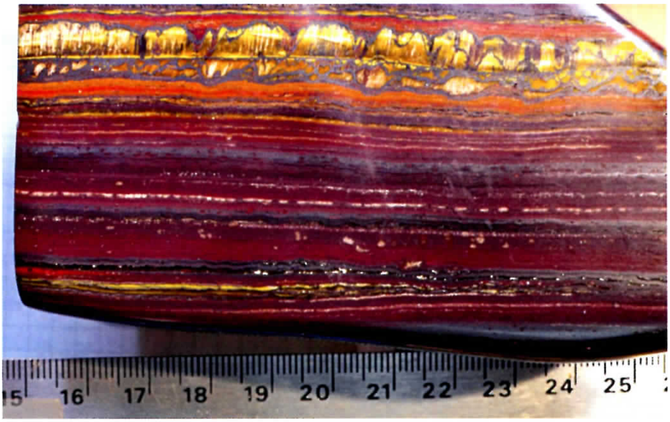

Fig. 4: Hand specimen of Banded Iron Formation, ~2.3 billion years old. The reddish brown-black bands are (ferric) iron ore.

A further oxygen-liberating event occurred between ~800-600 million years ago during which oxygen levels in the atmosphere approached present-day levels (~20%), and CO2 correspondingly decreased. This event was due to the rapid evolution of marine, multi-cellular, cyanobacteria-bearing plankton in the oceans.

The next major, organism-driven, event occurred with the evolution of higher plants and the development of terrestrial vegetation. The first well-developed forests appeared in the Devonian period and are thought to be responsible for the huge drop in atmospheric CO2 levels ~400–360 million years ago (Fig. 5). Further reduction in atmospheric CO2 continued through the Carboniferous with the development of the Northern Hemisphere coal swamps, and into the Early Permian due to the Southern Hemisphere (Gondwanan) glaciation.

This Palaeozoic 'greening' of the Earth's landscapes resulted in a fundamental increase in weathering and nutrient availability and, incidentally, provided ecological niches (and food) for the evolution of land animals (Gibling and Davies, (2012)).

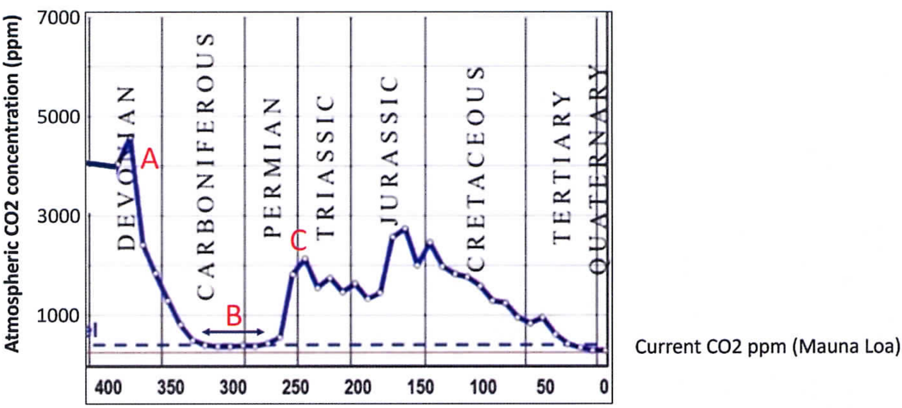

Fig. 5: Evolution of atmospheric CO2 levels over the last 400 million years (I). A = Devonian advent of terrestrial forests, causing massive drop in CO2 levels. B = Low CO2 levels continue due to Carboniferous coal swamps and Early Permian ice age. C = Major rise in CO2 levels due to massive volcanism and Permo-Triassic extinction event.

Plants and their associated 'micro-organisms': their role in present-day weathering and soil formation.

Bio-weathering due to micro-organisms operating at and below ground level is arguably the most important weathering process of all, because:-

1. It releases essential nutrients from rocks and minerals, and makes them available to other plants and animals. This is important because although organic nutrients can be made available by the decomposition of organic material, and carbon dioxide and oxygen are available from the atmosphere, the availability of base cations (e.g. Calcium, Magnesium, Potassium, Phosphorus etc.) and trace elements can only come from the weathering of soil and its parent material (minerals and rocks), dominantly by micro-organisms, especially cyanobacteria (Finlay et al (2020)).
2. It produces clay minerals from the parent rock which, together with humic material and silt / sand, forms soil – providing other plants with a stable growing medium and a supply of bio-available nutrients.
3. It acts as a carbon sink – withdrawing CO2 from the atmosphere and sequestering it as carbonate and bio-carbonate compounds.

These processes work regardless of the nature of the rock / mineral substrate, but do leave soils which reflect the underlying geology, i.e. the light, thin soils of the Cotswold 'brash' on the High Wolds; the heavy, poorly-drained clayey soils of the pastures around Moreton in Marsh (glacial clay) and some dip-slope river valleys (Liassic shales); and the fertile alluvial soils of the lowland water meadows.

The most important micro-organisms in this soil-forming weathering process are cyanobacteria, and those associated with mosses and lichens, which together are the vital 'first colonisers' of virgin landscapes. This can be seen, for example, in the way mosses and lichen progressively colonise Cotswold roofs (rFig. x) and gravestones (Fig. 7B), i.e. the extent of moss or lichen cover is an indication of the age of the substrate.

Fig. 6: Scanning electron micrograph of the surface of a mineral (feldspar) grain covered by grooves thought to be created by fungal hyphae (two visible). From Hoffland et al (2004). Each scale division = 1/100th of a millimetre.

Mosses are simple, non-vascular, flowerless plants, usually small and green, whereas lichens are not plants but an algal-fungal symbiosis: they are rarely green, and lack proper roots and leaves of any kind (see Robillard (2017)).

Mosses have leaflets made of photosynthetic cells (just like flowers and trees), but unlike vascular plants, mosses do not have specialized tissues to actively transport water and nutrients from below ground to the leaf tips and back. Instead mosses simply absorb water and nutrients. Mosses do not have proper roots, just thread-like rhizoids that anchor them to the substrate. The 'roots' of mosses harbour microbial/fungal rhizomes which provide (by chemical etching and dissolution) mineral nutrients to the moss. In turn the moss provides food to the fungus, and a favourable environment for microbial growth by providing UV protection and a suitably damp environment at the rock surface.

By contrast, lichens comprise a colony of algae surrounded above and below by fungal elements, in a mutually beneficial (symbiotic) relationship. The fungal element requires carbohydrate as a food source, whilst the algae requires shelter. The algae are photosynthetic and hence provide food to the fungi in return for shelter and a moist environment (Viles (2022)). This arrangement is paraphrased in the quotation:- *"Lichens are fungi that have discovered agriculture"* (Trevor Goward)

The basal surface of the lichen is often formed by a dense mat of fungal filaments and it lies on (and within) the mineral/rock substrate: the fungal filaments (hyphae) follow cracks, pores, and other spaces on mineral surfaces (Fig: 6).

In the case of both mosses and lichens, it is the 'root' system (fungal hyphae in the case of lichens, and rhizoids in the case of mosses) that is the agent that achieves the weathering - they can both corrode the mineral / substrate by chemical means and break up the mineral / substrate by expanding and contracting the hyphae / rhizoids during cycles of wetting and drying. Similarly with cyanobacteria: their colonisation of silicate rocks (sandstone, granite) is a worldwide phenomenon of arid climates (deserts, savannahs, steppes) and plays a major role in the biochemical weathering of the near-surface layers of these rocks (Olsson-Francis et al (2012)), accerating exfoliation (see Fig. 5 of previous article).

Several studies have shown that rock surfaces covered by lichen or mosses weather at a much faster rate than bare rock surfaces*, and also that lichens and mosses each create different assemblages of clays and other compounds from the same substrate, suggesting that, under certain conditions, a non-competitive strategy has evolved for maximizing the release of inorganic nutrients from the rock and making them bio-available in the soil (Jackson, 2015).

In addition to rock (outcrops, walls, gravestones etc. (Fig. 7)), lichens and mosses can grow on almost any other natural surface, including bark, leaves, and hanging from branches.

Note that all plant roots and tree roots have mycorrhizal fungi intimately associated with them. The fungi receive sugars from the parent plants and provide conduits for long-distance transport of weathering products (nutrition and moisture) back to the parent plants, and between one plant and other adjacent plants. Indeed a fungal network underlies the entire forest floor, as discovered by Simard (2021).

*This is not a reason or excuse for the removal of lichen or moss from their habitat. They can be protective from other forms of weathering, and should always be left in place.)

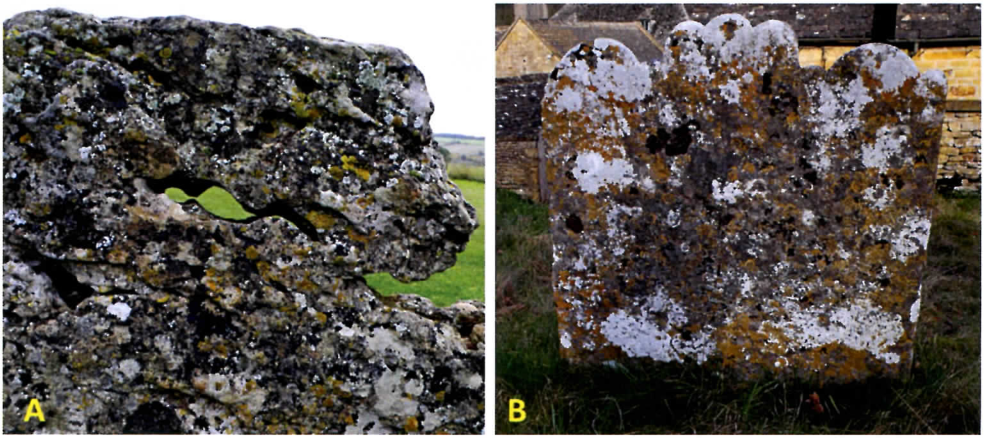

Fig. 7: Yellow, white, and black lichen growing on (A) the Rollright Stones, and (B) a gravestone in Upper Slaughter churchyard.

As an aside, and to complete the history of atmospheric CO2 levels (Fig. 8): the further decrease in CO2 after the massive volcanic episodes of the Late Permian – Early Triassic, and the Mid – Late Jurassic, i.e. through the Cretaceous to Quaternary periods, is thought to be due to the evolution and diversification of (a) terrestrial flowering plants (including grasses), and (b) marine micro-organisms (e.g. algae, plankton, shellfish, and corals) which thrived in the warm ocean waters and locked up huge volumes of CO2 in their shells; in the resultant limestones (e.g. the Chalk); and in widespread organic-rich shale deposition. The growth of the Antarctic and Arctic ice sheets during the Tertiary period, culminating in the Quaternary Ice Ages, also caused the sequestration of large volumes of CO2 due to the cooling of mid-latitude ocean waters (colder water can absorb more CO2 in solution than warm water), and the trapping of CO2 in the lattices of ice crystals and in

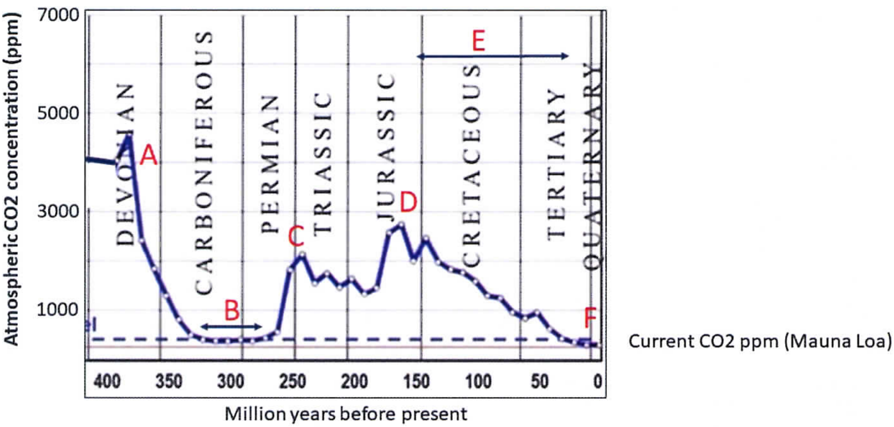

Fig. 8: Evolution of atmospheric CO2 levels over the last 400 million years (II). C, D = Major rise in CO2 levels due to massive volcanism, the Permo-Triassic extinction event, and large areas of warm ocean water (can't absorb so much CO2). E = Falling CO2 levels during the Cretaceous – Tertiary was due to widespread deposition of marine carbonates and organic-rich shales, the proliferation of terrestrial flowering plants, and the growth of the Antarctic and Arctic ice sheets. F = Pleistocene – Quaternary ice ages.

bubbles in the ice. CO_2 levels during the Quaternary Glacial periods (~180 ppm) were roughly one-third lower than during the pre-industrial Holocene period (~280 ppm).

Although all forms of weathering are essentially destructive processes, not all biological agents or processes are destructive. For example, coral reefs, mangroves, and sea-grass meadows all reduce wave energy and protect low-lying tropical coasts from marine erosion; marram grass stabilises coastal sand dunes from wind erosion; whilst heather and sphagnum moss protect peat bogs from erosion.

The role of vegetation in controlling weathering and erosion during glacial and inter-glacial periods in the Cotswolds has been previously highlighted (Jeans, (2022)): limited vegetation cover during glacials leads to high run-off and high sediment loads in rivers, whereas dense vegetation cover during warm inter-glacials leads to a marked reduction in run-off and much-reduced sediment load in rivers.

Understanding this kind of feedback between biological processes and the landscape is becoming increasingly important in Conservation as new 'Nature-based Solution' environmental restoration projects emerge (Larsen et al (2021)). The importance to human well-being of remedial processes like controlling floods, stabilizing shorelines and slopes, providing clean air and water, and increasing carbon capture, is why bioweathering and geomorphology are increasingly relevant in today's world.

Note: Because of the nature of the subject, this article is light on specific references to the North Cotswolds, but I thought it necessary (and hopefully of interest) to complete the discussion of the full spectrum of weathering.

Pete Jeans (Ph.D. (Geol)) Email: pete.jeans2@gmail.com | www.pj-exploration.co.uk

Acknowledgements: Once again, I would like to thank Robin Lauckner, Tom Prudence, and Bob Thompson for their comments and suggestions, which have greatly improved the clarity of this paper. In addition, my thanks are also due to Juliet Bailey for casting her expert eye over the lichen section of this paper and for her other helpful comments. (Any errors which may remain are entirely the author's responsibility!)

References:

Finlay, R.D. and 10 others (2020). Reviews and syntheses – biological weathering. Biogeosciences 17, 1507-1533.

Gibling, M.R. and N.S. Davies (2012). Palaeozoic landscapes shaped by plant evolution. Nature Geoscience, 5, Feb. 2012.

Hoffland, E. and 13 others (2004) The role of fungi in weathering. Front. Ecol. Envir. 2(5), 258-264.

Jackson, T.A. (2015). Weathering .... and soil formation caused by lichens and mosses. Geoderma, 251-252, pp 78-91.

Jeans, P.J.F. (2022). Evolution of Cotswold valleys through Time. GNS News, September 2022.

Larsen, A. and 3 others (2021). Biogeomorphology – quo vadis? Earth Surf. Proc. and Landforms, 46, 12-21.

Olsson-Francis, K. and 3 others (2012). The effect of rock composition on cyanobacterial weathering. Geobiology 10 (5) 434-444.

Robillard, C. (2017). What's the difference between mosses and lichen? https://nature.ca/en/moss-and-lichen

Simard, S. (2021). Finding the Mother Tree. Penguin books.

Viles, H.A. (2022). Biogeomorphology. Geol. Soc. London, Memoir 58, 205-212.