

Supplementary Material for

N₂-fixing tropical legume evolution: a contributor to enhanced weathering through the Cenozoic?

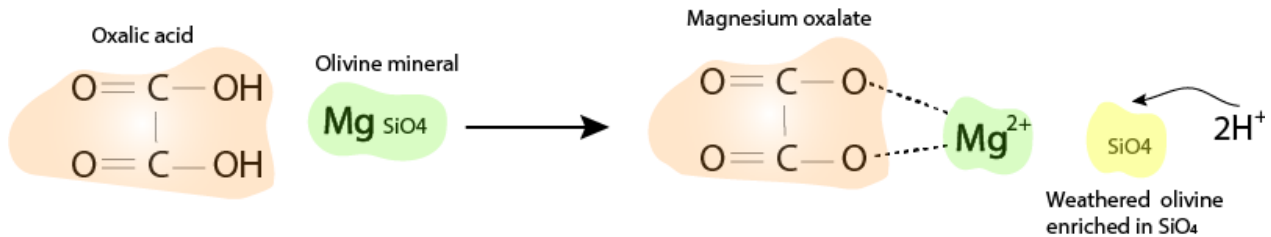
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Supplementary Figure 1. Illustrated glossary of weathering reactions

The following processes are often enhanced by biological (biotic) systems such as root exudation, microbial physiology, soil respiration and organic matter decomposition and leaching and therefore represent the basis of biological weathering [1].

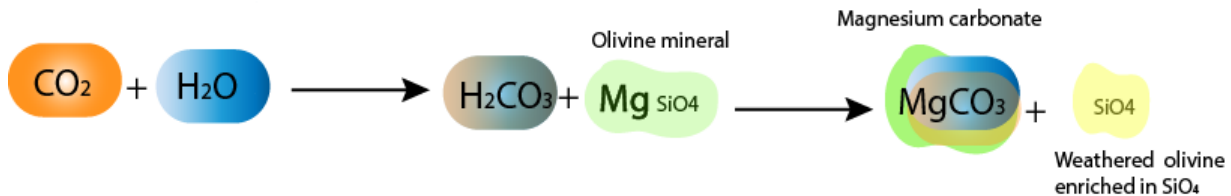
Chelation (acido-complexolysis; complexation) – the reaction of complexing between metal ions from minerals/rocks with organic molecules (chelating agents; chelators) via the formation of coordination bonds. Important in biological weathering. Organic acids such as citric acid, oxalic acid, tartaric acid, acetic acid, lactic acid, gluconic acid and amino acids are major chelating agents. Chelating organic acids may also produce protons during their dissociation which can further attack minerals through acidolysis which is why some sources refer to chelation also as acido-complexolysis [2].

Suggested example: Oxalic acid + olivine \rightarrow $[\text{Mg}^{2+} : \text{oxalate}]$ complex + weathered olivine + 2H^+



Carbonation – CO_2 in soil produced by biological activity such as respiration often dissolves in water forming the weak carbonic acid (H_2CO_3). Carbonic acid can react with silicate minerals producing metal carbonates. The process can be sped-up by the presence of the enzyme carbonic anhydrase [3].

Suggested example:



Acidolysis (simple acidolysis, acid attack, protonation) – a process in which protons (generated biologically or by acid dissociation) replace the metal cations from mineral surfaces and bring the mineral metals to solution.

Suggested example:

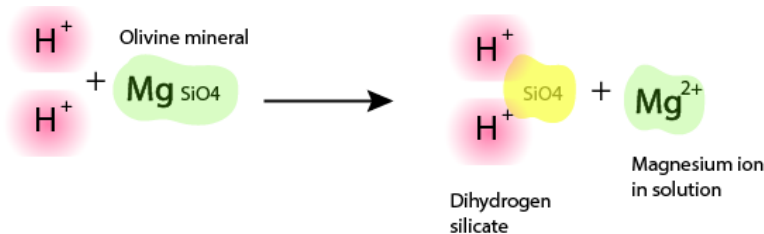
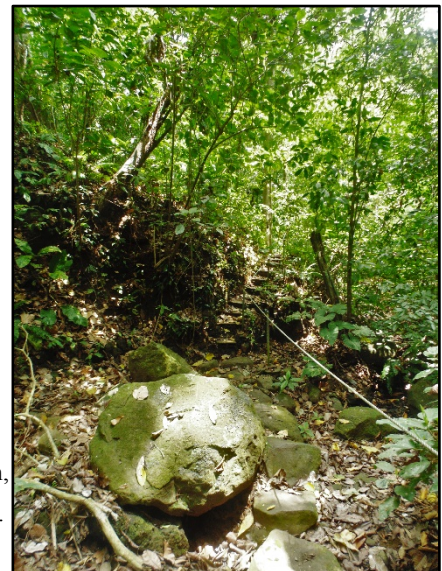


Figure I. Basalt boulders in the tropical forests of Barro Colorado Island, Panama – the presence of boulders (here seen with weathered surface of altered colour) may indicate that high amounts of volcanic mineral materials at different stages of weathering are contained within the soil horizons where chelation, acidolysis and carbonation driven by forest processes can stimulate their dissolution.

Photo credit: Dimitar Z. Epihov.



Supplementary Figure 2. Functional symbiotic diversity within Leguminosae – coupling extant and fossil evidence

Root microbial symbioses can be divided into 2 major groups - dipartite (that is symbioses between a plant host and a single symbiont group) and multipartite (that is symbioses between a plant host and two or more symbiotic partners). Plants with dipartite symbioses include arbuscular mycorrhizal (AM) plants, ectomycorrhizal (EM), ericoid mycorrhizal (ERM) etc. Plants with multipartite symbioses are the group of N₂-fixing and arbuscular mycorrhizal plants (NAM), N₂-fixing and ectomycorrhizal plants (NEM), and N₂-fixing dual arbuscular-ectomycorrhizal plants (NAEM).

Leguminosae is one of the most symbiotically-rich plant families with members known to exhibit AM, EM, NAM, NEM [4],[5] or NAEM [6] properties. Symbiotic assignment to fossil taxa is based upon the symbiotic characteristics of extant members of that taxon as found in the Supplementary curated by Werner *et al.* in [7] (except *Xylia* - [8] and *Maniltoa* - [9]). Lists of ectomycorrhizal legumes are found in [10] and [11].

Functional type

NAM

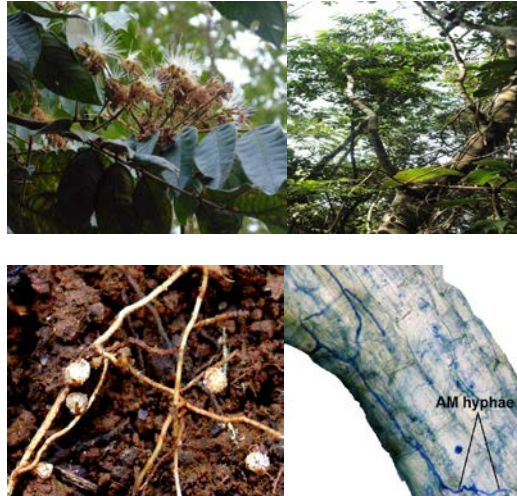


Figure I. N₂-fixing AM legumes of Neotropical rainforests: *Inga cocleensis* – an extant member of the ancient *Inga* genus with origins in the early Cenozoic. Shown here are flowers and leaves, canopy, *Burkholderia* root nodules and Trypan Blue-stained intraradical AM hyphae. Photo credit: Dimitar Z. Epihov

Palaeocene/Eocene Fossil Legume Taxa

Inga [12],[13],[14], *Prosopis* [15],[16], *Mimosa* [15], *Chamaechrista* [12], *Acacia* [13],[16],[17],[18],[19], *Swartzia* [16],[20], *Albizia* [15],[16], *Pentaclethra* [15],[19], *Adentanthera* [15],[19] *Ormosia* [16], *Sophora* [13],[16], *Robinia* [16],[20], *Diploptropis* [16], *Canavalia* [13], *Dalbergia* [13],[20], *Machaerium* [16], *Strongyolobos* [21], *Pongamia* [21], *Neptunia* [16], *Derris* [22], *Desmodium* [22], *Millettia* [22], *Maniltoa* [23], *Crudia* [23],[24], *Xylia* [16]

EM

Aphanocalyx [17], *Afzelioxylon/Afzelia* [25],[26], *Brachystegia* [27],[28], *Julbernardia* [29]

AM

Ablygonocarpus [15], *Gymnocladus* [20], *Cladrastis* [20], *Senna* [16], *Calpocalyx* [15], *Cassia* [30], *Cynometra* [31], *Peltogyne* [16], *Bauhinia* [20], *Vouapa* [21], *Hymenaea* [23], *Caesalpinia* [16]

Modern analogues of Cenozoic fossil forests. The occurrence of fossils of the above taxa at different sites suggests early Cenozoic forests exhibited compositional patterns analogous to major types of modern forests with Leguminosae as an important family in both species-rich NAM forests and monodominant forests of EM or AM legumes. We suggest fossils of *Inga*, *Swartzia*, *Machaerium* and the AM legume taxa (*Senna*, *Cassia*) might be analogous to species-rich NAM legume tropical rainforests of modern Amazon, Panama and Costa Rica [32]. Fossils of *Brachystegia* and *Julbernardia* are suggestive of monodominant EM dry tropical forests like miombo woodlands in Africa [33]. Abundant *Acacia* fossil records are often interpreted as dry tropical forests analogous to savanna *Acacia* woodland communities currently found in Africa and Mexico [34]. Fossil assemblages of *Cynometra*- and pollen of *Peltogyne*-affinity might be analogous to the monodominant legume AM communities forming *Cynometra alexandrii* forests in Africa and that of *Peltogyne gracilipes* in Amazon [35]. Finally, we suggest that the presence of fossil EM *Aphanocalyx* and *Afzelia* might be indicative as accessory EM species found in modern monodominant EM rainforests like the EM legume *Microberlinia bisulcata* monodominant forests in Cameroon [11],[36].

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