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Linking Iron Supply, Microbial Mineralization and Environmental Control in the Formation of Ferruginous Stromatolites

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Abstract: Ferruginous stromatolites are microbially laminated sedimentary structures in which iron enrichment is integrated into stromatolitic growth, stabilization and preservation. They are important archives for reconstructing early iron cycling, shallow-water redox structure and the ecological role of microbial communities in Precambrian oceans. This review synthesizes recent English-language literature on the formation mechanisms of ferruginous stromatolites from a source-to-sink perspective. Rather than using any site-specific quantitative dataset, the review focuses on four linked dimensions: conceptual definition and diagnostic criteria, iron source pathways, microbial mediation of iron mineralization, and environmental controls on growth and preservation. Current evidence indicates that no single process can explain all ferruginous stromatolites. Continental weathering, groundwater seepage, hydrothermal supply and volcaniclastic input may all contribute iron, but their relative roles are filtered by basin restriction, upwelling, water-column redox stratification and sea-level change. Microorganisms mediate enrichment through oxygenic oxidation, anoxygenic photoferrotrophy, microaerophilic Fe(II) oxidation, and extracellular polymeric substance adsorption that traps or templates poorly crystalline Fe(III) phases within laminae. Subsequent early diagenesis converts unstable precursors into hematite, magnetite, Fe-silicates or siderite, thereby controlling what is ultimately preserved in the rock record. The review emphasizes that ferruginous stromatolites should be interpreted as coupled products of iron supply, microbial processing and environmental focusing. A multi-proxy framework combining textures, mineralogy, isotopes and sedimentary context is therefore essential for distinguishing source models and for evaluating the significance of ferruginous stromatolites in Earth's oxygenation history.

Keywords: Ferruginous stromatolites, iron source, microbial mineralization, photoferrotrophy, cyanobacteria, Precambrian oceans.

1. Introduction

Stromatolites are laminated sedimentary structures generated by microbial trapping, binding and/or mineral precipitation, and they remain one of the most important archives for evaluating early biosedimentary systems [1, 2]. Ferruginous stromatolites occupy a special position within this broader category because they couple stromatolitic growth with iron enrichment and mineralization. Their scientific value lies not only in their morphology, but also in what they record about iron cycling, microbial metabolism and redox heterogeneity in ancient shallow-water settings [3–7].

The literature on ferruginous stromatolites has expanded through studies of Precambrian iron-rich microbialites, iron formations that preserve stromatolitic fabrics, Cryogenian ironstones, and modern ferruginous environments used as analogs [8–13]. Yet the formation mechanism remains debated. Competing models emphasize continental iron supply, hydrothermal input, groundwater fluxes, volcaniclastic contributions, oxygenic photosynthesis, photoferrotrophy, microaerophilic Fe(II) oxidation, or purely diagenetic reorganization [3–5, 8, 12–18].

This review follows the narrative logic of the review chapter in the author's thesis only at the level of structure, namely: ferruginous stromatolites in deep time, iron sources, and microbial iron mineralization. No field data, sample results or site-specific numerical values from that thesis are used here. Instead, the discussion is rebuilt from public English-language literature and organized into a qualitative synthesis focused on formation mechanisms.

2. Conceptual Scope and Diagnostic Criteria

The term ferruginous stromatolite is best used for stromatolitic structures in which iron is an integral component of lamina formation, early stabilization or preserved microfacies, rather than a late superficial stain [1–5]. In practice, the diagnosis commonly relies on three linked observations. First, the deposit must show genuine stromatolitic fabrics, including laterally persistent lamination, domal or columnar accretion, and evidence for microbial mediation. Second, iron-bearing phases or iron-rich fabrics must occur within the laminae, between adjacent laminae, or in closely coupled microfacies. Third, the iron enrichment should be interpretable in a source-to-sink framework rather than being solely a product of random post-lithification alteration [4, 5, 9, 10, 21].

These criteria matter because ferruginous stromatolites overlap conceptually with iron-rich microbialites, stromatolitic iron formations and ferruginous matgrounds. Not every laminated iron-rich rock is stromatolitic, and not every stromatolite containing iron is genetically ferruginous in the same sense. The most robust studies therefore integrate mesoscale morphology, thin-section fabrics, iron mineralogy, geochemical proxies and depositional context before drawing genetic conclusions [1, 2, 4, 8, 10, 21].

3. Iron Supply Pathways from Source to Sink

The first-order problem in any ferruginous stromatolite model is iron supply. Iron must enter the depositional system in a transportable form, become concentrated in the microbial growth zone, and then be fixed rapidly enough to survive local reworking and later diagenesis [3–5].

Continental weathering is one major source pathway. Weathering products can deliver iron as colloidal Fe(III) phases, Fe-bearing detritus, organically complexed iron, or dissolved Fe(II) carried by reducing groundwater before oxidation near the sediment-water interface [3, 4, 11, 12]. This model is attractive in marginal marine and restricted-platform settings where siliciclastic input, Fe–Al–Ti covariance, and detrital mineral associations suggest a continental link [4, 11]. However, continental sourcing alone does not explain why iron becomes strongly partitioned into specific stromatolitic laminae rather than being dispersed throughout the host sediment.

Hydrothermal input provides an alternative or complementary pathway. In ferruginous basins, Fe(II)-rich deep waters ultimately derived from hydrothermal systems can be transferred into the photic zone through upwelling or basin mixing, then oxidized biologically or abiotically and captured by microbial communities [5, 8, 17, 21, 22]. This mechanism is widely discussed for iron formations and is also relevant where ferruginous stromatolites developed on basin margins or within redox-stratified shelves [5, 8, 21]. Yet hydrothermal interpretations must be tested carefully because some classical hydrothermal markers are non-unique and can be overprinted by detrital or diagenetic effects [4, 21].

Groundwater seepage and volcaniclastic input are additional pathways that may locally matter. Groundwater can bypass oxidized surface waters and deliver reduced iron directly into shallow depositional sites [3, 12]. Volcaniclastic material may contribute reactive Fe phases that are later dissolved, transformed or scavenged by microbial mats [3–5, 10–12]. In most cases, the most realistic model is not a single-source endmember but a mixed system in which multiple sources are focused by basin restriction, upwelling, shoreline migration or sea-level change (Figure 1, Table 1).

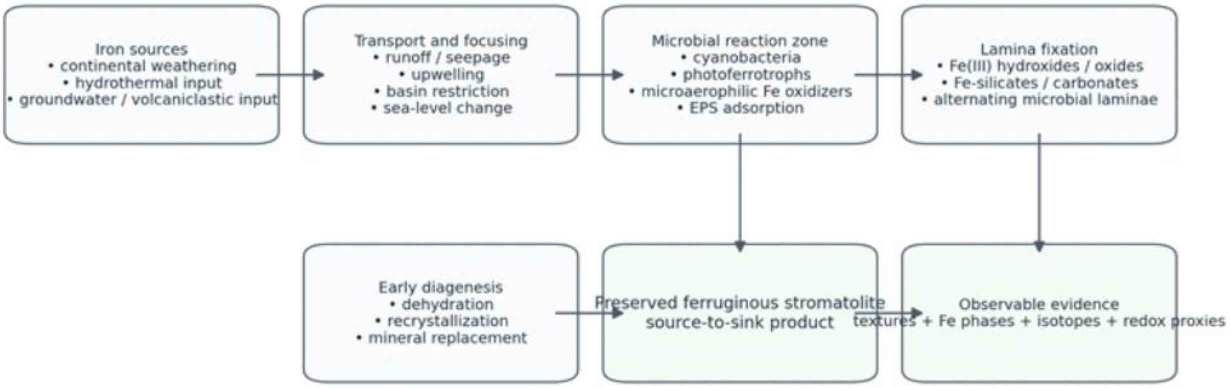

Figure 1. Conceptual source-to-sink workflow for ferruginous stromatolite formation

Table 1. Major source-to-sink models for ferruginous stromatolite formation

Model	Likely transport form	Key sedimentary / geochemical clues	Microbial role	Main uncertainty
Continental weathering and runoff	Fe(III) colloids, Fe-bearing detritus, organically complexed iron	Detrital association; Fe–Al–Ti covariance; marginal-marine or restricted platform setting	EPS trapping and localized oxidation partition iron into laminae	Difficult to separate from mixed hydrothermal or groundwater contributions
Reducing groundwater seepage	Dissolved Fe(II) delivered beneath or across shallow redox boundaries	Shallow-water seepage context; local redox interfaces; limited detrital dilution	Cyanobacteria and Fe oxidizers create reaction fronts near the mat surface	Hydrogeologic evidence is rarely preserved directly
Hydrothermal input and upwelling	Deep-water or vent-derived Fe(II) transferred into the photic or marginal zone	Ferruginous basin setting; stratified water column; upwelling-sensitive margin	Photoferrotrophs, cyanobacteria or microaerophilic Fe oxidizers convert Fe(II) to Fe(III)	Classical hydrothermal markers can be non-unique or diagenetically modified
Volcaniclastic contribution	Reactive volcanic ash or glass supplying labile Fe	Ash layers, volcaniclastic admixture, episodic nutrient and Fe release	Microbial mats scavenge or template dissolved / nanoparticulate iron	Usually acts as an auxiliary rather than exclusive source model

4. Microbial Mediation of Iron Enrichment

Iron supply alone cannot explain ferruginous stromatolites. Microbial mediation determines where iron is fixed, how it is partitioned between laminae, and which precursor phases are stabilized long enough to enter the rock record [8, 9, 13–20].

Oxygenic cyanobacteria are central to many models. By producing oxygen and modifying local pH, cyanobacterial mats can promote oxidation of dissolved Fe(II) and the precipitation of Fe(III) oxyhydroxide precursors in or near the mat surface [8, 14–16]. Laboratory and environmental studies further show that cyanobacterial communities can remain active under ferruginous conditions by spatially separating photosynthesis from iron precipitation or by using oxygen production as a protective mechanism against iron encrustation [14–16].

Anoxygenic photoferrotrophs provide a different pathway.

These organisms directly oxidize Fe(II) using light rather than oxygen, thereby linking phototrophy to primary iron oxidation in low-oxygen waters [17, 18, 22]. Their relevance is especially strong in discussions of Archean and Paleoproterozoic ferruginous systems, but they also provide a conceptual framework for interpreting stromatolitic iron enrichment where oxygen was scarce or strongly stratified [17, 18].

Microaerophilic Fe-oxidizing bacteria and extracellular polymeric substances (EPS) add further complexity. Fe-oxidizers can thrive at oxic-anoxic interfaces and directly produce iron-rich microbial mats [13]. EPS, in turn, adsorbs metal ions, binds nanoparticles, templates mineral nucleation and traps poorly crystalline Fe(III) phases within the laminae [13, 15, 19, 20]. This mechanism is important because it explains why iron enrichment commonly tracks dark, organic-rich or microbially active laminae rather than the entire rock volume.

Finally, early diagenesis transforms the products of microbial mediation. Poorly crystalline Fe(III) precipitates can dehydrate, recrystallize or react with silica, carbonate and organic matter to form hematite, magnetite, Fe-silicates or siderite [4, 5, 8, 9, 21]. Therefore, preserved mineralogy should be read as a filtered archive of earlier microbial and geochemical processes, not as a direct snapshot of the initial precipitate.

5. Environmental Controls on Growth and Preservation

Ferruginous stromatolites are environmentally selective structures. They require enough iron to sustain mineralization, enough light or redox disequilibrium to support key microbial metabolisms, and sufficiently low dilution or disturbance to preserve laminae [1–7].

Redox structure is the most fundamental control. Ferruginous water columns, shallow oxygen oases, and sharp redox gradients create the conditions under which Fe(II) can be delivered to near-surface habitats and oxidized rapidly in a restricted zone [6–9, 22, 23]. This is why ferruginous stromatolites are especially informative for reconstructing local, not necessarily global, oxygenation. They can record microbially generated oxygen in otherwise iron-rich systems or reveal phototrophic iron oxidation where free oxygen was limited [6–8, 17, 22].

Sea-level change, basin restriction and hydrodynamics are equally important because they regulate focusing and retention. Relative shallowing may enhance clastic and iron delivery from nearby land areas, increase basin restriction, and promote retention of externally supplied iron in marginal settings. More open conditions can disperse reactive iron and reduce the opportunity for localized enrichment. In this sense, ferruginous stromatolites are best seen as products of environmental focusing rather than simply high regional iron availability [1, 2, 4, 10].

Preservation further depends on pH, alkalinity, silica activity, carbonate saturation, organic reactivity and later diagenetic overprinting [3–5, 21]. These controls determine whether primary Fe(III) phases remain recognizable, whether they are converted into hematite or magnetite, or whether they are redistributed into diagenetic carbonates and silicates. Accordingly, interpretation should always separate processes of enrichment from processes of mineral preservation.

6. Representative Records and Implications for Earth-System Evolution

Representative case studies show that ferruginous stromatolites are not restricted to a single age or basin type. Iron-rich stromatolites immediately predating the Great Oxidation Event in the Griquatown Iron Formation demonstrate that shallow microbial communities could generate localized oxygen production and rapid iron oxidation on the margins of ferruginous basins [8]. Late Paleoproterozoic stromatolitic iron-rich systems from the Lake Superior region show that microbial iron oxidation and stromatolitic fabrics remained important in redox-stratified oceans after the initial rise of atmospheric oxygen [9]. Cryogenian ironstones in Namibia extend the discussion into Neoproterozoic settings and indicate that unusual ferruginous stromatolitic systems could also form under extreme climate and basin conditions [10].

These examples have broader implications. First, ferruginous stromatolites reinforce the idea that local redox structure and microbial ecology can diverge sharply from basin-average conditions [6–8]. Second, they help bridge the gap between classical banded iron formations and shallow-water microbialites by showing that microbial communities can actively fix iron in laminated accretionary structures rather than merely living adjacent to iron deposits [5, 8, 9, 17, 19]. Third, they highlight that the significance of ferruginous stromatolites lies less in any single mineral phase than in the coupled evidence for iron supply, microbial processing and preservation. For Earth-system history, ferruginous stromatolites are therefore best interpreted as indicators of spatially structured oxygenation and dynamic iron cycling rather than as simple proxies for uniformly oxygenated shallow seas [6–8, 14, 22, 24]. The above representative records from different ages and settings provide critical clues for understanding the genesis and evolution of ferruginous stromatolites, and have also promoted the establishment of a multi-proxy comprehensive diagnostic framework (Table 2, Figure 2).

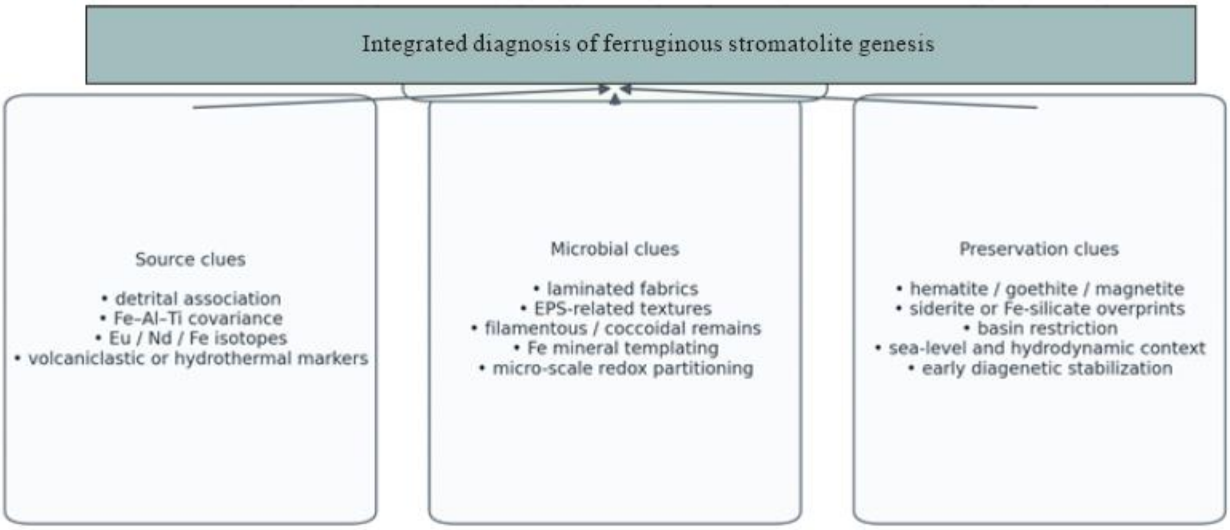

Figure 2. Proxy-based framework for diagnosing ferruginous stromatolite formation

Table 2. Representative ferruginous stromatolite and related ferruginous microbialite records

Representative record	Age / context	Dominant Fe facies	Interpretive emphasis	Significance
Griquatown Iron Formation, South Africa	Immediately before the Great Oxidation Event	Iron-rich stromatolitic laminae with rapid Fe oxidation	Localized oxygen production and shallow-margin iron trapping	Demonstrates oxygenic or mixed microbial iron oxidation on ferruginous basin margins
Gunflint–Biwabik / Lake Superior region	Late Paleoproterozoic redox-stratified ocean	Stromatolitic or laminated iron-rich facies	Persistent microbial Fe oxidation after the initial rise of oxygen	Links stromatolitic fabrics with iron-rich marine ecosystems
Cryogenian ironstones, northern Namibia	Neoproterozoic glacial to post-glacial ferruginous setting	Magnetite- and hematite-rich ironstone with stromatolitic affinity	Ferruginous deposition under unusual climate and basin restriction	Extends ferruginous stromatolite discussion into Cryogenian Earth-system change
Modern ferruginous analogs	Hydrothermal vents, ferruginous lakes and redox interfaces	Iron-oxidizing mats and Fe-rich microbial films	Actualistic testing of Fe oxidation, EPS trapping and mineral templating	Provides process-level analogs for interpreting ancient records

7. Conclusions

Ferruginous stromatolites are not the product of a single universal mechanism. Their formation requires the conjunction of iron supply, microbial mediation and environmental focusing. Continental weathering, groundwater seepage, hydrothermal input and volcaniclastic sources may all contribute iron, but microbial communities determine how that iron is fixed into laminae, while basin architecture and redox structure govern whether the resulting record is preserved. Accordingly, ferruginous stromatolites should be studied through an explicitly coupled source-to-sink framework that integrates morphology, mineralogy, geochemistry and sedimentary context. Such an approach offers a stronger basis for using ferruginous stromatolites to reconstruct early iron cycling, localized oxygenation and the evolving interaction between microbial ecosystems and Earth's surface environment.

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