

Mineral Composition: Sulfur Minerals

Introduction

Sulfur minerals occur in a variety of forms that may reflect biological activity, particularly in low-temperature, aqueous, or organic-rich environments where life can influence mineral structure, stability, and morphology. These minerals include different allotropes of elemental sulfur (S⁰), such as α-sulfur, β-sulfur, and γ-sulfur (rosickyite), as well as iron sulfides like pyrite and various sulfates. Some of these forms are thermodynamically unstable under surface conditions yet appear in environments where microbial life is active or where organic compounds are abundant, raising interest in their biosignature potential.

Mechanisms and Formation

Elemental sulfur (S⁰) can form through both abiotic oxidation of sulfide in the presence of oxygen and through biological processes carried out by sulfur-oxidizing microorganisms. The most stable form at ambient conditions is α-sulfur, but β-sulfur and γ-sulfur can crystallize in specific geochemical contexts—typically at elevated temperatures (e.g., 95–120 °C for β-sulfur in fumaroles). However, these metastable forms have also been found in cold, organic-rich, and microbially active settings, suggesting alternative formation pathways.

Biological processes may contribute to sulfur mineralization in two ways: through biomineralization, where microorganisms directly mediate mineral formation, and through organomineralization, where minerals precipitate in the presence of organic compounds—sometimes without living cells. Extracellular polymeric substances (EPS) and cellular debris can serve as nucleation sites or influence crystal structure, potentially stabilizing mineral forms otherwise unlikely to form.

Biogenic Signals

Several features of sulfur minerals may indicate biological influence. The occurrence of β-sulfur or rosickyite in cold, low-temperature environments—especially in association with organic matter—has been interpreted by some as evidence of microbial sulfur oxidation or stabilization of metastable allotropes. Morphological biosignatures are also of interest: framboidal pyrite (raspberry-like aggregates of microcrystals) is common in microbial mats and anoxic sediments. Biologically mediated framboids tend to have fewer, larger crystallites and more regular shapes compared to their abiotic counterparts.

In pyrite-bearing environments, sulfur mineralization may preserve microfossils, biofilm textures, or geochemical signatures (e.g., sulfur isotope fractionation), particularly when rapid burial or silica encapsulation enhances preservation. Microbial sulfur cycling can also affect the redox gradients and local chemistry, influencing which mineral forms precipitate and under what conditions.

Abiotic Influences and Ambiguity

Sulfur minerals can form abiotically in diverse environments, including volcanic fumaroles, hydrothermal vents, and sedimentary systems. Laboratory studies have demonstrated that β-sulfur and rosickyite can form via organomineralization in the absence of microbes, stabilized by simple organic molecules like sugars or amino acids—some of which can be produced

abiotically. These results complicate interpretation: the presence of metastable allotropes does not guarantee a biological origin. Similarly, framboidal textures, once considered diagnostic of life, can form under purely chemical gradients or by mineral self-assembly.

Thus, sulfur mineral forms must be evaluated in full context: their spatial association with organics, the geochemical environment, accompanying isotopic signatures, and comparisons to well-characterized analogs in both biological and abiotic settings.

Why This Matters

Sulfur minerals are central to microbial metabolism and geochemistry in many environments, making them prime candidates for biosignature investigation. On early Earth, sulfur-based metabolisms likely played a key role in microbial evolution, and their mineral byproducts are preserved in the rock record. On Mars and other planetary bodies, sulfur-bearing minerals are widespread and accessible to remote sensing and surface missions. The challenge lies in interpreting ambiguous mineral forms—balancing structural or morphological clues with geochemical and contextual evidence. When integrated with multiple lines of inquiry, sulfur mineral assemblages may provide compelling, if complex, evidence for past or present life.