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# Sunspot cycles drove decadal fluctuations in shallow water oxygenation in the Mesoproterozoic

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**Abstract**

The mid-Proterozoic (~1.8–0.8 Ga) shallow ocean was dominantly anoxic and ferruginous, and has long been considered to have been redox-stable (the so-called “Boring Billion”), but recently recognized million-year-scale redox variability raises the question of whether even higher-frequency fluctuations occurred. Decadal-scale solar cycles drive climate variability, yet their influence on iron cycling and associated redox dynamics in mid-Proterozoic shallow marine settings remains unexplored. Here, we report sunspot cycles recorded in ~1.3 Ga marine red beds of the Luanshigou Formation, South China. The studied carbonate laminites consist of alternating coarse, hematite-poor intraclastic laminae, and fine, hematite-rich microbial mat laminae, reflecting seasonal fluctuations in hydrodynamic energy and redox conditions driven by wet–dry seasonal variability. The preservation of tufted microbial mats indicative of months-long growth supports an annual origin for each couplet. Long-term sedimentation rates (~14.3–34.9 μm/yr) are lower than the annual rate inferred from mean couplet thickness (~206 μm/yr), consistent with accumulation-rate underestimation over longer, incomplete stratigraphic records. Spectral analysis of laminite thickness, grayscale and geochemical data (Al, Fe/Al, P/Al) reveals periodicities of 11-yr Schwabe, 22-yr Hale, 35-yr Brückner and 70–90-yr Gleissberg cycles. We thus propose that in anoxic and ferruginous shallow marine settings of the mid-Proterozoic, sunspot activity modulated climate and thereby the development of microbial mats. This, in turn, formed localized oxygen oases that mediated Fe(II) oxidation and drove substantial short-term redox variability, indicating pervasive dynamic fluctuations across decadal to million-year timescales and further challenging the traditional “Boring Billion” paradigm.

**Key words:** red laminated carbonate; redox conditions; iron oxidation; microbial mats; authigenic hematite

## 1. Introduction

Understanding the drivers of climatic and environmental variability across different timescales is central to reconstructing Earth's surface evolution. The Sun modulates its irradiance and solar wind, thus impacting Earth's atmospheric circulation and magnetic field, as well as playing a pivotal role in climate dynamics (Gray et al., 2010; Ma et al., 2022). Solar cycles include the 11-year Schwabe, 22-year Hale, 70-to-90-year Gleissberg, and 210-year Suess cycles (Usoskin, 2017). On Earth, these cycles are recorded in both lacustrine and marine sediments deposited since the Paleoproterozoic (Table S1). For example, power spectrum analyses of carbonate laminites from the early Mesoproterozoic Wumishan Formation (~1.5–1.45 Ga) of North China have revealed two stable periodicities consistent with the Schwabe and Hale sunspot cycles, suggesting that sunspot activity exerted influences on microbial growth and primary production through modulating illumination, precipitation and temperature (Tang et al., 2014). Thickness variations of aeolian sediment laminae in a Holocene glacial lake, exhibiting 22, 40 to 50, and 200-year cycles, point to the influence of short-term solar activity on surface wind intensity and aeolian clay input (Anderson, 1992). Present-day variability in sunspot-related solar output induces climate change in a variety of ways. For instance, the late 17$^{th}$ century "Little Ice Age" has been attributed to the Maunder Minimum, a nearly 45-year period of minimal sunspot activity (Gray et al., 2010).

Evidence suggests that solar activity has influenced Earth's climate and environmental conditions significantly since the early Paleoproterozoic (Andrews et al., 2010; Ding et al., 2022). Most studies, however, have focused on the Phanerozoic, which is generally characterized by higher oxygen concentrations and lower dissolved Fe(II) in the oceans (Table S1; Mills et al., 2023). By contrast, anoxic and ferruginous oceans dominated in the Precambrian (Poulton and Canfield, 2011), resulting in intervals of widespread formation of marine red beds (Holland, 1984; Tang et al., 2020) and iron formations (Bekker et al., 2014). The formation of these deposits was likely closely linked to climate and associated redox variability, making them ideal sedimentary archives for identifying short-period climatic variations. One study suggests that the ~2 μm-scale laminites that occur in the ~2 Ga banded iron formations of the

Weeli Wolli Formation record a 23.3-year cyclicity, potentially linked to environmental changes driven by the Hale cycle (Trendall, 1973). Another study identified an ~80-year Gleissberg cycle in ~2.47 billion-year-old μm-scale banded iron formations, potentially resulting from the precipitation of iron (oxyhydr)oxides regulated by marine primary productivity (Ding et al., 2022).

The mid-Proterozoic shallow ocean has long been considered persistently low in oxygen and relatively stable (the "Boring Billion"; Planavsky et al., 2014). By contrast, recent studies have documented pulsed oxygenation on million-year timescales (Hardisty et al., 2017; Shang et al., 2019), as well as ~10-kyr redox oscillations (Song et al., 2023). However, the influence of short-period solar cycles on shallow-marine iron cycling and redox dynamics during this interval remains unknown, particularly on decadal timescales.

Here, we analyze well-preserved iron-rich carbonate laminites from the ~1.3 Ga Luanshigou Formation in the Shennongjia area of South China, which were deposited in a broadly anoxic, ferruginous shallow-marine environment. Our approach combines sedimentological, mineralogical, geochemical and time series analysis. These results provide new constraints on solar-scale modulation of shallow-water Fe cycling, thereby offering new insight into the drivers of short-term redox fluctuations in shallow mid-Proterozoic seawater.

## 2. Geological setting

The study area is located in the Shennongjia Forestry District in northwestern Hubei Province, within the northern Yangtze sub-block (Figure 1a–b; Liu et al., 2024). The Yangtze Craton was formed by the collision and amalgamation of several microcontinents during the Paleoproterozoic (Tian et al., 2022), after which the sedimentary environment remained relatively stable. Paleomagnetic study suggests that the area was located at ~30°N during the deposition of the Luanshigou Formation (Figure

1a; Liu et al., 2024). This latitude corresponds to a climatically-sensitive boundary within the subtropical high-pressure belt, situated between the tropical (Hadley) and mid-latitude (Ferrel) atmospheric circulation cells (Mahlobo et al., 2024).

The Shennongjia Forestry District (31°26'38.44" N, 110°16'20.07" E) contains good outcrops of the Mesoproterozoic succession (Figure 1c). The Shennongjia Group, the oldest strata in this area, is >10 km thick (Li et al., 2022). Its base is unexposed and its top is unconformably overlain by the Neoproterozoic Macaoyuan Group (Figure 1c; Li et al., 2013). The Shennongjia Group is divided into a lower subgroup (including the Yingwodong, Dayanping, Luanshigou, Dawokeng and Kuangshishan formations, in ascending order) and an upper subgroup (containing the Taizi, Yemahe, Wenshuihe, Shicaohe, Songziyuan and Wagangxi formations) (Li et al., 2022), and is primarily composed of shallow-marine carbonates, with some siliciclastic and minor volcaniclastic layers (Figure 1c; Li and Leng, 1991; Kuang et al., 2018).

In the Shennongding section, the Luanshigou Formation mainly consists of argillaceous silty dolostone with abundant stromatolites and biolaminites (Figure 1d; Kuang et al., 2018). The base of the formation is not exposed, and the upper part is disconformably overlain by conglomerate of the Dawokeng Formation (Figure 2a). The studied interval (Figure 1d) is ~279 m thick in the upper part of the formation, and was deposited in a peritidal depositional setting on a carbonate platform (Kuang et al., 2018). The lower unit (0−67 m) of the studied interval is dominated by grey, thick-bedded argillaceous silty dolostone, with chert nodules or bands (Figure 2b). The middle unit (67−258 m) consists mainly of red, medium-to-thick-bedded, densely laminated argillaceous silty dolostone (Figure 2c−e), with abundant centimeter-scale stromatolites (Figure 2f) and locally developed minor erosional surfaces (Figure 2e). The upper unit (258−279 m) is characterized by grey, thick-bedded argillaceous silty dolostone with some large columnar stromatolites. In this study, a well-preserved and continuous red carbonate laminite showing no obvious sedimentary hiatuses was collected at a stratigraphic height of 192 m (the middle unit; Figure 1d).

No direct age constraints have yet been obtained for the Luanshigou Formation, but its age can be indirectly constrained from stratigraphic relationships (Figure 1c). A youngest detrital zircon U-Pb age of 1398 ± 20 Ma has been reported from the underlying Dayanping Formation, and a zircon U-Pb age of 1215.8 ± 2.4 Ma was obtained from the overlying Yemahe Formation (Li et al., 2013). A dolomite U-Pb age of 1285.7 ± 66.6 Ma from the upper Kuangshishan Formation provides a broad age constraint for the lower Shennongjia Group (Jiang et al., 2024). A Re-Os age of 1258.3 ± 8.5 Ma from black shale in the lower Taizi Formation has recently been reported in a conference abstract (Gao et al., 2024), while broadly consistent with this framework, it is cited here as supporting information pending peer review. Based on these, the age of the Luanshigou Formation can be roughly constrained at ~1.27 Ga (Liu et al., 2024).

## 3. Materials and methods

Red carbonate laminites were collected from the upper part of the Luanshigou Formation (Figure 1d) in the Shennongding section, South China. These sediments were deposited in a peritidal environment on a carbonate platform (Figure 2; Kuang et al., 2018). An ~30 cm interval of well-preserved laminites showing no signs of significant metamorphism or recrystallization was collected from an outcrop face (Figure 3a). In the laboratory, a slab was cut perpendicular to bedding with two parallel cuts. The central portion (a 177 mm-thick continuous section) was used to prepare polished slabs for cyclostratigraphic and geochemical analyses (Figure 3b), while the flanking portions were reserved for thin section preparation. To avoid kerf loss and to preserve fine lamination, no saw cuts were made along the stratigraphic direction. Instead, the flanking material was manually broken into ten consecutive fragments (~10 × 10 cm), which were then impregnated with epoxy and ground into large-format thin sections (Figure 3c and d), ensuring continuous stratigraphic coverage without gaps or overlap.

Microscopic features were observed using a Stereo Discovery V20 microscope, a Zeiss Axio Scope A1 microscope, and a Zeiss Supra 55 Field Emission Scanning Electron Microscope (FESEM) at the FESEM Laboratory of the China University of Geosciences (Beijing). Selected small slabs were polished by ion milling (GATAN Ilion 697) prior to FESEM analysis, which was performed at an accelerating voltage of 20 kV and a working distance of 15 mm. Secondary electron imaging detection was used to characterize topographic features, and an angle sensitive backscattered (AsB) detector was employed to reveal compositional differences. Element concentrations were semi-quantitatively analyzed by an Oxford energy-dispersive X-ray spectroscopy (EDS) connected to the FESEM. The spot diameter of signal acquisition area was about 2 μm. An Oxford NordlysNano Electron backscatter diffraction (EBSD) camera connected to the FESEM was used to collect the signal of the pre-tilted 70° samples. Diffraction patterns were collected and automatically indexed in real time using AZtec software from Oxford instrument HKL Technology. The fitting algorithm included six to eight Kikuchi bands. Only measurements with mean angular deviation values below 1.0° were accepted.

A thick polished slab was selected for line scanning analysis to obtain variations in X-ray intensity for the elements Al, P and Fe (in counts per second; cps), using an M4 Tornado (Bruker, Germany) benchtop μXRF device at the China University of Geosciences (Beijing). The analysis was conducted under the following conditions: an acceleration voltage of 50 kV; a probe current of 300 μA, and a step size of 20 μm. In addition, grayscale profiles were extracted from the same polished slab using the ImageJ software package (Abràmoff et al., 2004).

Power spectral and evolutionary Fast Fourier Transform (eFFT) analyses were conducted using Acycle v2.8 software (Li et al., 2019a; Li, 2026). The grayscale and geochemical series (Al, P/Al, Fe/Al) were first linearly interpolated to a uniform spacing using the "Interpolation Pro" function, with intervals set to the median sampling of the grayscale (0.0465 mm) and geochemical (0.02005 mm) datasets. The P/Al series was logarithmically transformed as $y = \log_{10}(x + 0.1)$ to avoid taking the logarithm of zero values, and the Fe/Al series was transformed as $y = \log_{10}x$, both using the "Data Transformations" module. The grayscale and geochemical series were detrended by subtracting a 30% LOWESS (Locally Weighted Scatterplot Smoothing) trend, whereas the thickness series was detrended using a second-order polynomial due to its relatively short length, both via the "Detrending" function. Power spectra were computed using the Lomb-Scargle spectrum, with the spectral background estimated by Weedon's smoothed window average (SWA) method (Weedon et al., 2019). The significance of spectral peaks was evaluated against noise using both $\chi^2$ confidence levels and false discovery rate (FDR) correction to reduce multiple-testing artifacts (Weedon et al., 2019). The parameters used for Acycle time-series analyses (Li, 2026) are provided in Table S2. To test whether the identified spectral peaks were primarily controlled by localized variations in couplet thickness, we further performed a segmented spectral robustness test using the front, middle, and last 70% of the grayscale, Al, P/Al and Fe/Al records.

X-ray diffraction analysis was performed using a Rigaku Smart Lab diffractometer at the China University of Geosciences, Beijing. Approximately 500 mg of sample powder was extracted from a polished slab using a diamond micro-drill and then ground to 300 mesh in an agate mortar. Measurements were conducted with Cu Kα1 radiation (λ = 1.5406 Å) under the following conditions: 40 kV accelerating voltage, 200 mA current, scanning range of 3°–70° (2θ), and a scanning speed of 0.02°/s. Mineral identification was carried out using MDI Jade 4.5 software.

I/(Ca+Mg) ratios were determined at the National Research Center for Geoanalysis, Beijing, China. Altogether, 19 samples were drilled from laminites with a diamond micro-drill. Each sample (~24 mg) was washed with Milli-Q water, dried, and digested in 4 mL of 3% $HNO_3$ with 30-minute ultrasonication.

After centrifugation, the supernatant was split for separate analyses. For iodine measurement, 1 mL of supernatant was treated with 1 mL of 3% tertiary amine solution to stabilize iodine, diluted 1:1000 with Milli-Q water, and analyzed within 48 h by ICP-MS/MS (Thermo iCAP TQ) to minimize iodine loss. Instrument sensitivity for iodine was maintained at ~50 kcps for 1 ppb standard. For Ca, Mg, Mn and Sr concentrations, another aliquot of supernatant was diluted 1:100,000 with 3% $HNO_3$ and analyzed by ICP-MS/MS. Quality control was performed using dolomite reference material JDo-1, yielding uncertainties of 0.72% for I, and 0.71%, 0.53%, 1.43% and 0.72% for Ca, Mg, Mn and Sr, respectively (Tables S3 and S4). The method detection limit for I/(Ca+Mg) was below 0.1 μmol/mol.

## 4. Results

The red carbonate laminites consist of densely packed laminar couplets, each composed of alternating coarse (light) and fine (dark) laminae (Figure 4). Couplet thicknesses range from 74 to 736 μm, but most values fall between 125 and 225 μm, with a mean of ~206 μm, a standard deviation of 108 μm, a standard error of 5 μm, and a coefficient of variation of 52% (Figure 5a and b; Table S5). Approximately 11 such couplets group into a larger-scale couplet set (Figure 4a). Within each set, nearly half of the couplets are dominated by fine laminae, giving a darker overall appearance, while the other half are dominated by coarse laminae, resulting in a lighter appearance (Figure 4a). Microscopically, the laminites comprise abundant subangular dolomite intraclasts (10–100 μm) and minor terrigenous detritus, including irregular anhedral hematite, ilmenite and feldspar, within a matrix of sub-μm-scale authigenic hematite and intraclastic dolomite with subsidiary quartz and illite (Figure 4b). These components are organized differently in each laminar couplet. The coarse (light) laminae are characterized by coarse intraclastic dolomite, detrital quartz, feldspar, illite, and large (50–100 μm) irregular grains of ilmenite and hematite, containing only minor amounts of authigenic hematite (<1 μm; Figure 4c and d). By contrast, the fine (dark) laminae show greater bending and tortuosity, and are dominated by fine dolomite and abundant minute (<1 μm) authigenic hematite crystals (Figure 4e–h). Elemental mapping reveals lower Fe and Al concentrations in the coarse (lighter) laminae compared to the fine (darker) laminae (Figure 4i). The fine laminae also contain frequent microbial-related fabrics, such as near-vertical detrital ilmenite strips (Figure 4j; cf. Noffke et al., 2003) and tufted structures with ~0.3 mm relief (Figure 4k; Noffke et al., 2013). All of these features are associated with organic matter, as evidenced by faint orange-red autofluorescence exhibited by the fine laminae (Figure 4l).

Five proxies were analyzed to determine periodicity: grayscale (primarily reflecting hematite content), Fe/Al and P/Al ratios (dominantly reflecting Fe (oxyhydr)oxides and associated P sequestration), Al contents (indicating terrigenous detrital deposition), and thickness (reflecting sedimentation rate) (Tables S5–S7; Figures 5–8). To reconstruct iron content variations, continuous spectral analysis was conducted on a 177.7-mm-thick polished slab (Figure 3b). Cycle lengths in laminar couplets, expressed as the number of couplets per cycle, were calculated as follows: for the grayscale and geochemical series, cycle length = 1 ÷ frequency (cycles/mm) ÷ mean laminar couplet thickness (0.206 mm); for the laminar couplet thickness series, cycle length = 1 ÷ frequency (cycles/LC). Power spectra of the detrended thickness, grayscale, Al, Fe/Al and P/Al series reveal prominent peaks, with the most significant at ~77 laminar couplets in grayscale (exceeding the 5% false discovery rate threshold, Figure 7a). Additional peaks exceeding the 95% $\chi^2$ confidence level are identified at ~67, ~13, ~5, ~3 and ~2 laminar couplets in thickness (Figure 5c–e); ~40, ~15, ~8, ~5, ~4, ~3, ~2 and ~1 laminar couplet(s) in the grayscale; ~79, ~36, ~12, ~8, ~3, ~2 and ~1 laminar couplet(s) in Al; ~73, ~36, ~22, ~12, ~3, ~2 and ~1 laminar couplet(s) in P/Al and ~68, ~35, ~22, ~13, ~11, ~8, ~4, ~3, ~2 and ~1 laminar couplet(s) in Fe/Al (Figures 7 and 8) . However, evolutionary Fast Fourier Transform (eFFT) indicates that only the ~70, ~35, ~22 and ~11 couplet cycles persist throughout the dataset, whereas other spectral peaks show limited persistence and may represent stochastic signals or non-stationary processes (Figures 5–8). Segmented spectral analysis further confirms that these dominant cycles recur consistently in different parts of the record (Figure S1).

The I/(Ca+Mg) ratios of the red carbonate laminites are consistently low, with a mean value of 0.20 ± 0.04 μmol/mol ($n$ = 19; Table S8). This value falls below the established Precambrian baseline of 0.5 μmol/mol, suggesting an anoxic marine setting (Lu et al., 2017). These samples also have elevated Mn/Sr (11 ± 3 ppm/ppm) and Mg/Ca ratios (1.01 ± 0.03 mol/mol). No significant correlation is observed between I/(Ca+Mg) and either Mn/Sr ($R^2 = 0.07$, $p = 0.26$) or Mg/Ca ($R^2 = 0.07$, $p = 0.27$) (Table S8).

## 5. Discussion

### *5.1. Duration of Each Laminar Couplet*

The formation of lamination is commonly controlled by periodic factors, but the duration of each laminar couplet can vary widely, from a day (Okumura et al., 2011) to a month (Davis, 2012) or a year (Gao et al., 2026). Geochronological and cyclostratigraphic constraints provide first-order estimates of long-term sedimentation rate. Detrital zircon U-Pb dating of the underlying Dayanping Formation yields a youngest age of 1398 ± 20 Ma (Li et al., 2013), and Re-Os dating of black shale from the overlying lower Taizi Formation gives 1258.3 ± 8.5 Ma (Gao et al., 2024). These constraints imply that ~2000 m of strata were deposited over ≤140 Myr, corresponding to a rate of >14.3 μm/yr. Based on the ages of the overlying Yemahe Formation (1215.8 ± 2.4 Ma; zircon U-Pb age by LA-MC-ICP-MS; Li et al., 2013) and Taizi Formation, ~1500 m of sediment was deposited over ~43 Myr, yielding a rate of ~34.9 μm/yr. Because the Re-Os age of the Taizi Formation has not yet been formally peer-reviewed, we further calculated an estimate independent of that age. The published constraints from the Dayanping and Yemahe formations indicate ~3500 m of strata deposited over ≤182 Myr, corresponding to a rate of >19.2 μm/yr. Cyclostratigraphic analysis of the Yemahe Formation independently indicates a rate of ~17.9 μm/yr (Zhou et al., 2024).

In the study interval, 434 laminar couplets were measured, constituting a continuous and well-preserved depositional succession (Figure 5a) that reflects relatively stable sedimentation. If the laminar couplets represent one year, the implied sedimentation rate (~206 μm/yr) exceeds all three long-term estimates (~14.3–34.9 μm/yr) by roughly an order of magnitude. Although this discrepancy might initially suggest a decadal origin for each couplet, an annual interpretation is better supported by sedimentological and microbial-mat evidence. First, microbial mats can enhance sediment trapping, binding and early cementation, thereby amplifying apparent lamina thickness (Figure 4j–l; Noffke et al., 2013). Second, the mean annual lamina thickness records local gross accumulation within a short, well-preserved interval, whereas the long-term estimates represent time-averaged net accumulation over millions of years and inevitably include the cumulative effects of hiatuses, erosion and condensation, consistent with the Sadler effect (Sadler, 1981). This stratigraphic incompleteness is evidenced by a regional disconformity between the Kuangshishan and Taizi Formations (Figure 1c; Li et al., 2013), and by frequent erosional surfaces within the Luanshigou Formation (Figure 2e). The Sadler effect is further supported by well-constrained modern compilations, such as the time-interval synthesis of sediment accumulation rates across the Mississippi Delta, which shows a clear negative scaling between calculated accumulation rate and measurement timescale even over intervals of days to millennia (Jenkins, 2018). Additionally, the mean couplet thickness of ~206 μm falls well within the range documented for annual microbial laminites ($10^2$–$10^3$ μm; Table S1). For example, Mesoproterozoic carbonate biolaminites in the Wumishan Formation (North China) have an average annual couplet thickness of ~528 μm (Tang et al., 2014), and biogenic carbonate varves in Holocene Lake Soppensee (Switzerland) exhibit couplet thicknesses of 250–700 μm (Livingstone and Hajdas, 2001). While these comparative examples come from different depositional settings, they demonstrate that annual microbial laminites of comparable thickness are widely documented.

The fine laminae exhibit distinct orange-red autofluorescence under UV light (Figure 4l), indicating the presence of kerogen derived from organic matter (Gerdes et al., 2000; Tang et al., 2013). In addition to this organic signature, the presence of well-preserved tufts, in the form of vertical growth structures formed by filamentous cyanobacteria, provides key evidence for the development of a mature, cohesive microbial mat (Figure 4k; Gerdes et al., 2000; Noffke et al., 2013). The formation of such structures requires sustained microbial growth and sediment stabilization over months, far exceeding a diurnal timescale (Gerdes and Klenke, 2007). This interpretation is further supported by the common occurrence of near-vertical, strip-shaped particles trapped within the laminae, which attest to the sediment-binding capacity of the original filamentous microbial networks (Figure 4j; Gerdes et al., 2000; Noffke et al., 2003). Collectively, the co-occurrence of kerogen, mat growth structures and trapped particles indicates that the dark laminae represent an extended period of seasonal microbial development under hydrologically quiescent conditions. Consequently, the repetitive alternation of these organic-rich layers with coarse, intraclast-dominated light laminae supports an annual, rather than diurnal, origin for the laminar couplets.

The Luanshigou laminites are characterized by rhythmic alternations of coarse, hematite-poor intraclastic laminae, and fine, hematite-rich microbial mat-derived laminae (Figure 4). This repetitive lamination reflects seasonal fluctuations in hydrodynamic energy, consistent with deposition on a low-latitude carbonate platform that was frequently influenced by storm events and strong currents (Bosence, 2005). During wet seasons, corresponding to enhanced high-energy runoff, storm-induced hydrodynamics not only suppressed microbial mat development but also fragmented and reworked intra-basinal carbonate sediments, leading to the accumulation of coarse intraclast-dominated laminae;

whereas during dry seasons, stabilized water conditions favoured microbial mat proliferation, facilitating hematite precipitation and the formation of fine, iron-rich laminae (Figure 9a; Li et al., 2018). Structurally and genetically, these laminites closely resemble seasonal varve couplets documented in the late Holocene deposits of Jiang Co Lake, providing a robust modern counterpart that strongly supports the interpretation of the Luanshigou laminites as seasonally-controlled, annual deposits (Ji et al., 2021).

### *5.2. Solar Cycles Recorded in the Red Beds*

The Luanshigou laminites are well preserved, and their chemical signals remain unaffected by later diagenetic alteration. Microscopic observations reveal that these finely laminated structures have been well preserved since deposition, and exhibit minimal deformation or evidence of metamorphism (Figure 4). Furthermore, hematite in the red beds preserves primary paleomagnetic information, accurately recording paleolatitude, consistent with an origin from dehydration of precursor ferric mineral phases during burial diagenesis, rather than later stage alteration (Liu et al., 2024). Relatively high $\delta^{18}O$ values (> −10‰) in the Luanshigou carbonates (Li et al., 2022) suggest limited late-stage alteration, given the sensitivity of $\delta^{18}O$ to diagenetic resetting by meteoric or hydrothermal fluids (Kaufman and Knoll, 1995). Furthermore, laser Raman analysis of organic matter in the adjacent Taizi Formation suggests a low metamorphic temperature (~280°C; Li et al., 2022), pointing to a weak regional thermal overprinting. Collectively, these lines of evidence indicate that the elemental variations in the Luanshigou laminar couplets were only minimally affected by post-depositional processes, and can therefore be reasonably interpreted to reflect primary environmental conditions.

In the studied laminites, darker laminae exhibit higher iron concentrations, consistent with the use of rock color (including grayscale) as a qualitative paleoclimate proxy (Li et al., 2019b). In ferruginous environments, iron and phosphorus are closely coupled, as phosphorus released during organic matter decomposition may be efficiently scavenged and co-precipitated with Fe (oxyhydr)oxides, resulting in a positive sediment correlation (Table S7; März et al., 2018). Aluminum, which is primarily hosted in clay minerals such as kaolinite and illite, making its content a reliable tracer of lithological variation, has higher values in fine-grained sediments (Bergaya and Jaber, 2011). Fe/Al and P/Al ratios are therefore used, rather than absolute concentrations, to minimize the influence of detrital input.

Power spectral and evolutionary Fast Fourier Transform (eFFT) analyses of the lamina thickness, grayscale and geochemical series (Al, P/Al and Fe/Al) were used to isolate periodicities that robustly reflect environmental forcing. To this end, three selection criteria were applied: (1) the spectral peak should exceed the 95% $\chi^2$ confidence level; (2) the cycle should be recorded by multiple independent proxies, and (3) the cycle should exhibit persistent power throughout the dataset in eFFT. After applying these criteria, a dominant periodicity of ~77 laminar couplets in the grayscale record (<5% FDR), together with additional persistent cycles at 67–79, 35–40, ~22 and 11–15 laminar couplets (>95% CL), is identified (Figures 5–8; Table S9). Given the annual origin for each laminar couplet, these stratigraphic rhythms can be translated into temporal cycles, and are interpreted to represent the 70 to 90-yr Gleissberg, ~35-yr climatic Brückner, 22-yr Hale, and 11-yr Schwabe cycles (Brückner, 1890; Usoskin, 2017).

Independent spectral analysis of the couplet-thickness series and segmented robustness tests confirm that the principal periodicities are stable against variations in individual couplet thickness; further discussion and supporting data are provided in the Supplementary Materials. Among these, the relatively less well-recognized ~35-yr climatic Brückner cycle is captured in this study, possibly due to amplification associated with the paleogeographic setting at ~30°N. This location lies within the subtropical high-pressure belt, where small-scale climatic forcing can be amplified into pronounced wet–dry variability (e.g., Xu and Yang, 1993). The cyclic fluctuations in grayscale and Fe/Al ratios, which are primarily controlled by variations in hematite abundance, may thus preserve a high-fidelity record of

Fe(II) oxidation dynamics in Mesoproterozoic shallow marine environments. High-frequency cycles of ~2–8 laminar couplets commonly satisfy criteria (1) and (2), but fail criterion (3). In eFFT they appear only intermittently, primarily occupying low-power (blue) zones in the grayscale record and lacking continuity across the entire dataset (Figure 8). The ~11-couplet bundling (Figure 4a), together with the paleolatitudinal setting of the study area at ~30°N near the subtropical high-pressure belt where ENSO teleconnections are indirect and unstable (Figure 1a; Trenberth et al., 1998), points to solar-scale modulation as the more likely driver of wet–dry variability and hematite formation. This does not exclude the possibility that some of these higher-frequency signals carry an ENSO-like signature, but the 2–8-year band does not represent the dominant cyclicity.

### *5.3. Response of Laminite Cyclicities to Solar Activity*

Sedimentary cyclicity records suggest that solar activity may have modulated Earth's climate during the Mesoproterozoic through multiple coupled pathways. Total solar irradiance variations can directly influence surface temperatures (Cubasch and Voss, 2000), while galactic cosmic rays modulate cloud cover via changes in atmospheric ionization (Marsh and Svensmark, 2000). Solar UV irradiance modifies the thermal structure of the middle atmosphere (Haigh et al., 2010), and in the Mesoproterozoic, this pathway may have been amplified: geological iodine records indicate that ozone levels were likely very low (Liu et al., 2025), which would have allowed enhanced UV penetration to the surface and a more direct climatic influence than at present. These mechanisms are not mutually exclusive and likely operated together, collectively linking solar variability to the shallow-marine depositional system.

The impact of sunspot activity on shallow marine iron cycling may vary depending on the origin of the hematite in the red laminites. Proposed genetic pathways for hematite formation can be broadly divided into terrigenous detrital input (e.g., Lepp and Goldich, 1964) and authigenic origins, which include oxidation of ferruginous water at the redoxcline, with subsequent diagenetic dehydration of primary Fe hydroxides to hematite (Song et al., 2017; Tang et al., 2020), and iron oxidation mediated by oxygenic cyanobacteria or microaerophilic iron-oxidizing bacteria (Planavsky et al., 2009). In our case, microscopic observations reveal that ilmenite and hematite in the coarse (lighter) laminae occur as larger (up to 50−100 μm), sub-angular detrital grains with only minor fine-grained authigenic hematite (<1 μm; Figure 4c and d). By contrast, hematite in the fine (darker) laminae is predominantly composed of sub-micrometer-sized, euhedral hexagonal crystals closely associated with microbial mats (Figure 4e–h), supporting an authigenic origin (Tang et al., 2020).

Enrichment in authigenic hematite within microbial mat laminae indicates that iron oxidation was closely associated with microbial activity rather than direct seawater oxidation (Heard et al., 2022). This inference is also supported by low carbonate I/(Ca+Mg) values in our samples (0.20 ± 0.04 μmol/mol; Table S8), below the Precambrian baseline (0.5 μmol/mol) (Lu et al., 2010). This could be a result of diagenetic dolomitization (Hardisty et al., 2017) and/or low seawater oxygen levels (Lu et al., 2010). The absence of correlation between I/(Ca+Mg) and both Mn/Sr ($R^2 = 0.07$, $p = 0.26$) and Mg/Ca ($R^2 = 0.07$, $p = 0.27$) suggests a limited influence of diagenetic dolomitization on the I/(Ca+Mg) values. Thus, the low I/(Ca+Mg) in the Luanshigou laminites likely reflects low seawater oxygen levels, suggesting that oxygen availability was likely not sufficient to completely oxidize Fe(II), and hence microbial activity would have played a role in hematite precipitation (Heard et al., 2022).

The development and preservation of microbial mats, as well as the formation of intraclast carbonates, are both strongly controlled by hydrodynamic conditions (Noffke, 2000; Einsele, 2013). Microbial mats initiate through the secretion of extracellular polymeric substances, which bind sediment grains and stabilize the substrate (Gerdes et al., 2000). Under elevated hydrodynamic energy, however, nascent microbial mats are readily eroded, and even mature mats can be disrupted or removed once a critical shear stress threshold is exceeded (Noffke, 2000). As a result, persistent mat preservation requires prolonged intervals of low-energy conditions. In addition, the Luanshigou Formation is dominated by intraclast carbonates, and its formation was primarily controlled by hydrodynamic processes (e.g., wave and storm activity) that drove sediment fragmentation and reworking (Einsele, 2013). This interpretation is further supported by the microstructural characteristics of ~11 laminar couplet sets (Figure 4a), indicating a strong hydrodynamic control on their deposition. Within a single sunspot cycle, the succession shifts from inorganic coarse laminae to fine, microbially-rich laminae (Figure 4a), which may reflect a climatic transition from wet to dry conditions under the influence of solar variability.

During periods of high sunspot activity, increased total solar irradiance (only ~0.1% of total solar output; Lean and Rind, 2001) and enhanced UV radiation lead to surface warming (Cubasch and Voss, 2000; Haigh et al., 2010). Although oceanic thermal inertia limits the direct temperature response to no more than ~0.1°C (Gray et al., 2010), the more consequential climatic effects operate through atmospheric circulation. Specifically, enhanced radiation modifies the stratospheric thermal structure, driving a poleward expansion of the Hadley circulation and a corresponding poleward shift of the subtropical arid zone, thereby suppressing precipitation at around 30° latitude (Clayton, 1923; Wang et al., 2005). Meanwhile, the stronger solar wind reduces the influx of galactic cosmic rays, resulting in decreased cloud cover and higher cloud altitudes (Andrews et al., 2010). As a result, lower precipitation, and reduced storm frequency and wave energy under these dry conditions, would have favored the settling and preservation of fine-grained sediment, which led to: (1) deposition of fine clay minerals, as reflected by Al variations; (2) sustained microbial mat growth; (3) enhanced Fe oxidation and enrichment; and (4) increased phosphate uptake by Fe (oxyhydr)oxides. Together, these processes facilitated the formation of fine-laminae-dominated couplet sets (Figure 9b; upper yellow interval in Figure 9c). By contrast, during periods of low sunspot activity, increased precipitation and storm frequency would have suppressed microbial mat development through physical disturbance, thus limiting Fe(II) oxidation and favoring the deposition of coarse-laminae-dominated couplet sets (Figure 9d; lower yellow interval in Figure 9c).

An alternative hypothesis suggests that sunspot activity may have influenced continental phosphorus fluxes into the ocean, thereby stimulating microbial mat development and promoting Fe(II) oxidation in shallow seawater. However, this mechanism appears internally inconsistent, since although enhanced rainfall during low sunspot activity would elevate terrestrial phosphorus inputs from continental weathering (potentially stimulating microbial growth and oxygenic photosynthesis), the concurrent intensification of storm activity would disrupt mat establishment and preservation. A more coherent model is that sunspot activity primarily regulated microbial mat development, which in turn drove iron redox cycling and subsequently influenced phosphorus uptake. This interpretation is supported by the positive correlation between P/Al and Fe/Al ($r = 0.69$, $R^2 = 0.47$, $p < 0.01$; Table S7), indicating coupled Fe–P behavior.

This coupled Fe–P behavior is fundamentally different to phosphorus cycling in modern oceans, where regeneration from organic matter predominates (Schlesinger and Bernhardt, 2013). In the anoxic and ferruginous Proterozoic deep ocean (Poulton and Canfield, 2011), however, P recycling was likely markedly suppressed due to drawdown in association with Fe minerals (Reinhard et al., 2016), which would have exerted negative feedback on primary productivity (Song et al., 2023; Poulton, 2017). Our data thus highlight a major controlling factor on microbially-induced Fe (oxyhydr)oxide precipitation and hence fluctuations in the intensity of P drawdown, via changes in sunspot activity.

The patterns provide one of the earliest examples of short-term solar forcing of Earth's shallow-water iron cycle, which in turn would have contributed to short-term fluctuations in mid-Proterozoic shallow-marine oxygenation. Thus, our results extend the perspective of Mesoproterozoic redox variability from the million-year scale (Hardisty et al., 2017; Shang et al., 2019) to high-frequency fluctuations on decadal timescales, indicating that Proterozoic redox conditions varied across multiple temporal scales. We further propose that, under low-oxygen Precambrian conditions, solar activity may have modulated microbial mat productivity in ferruginous shallow marine environments, thereby influencing Fe(II) oxidation. Microbial mats acted as local sites of oxygen production and redox regulation (Heard et al., 2022; Cañadas et al., 2025), providing a biological link between solar-driven climatic variability, iron cycling and shallow-water redox dynamics. Although the observed periodicities and lamina stacking patterns are consistent with known solar cycles and a solar-forced sedimentary origin, the precise transmission pathway from irradiance changes to lamina formation remains unresolved. Future paleoclimate simulations could test how solar activity influenced Earth's climate at ~1.3 Ga.

## 6. Conclusions

In order to better understand the potential influence of sunspot activity on Mesoproterozoic shallow water oxygenation, red carbonate laminites from the ~1.3 Ga Luanshigou Formation in the Shennongjia area, South China were studied through analyses of lithology, geochemistry and power spectra. The following conclusions can be drawn.

(1) Red carbonate laminites of the Luanshigou Formation are composed of laminar couplets characterized by alternating coarse and fine laminae. The coarse laminae represent inorganic, clast-rich deposition during a wet and stormy season, while the fine laminae represent microbial mats formed during a dry and calm season. The laminar couplet is annual in origin.

(2) In the red carbonate laminites, 11-yr-Schwabe, 22-yr-Hale, 35-yr Brückner climatic, and 70–90-yr-Gleissberg cycles can be identified.

(3) Sunspot activity may have affected hydrodynamic conditions by regulating climate and the

development and preservation of microbial mats, resulting in periodic changes in iron cycling, thereby driving substantial short-term variability in shallow water redox conditions through the mid-Proterozoic.

(4) Combined with previously documented million-year-scale redox oscillations, our results reveal pervasive redox dynamics from decadal to million-year timescales, further challenging the traditional "Boring Billion" paradigm.

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## Supplementary materials

Supplementary material, including all data, associated with this article can be found in the online version, at XXX.

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**Figure Captions**

**Figure 1.** Geological setting and stratigraphy of the study area. (a) Global paleogeographic reconstruction at ~1.3 Ga, showing the location of the study area relative to major continental blocks

(modified from Liu et al., 2024). The study area is located on the northern margin of the Yangtze Block. (b) Geological map illustrating the distribution of the Shennongjia Group and the location of the studied section (modified after Li and Leng, 1991). The upper left inset shows the major tectonic subdivisions of China. (c) Stratigraphic column of the Mesoproterozoic Shennongjia Group (modified after Li et al., 2022). U-Pb ages from baddeleyite in mafic dikes and zircon in tuff layers, and Re-Os ages from black shales, are from: (1) Li et al. (2013); (2) Du et al. (2016); (3) Li et al. (2013); (4) Gao et al. (2024); (5) Jiang et al. (2024); (6) Li et al. (2013). (d) Stratigraphic column of the studied interval, indicating the sampling horizon (red arrow).

**Figure 2.** Carbonate laminites and associated lithofacies from the study section, interpreted as peritidal deposits (Kuang et al., 2018). (a) Basal conglomerate of the overlying Dawokeng Formation. (b) Luanshigou Formation dolostone with thin chert bands (arrows). (c) Reddish silty dolostone characterized by densely spaced laminar couplets. (d) Reddish laminated argillaceous dolostone exhibiting a weakly developed domal structure (arrows). (e) Reddish argillaceous carbonate laminite, exhibiting frequent small-scale erosional surfaces (arrows). (f) Columnar stromatolite developed in dolostone.

**Figure 3.** Field sampling, a 177.7-mm-thick polished slab, and continuous large thin-section acquisition from the Luanshigou Formation. (a) Field outcrop of laminated argillaceous dolostone showing continuous laminar couplets. Dashed box indicates the sampled interval. (b) Polished slab (~177.7 mm

thick) extracted from the outcrop, showing well-developed sub-millimeter-scale laminae. (c and d) Continuous large thin section from the ~177.7 mm-thick polished slab, showing straight, continuous, and well-preserved laminae.

**Figure 4.** Microscopic and mineralogical features of the red carbonate laminites from the Luanshigou Formation, Shennongjia area. (a) Photomicrograph of the carbonate laminites, illustrating a representative ~11-couplet cyclicity. Lcs = laminar couplets. Red arrows indicate the dark laminae within each couplet, with each marking one laminar couplet. (b) Representative X-ray diffraction (XRD) pattern indicating dolomite, quartz, hematite, ilmenite, illite and feldspar. (c and d) BSE image of a coarse lamina composed of abundant intraclastic dolomite (Dol), large, irregularly shaped terrigenous detrital hematite (D-Hem), ilmenite (Ilm) and feldspar (Fsp), within a fine-grained matrix of dolomite and authigenic hematite (A-Hem). (e) High-magnification BSE image of fine laminae showing flaky hematite with face-to-edge contacts and euhedral hexagonal hematite crystals. (f) Higher-magnification BSE image of a fine lamina displaying a euhedral hexagonal hematite crystal. (g) Electron backscatter diffraction (EBSD) pattern of the hexagonal hematite grain marked in panel (f) with a "+" symbol. (h) BSE image and corresponding EDS elemental line scans of Fe, O and Si. Higher Fe and O, and lower Si concentrations occur in the authigenic hematite relative to the matrix. (i) BSE image and corresponding EDS elemental map scans of Fe and Al. Higher Fe and Al concentrations occur in the fine laminae (FL) relative to the coarse laminae (CL). (j) BSE image showing a vertically preserved detrital ilmenite (Ilm) grain within a lamina. (k) Plane-polarized light photomicrograph illustrating wavy, organic-rich dark laminae (arrows)

and small tufted structures (lower left arrows). (l) Fluorescence photomicrograph of the area boxed in panel (k), showing orange-red autofluorescence from organic matter in the fine laminae.

**Figure 5.** Statistical analyses and time-series of laminar couplet thickness in the Luanshigou Formation. (a) Photomicrograph of Figure 3c. (b) Variations and statistics of annual laminar couplet thickness in panel (a). (c) Data shown include the original thickness (blue), their second-order polynomial trend (yellow), and the corresponding detrended residuals (orange). Negative residual values indicate deviations below the fitted second-order polynomial trend and do not represent negative physical measurements. (d) Power spectra (black curves) of the detrended thickness series shown in panel (c). Bold labels indicate cycle lengths in laminar couplets (LC), calculated as 1 ÷ frequency (cycles/LC), whereas the numbers below in normal font denote frequencies (x-axis values). 1 LC corresponds to 1 yr. Thus the ~67 and ~13 LC cycles correspond to the Gleissberg (G; 70–90 yr) and Schwabe solar cycles (S; ~11 yr), respectively, whereas the ~2, ~3 and ~5 LC cycle falls within the ENSO-like band (2–7 yr). (e) Evolutionary Fast Fourier Transform (eFFT) spectrograms of the thickness.

**Figure 6.** Grayscale and X-ray fluorescence (XRF) records from the thick polished slab in Figure 3b. The arrow indicates the line-scanning track. Data shown include the original grayscale, Al, P/Al and Fe/Al series (blue), their 30% LOWESS trends (yellow), and the corresponding detrended residuals (orange). Negative values represent deviations below the fitted LOWESS trend and do not indicate

negative physical measurements. To better visualize the variations in P/Al and Fe/Al, a logarithmic (log) scale is applied to the y-axis.

**Figure 7.** Time series analysis of the grayscale and element records from the Luanshigou laminites at 0–0.5 cycles/mm. (a–d) Power spectra (black curves) of the detrended grayscale (a), Al (b), P/Al (c), and Fe/Al (d) series, derived from the thick polished slab shown in Figure 3b. Bold labels indicate cycle lengths in laminar couplets (LC), calculated as 1 ÷ frequency (cycles/mm) ÷ average laminar couplet thickness (0.206 mm), whereas the numbers below in normal font denote frequencies (x-axis values). 1 LC corresponds to 1 yr. Thus the 68–79, 35–40, ~22, and 11–15 LC cycles correspond to the Gleissberg (G; 70–90 yr), Brückner climatic (B; ~35 yr), Hale (H; ~22 yr), and Schwabe solar cycles (S; ~11 yr), respectively. (e–h) Evolutionary Fast Fourier Transform (eFFT) spectrograms of the grayscale (e), Al (f), P/Al (g), and Fe/Al (h) series.

**Figure 8.** Time series analysis of the grayscale and elemental records from the Luanshigou laminites at an expanded frequency range (0–5 cycles/mm). (a–d) Power spectra (black curves) of the detrended grayscale (a), Al (b), P/Al (c), and Fe/Al (d) series, derived from the thick polished slab shown in Figure 3b. Compared to the low-frequency analysis (0–0.5 cycles/mm; Figure 7), this range highlights shorter-wavelength variability. Cycle lengths are expressed in laminar couplets (LC) using the same conversion as in Figure 7. 1 LC corresponds to 1 yr. Thus the 2–8 LC cycle falls within the ENSO-like band (2–7

yr). (e–h) Evolutionary Fast Fourier Transform (eFFT) spectrograms of the grayscale (e), Al (f), P/Al (g), and Fe/Al (h) series.

**Figure 9.** Sedimentary fabric and proposed solar-climate coupling model for the Luanshigou laminites. (a) Seasonal formation model of the two lamina types: coarse, hematite-poor silt-sand laminae deposited during high-energy wet seasons, and fine, hematite-rich argillaceous laminae associated with microbial mats developed during low-energy dry seasons. (b) Proposed climatic response during solar maxima: enhanced solar UV irradiance drives a poleward expansion of the Hadley circulation and shifts the subtropical arid zone, suppressing precipitation at ~30°N; combined with increased total solar irradiance and reduced GCR flux, this decreases cloudiness and storm frequency. The resulting stable hydrodynamic conditions promote microbial mat growth, Fe(II) oxidation, and deposition of fine-laminae-dominated couplets. (c) Representative thin section photograph showing variations in lamina character across a solar cycle: finer particles, well-developed microbial mats, and higher authigenic hematite content during drier intervals (darker couplet set), and coarser particles with reduced mats and hematite during wetter intervals (lighter couplet set). FL = Fine lamina; CL = Coarse lamina; HC = Hydrodynamic condition; SC = Solar cycle; Cli. = Climate. (d) Proposed climatic response during solar minima: reduced solar UV irradiance and lower total solar irradiance, combined with an enhanced galactic cosmic ray (GCR) influx increases cloud cover and precipitation. The resulting higher hydrodynamic energy suppresses microbial mat development and Fe(II) oxidation, thereby favoring deposition of coarse-laminae-dominated couplets.