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Supplementary Information for

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

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Text S1. Robustness of spectral periodicities to couplet thickness variations

Spectral analysis of the grayscale, Al, P/Al and Fe/Al records reveals dominant cycles at ~68–79, ~35–40, ~22 and ~11–15 laminar couplets (main text Figures 5 and 7). Given the annual origin of each laminar couplet, these stratigraphic rhythms can be translated into temporal cycles and are interpreted to represent the 70 to 90-year Gleissberg, approximately 35-year climatic Brückner, 22-year Hale, and 11-year Schwabe cycles (Brückner, 1890; Usoskin, 2017). Because this temporal interpretation partly relies on converting depth-domain frequencies using the mean laminar-couplet thickness, we further evaluated the sensitivity of the inferred periodicities to variations in individual couplet thickness. Although individual laminar-couplet thicknesses vary substantially (coefficient of variation = 52%; standard deviation = 108 µm), the small standard error of the mean (5 µm) indicates that the mean thickness of 0.206 mm is statistically well constrained and can serve as a reasonable first-order scaling factor for depth–time conversion. In addition, spectral analysis of the laminar-couplet thickness series, conducted directly in the couplet-number domain without relying on mean-thickness conversion, yields solar-activity-related periodicities consistent with those identified in the grayscale and geochemical records (main text Figures 5 and 7).

Segmented spectral robustness tests further confirm that the principal cycles recur consistently across different parts of the section (Figure S1). Specifically, the Gleissberg cycle (~68–79 laminar couplets) appears in all four proxies and exceeds the 5% false discovery rate threshold in the grayscale record. The Brückner cycle (~35–40 laminar couplets) is identified in all three Al windows, in the front and middle P/Al windows, and in the last Fe/Al window. The Hale cycle (~22 laminar couplets) is detected in all three

Fe/Al windows, and in the front and middle P/Al windows. The Schwabe cycle (~11–15 laminar couplets) occurs in all three P/Al windows, in the middle and last Al windows, and in the last Fe/Al window. The corresponding depth-domain frequencies remain within narrow ranges: 0.06–0.08 cycles per millimetre for the Gleissberg cycle, 0.14–0.15 for the Brückner cycle, 0.21–0.22 for the Hale cycle, and 0.39–0.44 for the Schwabe cycle.

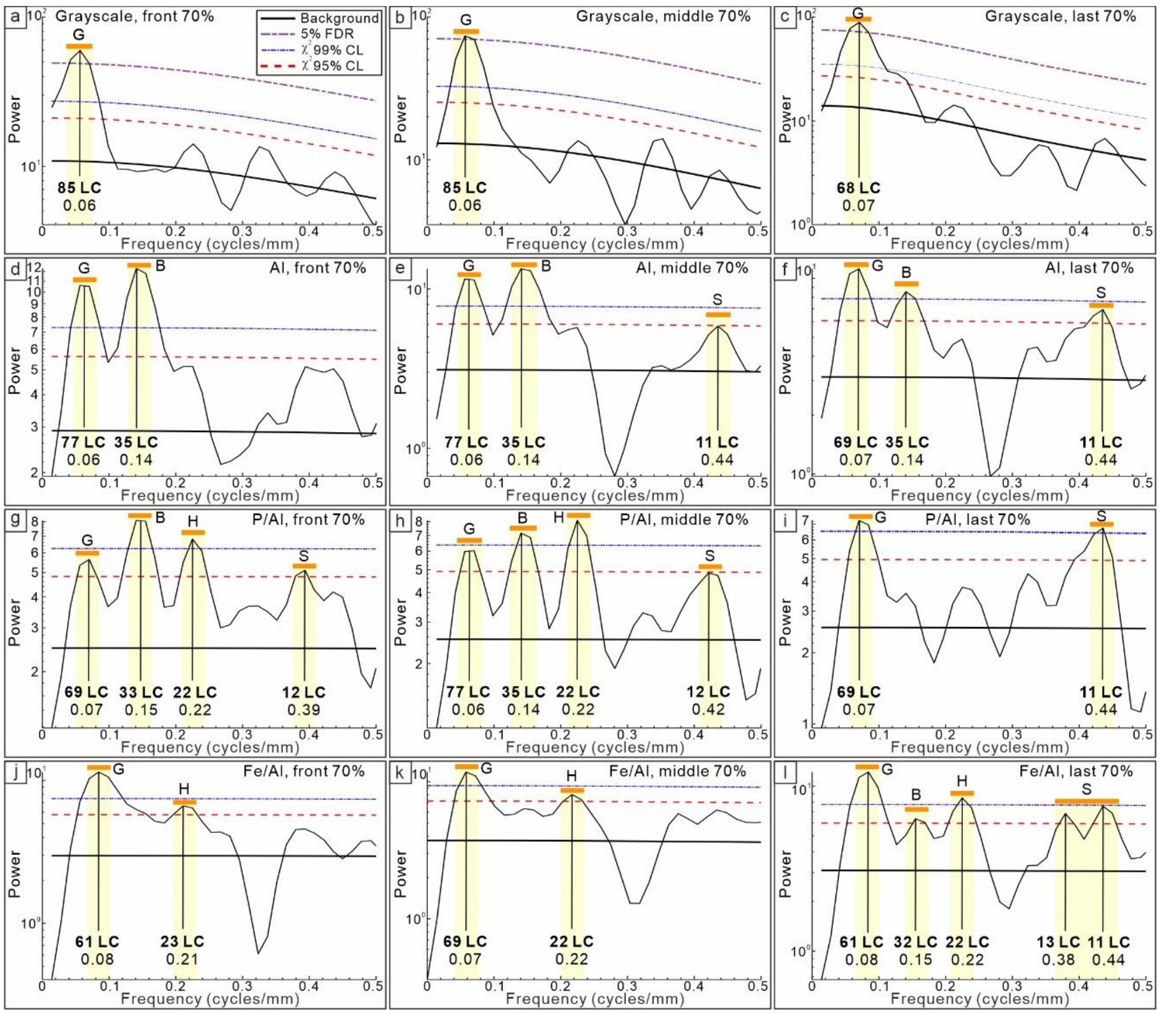

Figure S1. Segmented spectral robustness analysis of grayscale and elemental proxy records from the Luanshigou laminites. Periodograms were calculated separately for the front, middle, and last 70% overlapping windows of each record. (a–c) Grayscale; (d–f) Al; (g–i) P/Al; and (j–l) Fe/Al. Bold labels 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 61–85, 32–35, 22–23 and 11–13 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.

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Usoskin, I.G., 2017. A history of solar activity over millennia. Living Reviews in Solar Physics 14, 3. https://doi.org/10.1007/s41116-017-0006-9

Table S1. Examples of Schwabe sunspot, solar Hale and Gleissberg cycles recorded in sedimentary rocks.

Table S2. Detailed parameters used in data processing by Acycle.

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