2470 million-year-old banded iron formation reveals a climatic oscillation consistent with the Gleissberg solar cycle

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Modern-day solar cycles due to the solar magnetic field oscillation are well recognized. Owing to the response of Earth's climate to solar activity fluctuation, solar cycles in the Phanerozoic Eon have been recorded by laminites and fossil tree rings. However, the existence of magnetic cycles within the Sun younger than 3100 million-year-old is still unknown. The deposition of Precambrian banded iron formations (BIFs) reflects the primary productivity of the early ferruginous oceans and is coupled to climatic fluctuations. Here we apply synchrotron-radiation-based μ -XRF with a 20 μ m interval on a 60 mm long, 2470 million-year-old BIF from the Kuruman Formation, South Africa. Our spectral analyses of multiple elemental concentration series reveal prominent and consistent 80-year cyclicity, which is best explained by the Gleissberg solar cycle. We hypothesize that solar cycles have already modulated the early Paleoproterozoic climate mainly through high energy irradiance coupled solar radiative forcing oscillation and the solar magnetic field controlled galactic cosmic ray fluctuation. Our result provides the record of solar magnetic field oscillations with stable and close-to-present cycle durations at least since the beginning of the Paleoproterozoic Era.

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Driven by the Sun's magnetic field oscillation¹, solar irradiance fluctuation has an 11-year cycle at present². Longer solar activity periods, such as the 22-year-Hale cycle³, the 80-to-90-year Gleissberg cycle⁴, and the 210-year-Suess cycle⁵, are also recognized based on sunspot trends or cosmogenic radioisotope proxies. It is well accepted that some of the Earth's climatic cycles are coupled to the solar cycles⁶. Such cyclic climatic variations are revealed in sedimentary archives of Cenozoic⁷, Mesozoic⁸, Paleozoic⁹, Neoproterozoic¹⁰, and Mesoproterozoic¹¹, but no convincing evidence from older sediment records^{12,13}. When did the Sun's magnetic field exhibit stabilized cycles? Did the lengths of such cycles change through the Sun's history? Such knowledge will not only inform us of the solar influence on the early Earth's climate, but also have implications to the evolution of Sun-like stars in the main-sequence of the Hertzsprung–Russell diagram and their dynamos.

Banded iron formations (BIFs) are distinctive Precambrian chemical sedimentary deposits with alternating iron and silica-rich bands precipitated from ferruginous oceans¹⁴. The proposed iron precipitation mechanisms include oxidation by molecular oxygen (produced by oxygenic phototrophs)¹⁵, photoferrotrophs^{16,17}, and microaerophilic iron-oxidizing chemolithotrophs¹⁸, all of which are linked to Precambrian marine primary productivity. In modern oceans, climate variability modulates the change in the depths of the marine nutricline, photocline, and thermocline, which have significant impacts on marine primary productivity¹⁹. Superior-type BIFs were deposited on wide continental shelves far from hydrothermal vents¹⁴. Therefore, unlike those of Algoma-type BIFs, their rhythmic structures were not controlled by volcanic activity, but might have recorded the fluctuation of marine primary productivity in response to climatic cycles. The 2470 million-year (myr) Kuruman BIF of the Transvaal Supergroup, Kaapvaal Craton, South Africa, exhibits exquisite microbanding (Fig. 1) and low-grade metamorphism, representing one of the best-preserved Superior-type BIFs in the world²⁰. Its depositional rate was recently constrained to be around 10 m per myr by zircon U–Pb dating²¹, which is consistent with the proposed ca. 20 nm diurnal deposition of hematite nanobands within the Kuruman BIF²² combined with ca. 17.5 h day length at the earliest Proterozoic²³. Therefore, the Kuruman BIF is ideal for the identification of any short-term climatic variation.

Here, we applied synchrotron-radiation-based μ -XRF analysis on a 60 mm-long, thinly laminated specimen with a 20 μ m interval to obtain elemental relative concentration series. Spectral analysis was carried out for all measured elements to investigate potential solar forcing-related cyclic climatic variations in the early Paleoproterozoic Era.

Results

A drill core sample of the Kuruman BIF with microbands was selected for this study (Fig. 1). Its petrology was previously described in detail in Li²². A line of 2972 points was scanned by the synchrotron-radiation-based μ -XRF with an interval of 20 μ m. Relative elemental concentrations in counts per second (cps) of Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, and As were obtained by fitting the μ -XRF dataset using PyMca²⁴ (Fig. 1, Supplementary Fig. 1 and Supplementary Data 1). Among all the detectable elements, Fe has the highest abundance, with its concentration fluctuating across iron-rich and silica-rich microbands in the sample. Manganese, although holding a large standard deviation, has a moderate average concentration. The concentrations of other elements in the sample are low. The elemental spectra of Ti, Cr, Cu, Zn, Ga, and Ge show moderate to strong positive linear correlations with that of Fe (Supplementary Fig. 2 and Supplementary Table 1). Other detected elements, i.e.,

V, Mn, Ni, As, show weak to negligible linear correlation with Fe (Supplementary Fig. 2 and Supplementary Table 1). Among all the measured elements, the spectra of Fe and Ni exhibit red-noise backgrounds, which is typical for climatic time series, and thus provided meaningful results in spectral analysis using REDFIT²⁵. Other elements fail the red-noise background test, indicating strong non-climate-controlled delivery into the sediment. The spectral analytical results applying an oversampling factor of 4, and a Welch-overlapped-segment-averaging (WOSA) segment number of 10 with the Blackman–Harris window are shown in Fig. 2. The spectral amplitude above the critical confidence level only has a $(1/n) \times 100\%$ probability (where n is the number of data points within each WOSA segment) of being generated by red-noise processes. In this study, only peaks that pass the critical confidence levels are considered statistically significant to rule out any fake signal due to sampling fluctuations^{25,26}. Both Fe and Ni show strong signals (above critical confidence level, i.e., 99.77%) around the frequency of 1.25 mm^{-1} (Fig. 2, this peak is also evident in Cr, Cu, Ga, Ge, Ti, and Zn shown in Supplementary Fig. 3), which correspond to a period of 0.8 mm. Spectral analyses applying other data windows and WOSA segment numbers yield similar results. Wavelet transform analyses with data interpolation using the software PAST²⁷ confirm such signals (Supplementary Fig. 4). Four lutite ages from volcanic zircons throughout 200 m of the Kuruman BIF were recently reported²¹. We infer the stratigraphic chronology with a Bayesian monotone model using Bchron package in R (Supplementary Fig. 5)²⁸. The result implies a compacted depositional rate of the whole Kuruman BIF strata to be 10 m per myr, with a 95% confidence interval of 8.3–17.1 m per myr, which is largely consistent with the nanometer-scale scanning transmission electron microscope observation^{22,23} and previously published zircon-age-determined depositional rates²⁹. Therefore, the coherent 0.8 mm harmonic signal revealed by both Fe and Ni spectra suggests a cycle with a period of 80 years (with a 95% confidence interval of 47–96 years).

Discussion

The microbands and associated variability of the BIF's elemental concentrations indicate the influence of climatic cycles on its deposition, similar to Holocene sedimentary sequences⁷. Marine primary productivity has been shown sensitive to decadal to centennial climatic fluctuations¹⁹. Satellite remote sensing reveals that the present trend of ocean net primary productivity is coupled to climate variability, which influences ocean stratification and nutrient flux³⁰. Climatic oscillation may have affected early Paleoproterozoic marine primary productivity, with its variation preserved in BIFs deposited in an open shelf environment below the wave base²⁰. The debate regarding BIF formation by photoferrotrophs, microaerophilic iron-oxidizing chemolithotrophs, or molecular oxygen produced by oxygenic phototrophs is heated¹⁴. Nevertheless, any of these three microbial groups would have dominated the marine primary productivity and controlled the ferrous iron oxidation rate in ferruginous basins with BIF deposition. As a result, climate fluctuations may have been primarily recorded as the concentration of iron in BIF strata, given that iron oxyhydroxides were the precursor precipitates induced by microbial activities¹⁴. Moreover, bio-essential elements may have recorded climate-coupled primary productivity fluctuation when the elemental signature of microbes was recorded in BIFs³¹. Previous BIF stratigraphic analyses typically had resolutions of centimeter-scale²¹, which only extracted long-term variabilities (kyr to >100 kyr). Our micrometer-scale analysis results demonstrate coherent short-term cycles revealed by both the microbial metabolism-related major element, iron, and the bio-essential trace element, nickel. The Fe spectrum is consistent with

Fig. 1 Microbanded Kuruman BIF drill core sample with its Fe and Ni elemental spectra in cps. **a** Microbanded Kuruman BIF drill core sample. The intervals denoted by yellow dots represent 17 mm segments. **b, c** Fe and Ni elemental spectra of the sample in cps. Segments of systematic measuring anomalies (0–4.96 mm, 19.02–19.34 mm, 39.64–42.90 mm, and 55.70–59.42 mm) were removed. Two points have Ni concentrations much larger than the others, as denoted by the arrows.

a red-noise spectral model, typical for paleoclimatic time series, and exhibits a dominant peak of 80-year-period (with a 95% confidence interval of 47–96 years) (Fig. 2a). Elemental spectra of Ti, Cr, Cu, Zn, Ga, and Ge give a harmonious cycle period of ~80-year, similar to Fe (Supplementary Fig. 3). They show moderate to strong positive linear correlations with the spectra of Fe (Supplementary Fig. 2 and Supplementary Table 1), which could be attributed to the substantial co-precipitation or absorption effect of iron oxyhydroxides^{32–34}. The spectrum of Ni has a red-noise background and shows a strong signal of a 79-year-period (with a 95% confidence interval of 46–95 years; Fig. 2b). Nickel is essential for multiple key metalloenzymes of methanogens, including hydrogenases, methylcoenzyme M reductases, and CO dehydrogenases³⁵. The presence of methanogens in the Archean is supported by carbon isotope analysis of both kerogen³⁶ and methane in fluid inclusions³⁷ as well as filamentous microfossils with specific Ni-organic compounds³⁸. Studies of ferruginous ocean analogues have found that methanogenesis is the dominant organic carbon degradation pathway in ferruginous water bodies³⁹. During the depositional stage of the BIF precursor materials, the growth of methanogens within sediments should have been correlated with the organic matter flux from the photic zone, which is supported by the primary productivity. As a result, the Ni-required growth of methanogens and their Ni uptake

should also have been correlated with the Paleoproterozoic marine primary productivity, and recorded climatic fluctuations coupled to solar cycles. The spectrum of Ni concentration in our result displays a negligible correlation with that of Fe (Supplementary Fig. 2 and Supplementary Table 1), implying a time delay between iron oxyhydroxide deposition and organic matter settling followed by degradation through methanogenesis. On the other hand, the spectra of V, Mn, and As show no evident cycle with an 80-year period (Supplementary Fig. 6). In pre-GOE anoxic oceans, vanadium exists in the form of V(III), which readily hydrolyzes and precipitates as insoluble hydroxides, largely independent of microbial activity and iron cycling⁴⁰; Manganese holds unique depositional channels apart from co-precipitation with iron⁴¹; reduced As(III) has high solubility and will not be scavenged by iron oxyhydroxides⁴². Therefore, the elemental spectra of these three elements did not preserve climatic cycle signals and exhibit little correlation with that of Fe (Supplementary Fig. 2 and Supplementary Table 1).

The prominent and consistent ca. 80-year climatic cycle period recorded in the sedimentary archive 2470 myr ago fits well with the period of Gleissberg solar cycles. Multiple causes may lead to climate oscillations at different time scales. Orbital forcing drives the Earth's long-term climate cycles (Milankovitch cycles), with the shortest period being 23-kyr attributed to precession⁴³, and

Fig. 2 Spectral patterns of Fe and Ni for the Kuruman BIF section. a, b The spectral patterns of Fe and Ni are shown in black lines, largely consistent with their red-noise background (red lines). Peaks above the critical false-alarm level (99.77%, blue lines) are labeled. Analyses were carried out with an oversampling factor of 4, 10 WOSA segments, and the Blackman–Harris data window.

recorded in the geological record as far back as the Archean Eon⁴⁴. The lunar nodal tide cycle holds a period of 18.6-yr at present⁴⁵. With closer Earth–Moon distance in the Paleoproterozoic, a longer lunar nodal period should be expected⁴⁶. However, an 80-year nodal tide cycle 2470 myr ago would imply that the Moon is not older than 2500 myr (calculation in Supplementary Note 1), which contradicts its formation in the early Hadean⁴⁷. The correlation between solar cycles and the Earth's climatic variation has been confirmed by sunspot monitoring and direct Earth surface temperature measurements⁶. This correlation may have already been effective as early as the Paleoproterozoic Era. The 80-to-90-year Gleissberg solar cycle is evidenced by sunspot variation⁴, solar proton event history⁴⁸, cosmogenic isotope time series⁴⁹, geomagnetic activity⁵⁰, monsoonal pattern⁵¹, and season temperature evolution⁵². After rejecting the possibility of other climatic cycles, the Gleissberg cycle best explains the coherent peaks revealed by the spectra of Fe and Ni at an ~80-year period with high confidence levels (Fig. 2). Our result does not show the 11-year Schwabe cycle or the 22-year-Hale cycle, the recognition of which usually requires at least annually resolved sedimentary or tree-ring records^{11,53}. The absence of these shorter solar cycles in this study could be attributed to the relatively low temporal resolution of our μ -XRF analysis (20 μ m, i.e., ~2 year).

Our result is best explained by the existence and stabilization of the solar cycles with close-to-present periods in the early Paleoproterozoic Era. Solar cycles are the expression of the Sun's magnetic field variation, which is mainly induced by the Sun's differential rotation and outer layer convection¹. A young Sun releases less energy but rotates faster, producing a stronger magnetic field than the present Sun⁵⁴. Data from the Mount Wilson Observatory and the Kepler satellite confirm that young Sun-like stars of different ages have stable magnetic cycles^{55,56}. These observations of Sun-like main-sequence stars support the presence of stable solar magnetic cycles within the Sun 2100 myr after its formation. Solar-cycle reconstruction by the cosmogenic radioisotopes ¹⁴C and ¹⁰Be covers the entire Holocene⁵⁷. Fossil tree rings revealed the 11-year Schwabe cycle as early as the Permian⁵⁸. Biolaminites with naive depositional rate constraints extend this record into the Mesoproterozoic¹¹. No convincing evidence for solar cycles older than 1500 myr has been reported before. Both Hughes et al.¹³ and Dmitriev et al.⁵⁹ reported potential records of solar cycles based on the same part of argillite strata in mid-Paleoproterozoic Gowganda Formation. However, neither studies have considered red noise when analysing climatic time series, nor did they provide any depositional rate constraints to support their varve interpretation of the couplets. Another recent study, which sampled two sections within the same formation, only found 2.2–2.9-couplet-cycles consistent and statistically significant on a red-noise background⁶⁰. Our result suggests that the solar magnetic cycles have already been operational for at least 2470 myr, although the Sun's rotational rate decreases and its luminosity increases throughout the solar evolution⁵⁴. This criterion may shed light on the mechanism of solar magnetic cycle regulation and main-sequence star dynamos.

Variations of solar activity recorded in sedimentary cyclicity could have regulated the Earth's climate in the early Paleoproterozoic, similar to the present. Besides small variation of total solar irradiance over solar cycles directly modulating the Earth's surface temperature⁶¹, solar forcing is proposed to affect the modern-day climate through multiple pathways, including solar ultraviolet (UV) irradiance influencing the thermal and compositional structure of the middle atmosphere⁶², solar energetic particles destroying atmospheric ozone⁶³, and galactic cosmic rays modifying cloud cover by altering atmospheric ionization⁶⁴. However, their relative contributions and detailed mechanisms remain controversial⁶⁵. The atmospheric composition and structure of the pre-GOE Earth were characterized by elevated levels of carbon dioxide, extremely low molecular oxygen concentration, and a negligible ozone layer^{66,67}. The unique atmosphere entails potentially different influencing mechanisms of solar activity on the Earth's climate. With extremely low atmospheric oxygen and ozone, solar UV irradiance could penetrate the pre-GOE atmosphere and reach the Earth's surface. Unlike visible light and infrared radiation dependent on the bolometric luminosity of the Sun, high energy solar irradiance, including UV and X-ray irradiance, is induced by the solar magnetic field⁶⁸, thus exhibiting more significant fluctuation through solar cycles⁶⁹. Due to the faster rotation and consequently a stronger magnetic field, the 2100-myrs-old Sun may have emitted high energy irradiance 2.5 times higher than the present level⁶⁸. Therefore, the direct impact of solar radiative forcing on Earth's surface temperature through solar cycles, mainly attributed to high energy radiance variability, may have been more effective in the early Paleoproterozoic Era. The stronger magnetic field of a younger Sun should also have led to enhanced solar high energy particle emission and reduced galactic cosmic rays reaching Earth⁷⁰. Without an atmospheric ozone layer, the effect of solar energetic particles on the early Earth's climate is unclear⁶³. Nevertheless, cosmic ray intensity oscillation coupled with solar

magnetic cycles may have affected the Paleoproterozoic climate analogous to the present situation⁶⁴.

Conclusion

In this study, we provide the oldest evidence of possible 80-year Gleissberg solar cycle and demonstrate the solar-cycle-climate coupling recorded in BIF deposited in the early Paleoproterozoic Era. The high sensitivity of BIF deposition to climatic oscillations further strengthens its connection to microbial ecophysiology, which may shed light on the understanding of the early Earth's biogeochemical cycles. The close to modern solar-cycle periodicity 2470 myr ago, together with other records of solar cycles, indicates long-term stability of solar magnetic field oscillations despite the faster rotation and lower bolometric luminosity of the Sun in the earlier geological time.

Methods

μ -XRF measurements of the sample were performed at beamline BL15U1 of Shanghai synchrotron-radiation facilities (SSRF) with a designed 3.5 GeV electron storage ring and 150–250 mA current⁷¹. The photon energy of the beam was selected using a double crystal monochromator of Si (111). The sample was mounted at an x - y - z stage and oriented at 45° to the beam incidence. The incident beam was monitored using an ion chamber, and the fluorescence signal was measured with a Si (Li) solid-state detector perpendicular to the beam incidence, of which the energy resolution was 140 eV at 5.9 KeV. For these measurements, the beam size was controlled at 5 μ m $\times$ 3 μ m (horizontal $\times$ vertical). For the XRF measurement, the excitation energy was set at 14.0 KeV, and the dwelling time was set to 5 s. A line of 2972 points was scanned with an interval of 20 μ m, perpendicular to the BIF sample's microbands. Relative elemental concentrations in counts per second (cps) were obtained by fitting the μ -XRF profiles using PyMca²⁴ (Supplementary Data 1). A representative single point μ -XRF profile is shown in Supplementary Fig. 7. Segments with systematic measuring anomalies were removed (Supplementary Fig. 8). The program REDFIT (version 3.8e) was applied for spectral analysis without data interpolation²⁵. The appropriateness of fitting the elemental spectra with red-noise backgrounds, which is often the case for paleoclimatic time series, was first tested. To get a consistent frequency domain spectral estimate, we applied an oversampling factor of 4 and 10 WOSA segments with the Blackman–Harris window for spectral analyses. Only signals passed the critical false-alarm levels $[(1 - 1/n) \times 100\%$, where n is the number of data points within each WOSA segment] were considered statistically significant²⁶. Analyses with WOSA segment numbers from 5 to 13 and other data windows (rectangle, triangle, Welch, and Hanning) were carried out to verify our results. The continuous wavelet transform of the elemental spectra was analysed using the software PAST with linear data interpolation²⁷.

Data availability

The elemental spectra data are provided in Supplementary Data 1 and available in PANGAEA under the title “Relative elemental concentrations of Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, and As of a drill core sample of the Kuruman BIF with microbands measured by the synchrotron-radiation-based μ -XRF”.

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Author contributions

Y.L.L. planned the research. Y.L.L. and A.D. did the experiments. A.D. processed the data and did the model tests. A.D., Y.L.L., and A.H. co-wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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