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Climate control on banded iron formations linked to orbital eccentricity

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Abstract

Astronomical forcing associated with Earth's orbital and inclination parameters ("Milankovitch" forcing) exerts a major control on climate as recorded in the sedimentary rock record, but its influence in deep time is largely unknown. Banded iron formations, iron-rich marine sediments older than 1.8 billion years, offer unique insight into the early Earth's environment. Their origin and distinctive layering have been explained by various mechanisms, including hydrothermal plume activity, the redox evolution of the oceans, microbial and diagenetic processes, sea level fluctuations, and seasonal or tidal forcing. However, their potential link to past climate oscillations remains unexplored. Here we use cyclostratigraphic analysis combined with high-precision uranium-lead dating to investigate the potential influence of Milankovitch forcing on their deposition. Field exposures of the 2.48-billion-year-old Kuruman Banded Iron Formation reveal a well-defined hierarchical cycle pattern in weathering profile that is laterally continuous over at least 250 kilometres. The isotopic ages constrain the sedimentation rate at 10 m/Myr and link the observed cycles to known eccentricity oscillations with periods of 405 thousand and about 1.4 to 1.6 million years. We conclude that long-period, Milankovitch-forced climate cycles exerted a primary control on large-scale compositional variations in banded iron formations.

Banded iron formations (BIFs) are iron-rich (~30 wt %) and distinctively layered chemical sediments that were widely deposited in the Neoproterozoic to early Paleoproterozoic oceans,

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Data availability

The authors declare that the data supporting the findings of this study are available within the article and its supplementary information files. Raw data files of the weathering profile logs are available from the corresponding author upon request.

Author contributions

All authors have contributed to developing the ideas presented. F.J. conceived the project. F.H., M.L., J.D. and U.S. collected the field data. F.H. and M.L. did the cyclostratigraphic analyses and interpretation. J.D. carried out U-Pb dating work. M.L. wrote the article, with U-Pb contributions from J.D. and help from F.H., P.M. and U.S.

Competing interests

The authors declare no competing interests.

between 2.8 and 2.4 billion years ago^{1,2}. So far, they have been mainly related to hydrothermal plume activity^{3–6}, the evolution of continental shelves^{7,8}, diagenetic and microbial iron cycling^{9–11}, and the rise of oxygen in the oceans and atmosphere^{12,13}. In contrast, very little is known about the possible link between climate variability and BIF.

Here we focus on the potential influence of Milankovitch forcing on the formation of BIF. Secular climate variations ($10^4 - 10^6$ year scale) induced by cyclic changes in the Earth's orbit and inclination axis must have been operating at that time¹⁴ and may explain the rhythmic layering observed in BIFs^{15,16}. However, evidence for Milankovitch cyclicity in BIF has never been conclusively presented, despite claims for the presence of seasonal^{3,17,18} or tidal¹⁹ laminations and eustatic sea level alternations^{3,20} suggesting a climate control. A key problem is the uncertainty in BIF depositional rates due to the lack of high-quality radio-isotopic ages. Currently available U-Pb SHRIMP ages^{21,22} are insufficiently precise and accurate to independently test a potential Milankovitch origin for stratigraphic rhythms in BIF.

For this reason, we carried out a cyclostratigraphic study combined with high-precision chemical-abrasion isotope-dilution thermal ionisation mass spectrometry (CA-ID-TIMS) U-Pb zircon dating of the early Paleoproterozoic Kuruman Formation in the Griqualand West Basin, South-Africa (Supplementary Text S1). This 200-metre-thick BIF succession is a suitable target for exploring our Milankovitch working hypothesis, because it contains several volcanic ash layers²² which can be dated with high accuracy and precision using U-Pb high-precision isotope dilution techniques, and shows rhythmic bedding on multiple scales^{23,24}. Previous observations from the Kuruman BIF were solely based on drill-core^{16,25}. Instead, we concentrated on field exposures, as stratigraphic changes in composition are often visually enhanced by the effects of weathering.

Cycle hierarchy and possible origin

Field exposures of the Kuruman BIF show clearly-defined, regular alternations in the weathering profile (Fig. 1, Supplementary Fig. S1, S2). More specifically, a rhythmic alternation is visible between well-exposed, protruding BIF, and deeply weathered, poorly exposed intervals. The weathering-resistant intervals tend to form steep cliffs, whereas the unexposed sections form gentle slopes, thus causing variations in relief. These alternations occur on two distinct scales, namely at ca 5 m and 20 m, producing a hierarchical stacking pattern with typically two to four indurated ridges grouped together into larger scale bundles. Lithological observations indicate higher concentrations of iron oxide-rich beds in the indurated and iron carbonate-rich beds in the soft intervals (Supplementary Fig. S3 – S5). This is supported by XRF data (Supplementary Table S1).

The alternations form a characteristic pattern that is laterally continuous over 250 km. Starting in the Kuruman Hills at Kuruman Kop, we identified a characteristic succession of alternations which we could trace southwards over more than 60 kilometres (along the road from Kuruman towards Daniëlskuil). We subsequently recognised the same pattern near Prieska, 250 km towards the south. In total, we logged eight characteristic bundles (labelled 1–8), each made up of a number of exposed intervals (labelled a – d) with a typical

weathering profile i.e. relief (Supplementary Text S2). Proposed correlations are shown in Figure 2.

Spectral analysis results suggest a cyclic origin for the two scales of alternations observed in the Kuruman BIF weathering profile. Multitaper method (MTM) spectra with classical AR1 and LOWSPEC26 noise model confidence levels show concentration of power at two spatial wavelengths for the five different logs, i.e. around 4.3 – 6.3 m and 16 – 22 m (Fig. 3a, Supplementary Fig. S6), with peaks often but not always exceeding 90 - 95 % (Supplementary Text S3, Table S2). Bandpass filtering confirms the link between the 4.3 – 6.3 m and 16 – 22 m periods and the characteristic alternations observed in the field: maxima in the corresponding filter outputs coincide with the occurrence of the individual ridges (a – d) and bundles 1–8 (Fig. 2), respectively, with some exceptions (Supplementary Text S4). The two filtered signals reveal a 1:3 to 1:4 cycle ratio, with the longer-period waveform following the amplitude modulation of the shorter-period cycle. Additional filtering (Supplementary Fig. S8) and evolutive harmonic analysis (Figure 3b) indicate that the pronounced peak splitting (double peaks) in the two main frequency bands (Fig. 3a) are due to time-depth distortion. In Figure 3b, the two high amplitude peaks in the lower portion of the stratigraphy show a systematic shift towards higher frequencies between cycle 3b and 5a, suggesting an upward decrease in depositional rate.

Our cyclostratigraphic results strongly argue for a Milankovitch influence on the formation of the Kuruman BIF. The discovery of rhythmic alternations that are continuous over 250 km forms direct evidence for widespread, cyclic paleoenvironmental changes affecting the deposition. Astronomical climate forcing is the only mechanism that can explain the cyclic nature and hierarchical ordering of the characteristic alternations. Moreover, the systematic shift of the two dominant wavelengths with stratigraphic height (Fig. 3b) and the observed amplitude modulating relation in their bandpass filtered signals (Fig. 2) cannot be attributed to an autoregressive noise source and therefore provide strong supporting evidence for an astronomical origin of both cycles. A possible argument against our Milankovitch interpretation are the somewhat lower confidence levels of the 16 – 22 m components (Supplementary Table S2), but this can be explained in a number of ways (Supplementary Text S5).

From a cyclostratigraphic “Milankovitch” perspective, there are a few ways to interpret the distinct 1:3 to 1:4 cycle ratio that we observe in the Kuruman BIF. The most logical candidate is the combination of the Earth’s short (100 kyr) and long (405-kyr) eccentricity cycles (Hypothesis 1). Both cycles are known to have a strong stratigraphic imprint as amplitude modulators of the climatic precession cycle²⁷. Moreover, their periods are thought to be relatively robust in deep time. In particular the 405 kyr cycle is considered very stable, resulting from the rotational orbital motions of Venus and Jupiter ($g_2 - g_5$)²⁸. Alternatively, the pattern could be linked to the superposition of the 405-kyr and moderately strong, very long (now 2.4-Myr) eccentricity cycle (Hypothesis 2). In contrast to the 405 kyr cycle, the very long 2.4 Myr eccentricity cycle is unstable, because of the chaotic Earth–Mars secular resonance associated with the resonant argument $\theta = (s_4 - s_3) - 2(g_4 - g_3)$ ²⁹. As a consequence, its period may become shorter than 2.4, possibly down to 1.2 Myr^{30,31}. In this case, a shorter period around 1.2 – 1.6 Myr would fit the observed 1:3 to 1:4 ratio in the

Kuruman BIF. Other Milankovitch options that include precession or obliquity are unlikely since they do not match the observed ratio between the two cycles (Supplementary Text S6). Precise and accurate U-Pb geochronology should be able to distinguish between options 1 and 2.

Uranium-lead ages and link to long-period eccentricity

To obtain such high-precision U-Pb ages, we sampled different shale levels within the Kuruman BIF. Euhedral ash fall zircon crystals were extracted from four stilpnomelane lutite intervals from the GASESA and UUBH-1 drill-cores, spanning the entire stratigraphy (see Methods). All of the extracted zircon crystals were chemically abraded to remove the effect of decay-damage related Pb loss and dated using CA-ID-TIMS techniques. However, since the grains were small (100 - 50µm) and metamict, only moderate chemical abrasion was possible to avoid complete dissolution. Therefore, significant Pb loss is still observed in most grains. Fortunately, at least one grain from each sample gave concordant results (where both U-Pb geochronometers agree within uncertainty), which provides a high level of confidence in the calculated age. Only concordant analyses were used to calculate the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, through either a weighted mean in the case of multiple concordant analyses or of a single grain. This gives an age of 2484 ± 0.34 Ma (2σ) for the base and 2464.0 ± 1.3 Ma for the lutite closest to the top of the Kuruman BIF (Fig. 4a). Our new high-precision ages are in general agreement with previously published ages²², although they are ~10-20 times more precise, allowing a significantly better estimation of the depositional rate. The depositional rate was estimated using the Bayesian model Bchron³² and suggests an extremely consistent average rate of 10 ± 10 m/Myr for the 200 metres of Kuruman BIF deposition (Fig. 4b and Supplementary Fig. S10).

The average accumulation rate of 10 ± 10 m/Myr for the Kuruman BIF yields periods of 430 – 630 kyr and 1.6 – 2.2 Myr for the characteristic alternations and bundles, respectively. These periods are very close to and within uncertainty of the Earth's long (405 kyr) and very long (between 1.2 and 2.4 Myr) eccentricity cycles. In contrast, all other Milankovitch hypotheses are in conflict with the U-Pb results since they require depositional rates above the 20 m/Myr upper limit. Therefore, the consistency between the U-Pb and the cyclostratigraphic results strongly argues for Hypothesis 2.

Tying the small-scale alternations to the stable 405 kyr cycle, a 1:3 to 1:4 cycle ratio would suggest a period between 1.2 and 1.6 Myr for the very long eccentricity cycle. This is shorter but within uncertainty consistent with the average 1.6 – 2.2 Myr period constrained by the U-Pb results. Bandpass filtering (Supplementary Fig. S8) suggests that the actual cycle ratio lies between 1:3.5 and 1:4, implying periods between 1.4 – 1.6 Myr for g_4 – g_3 . Tuning the 4.5 – 6.1 m wavelengths in the Whitebank spectrum to the 405 kyr cycle (Supplementary Fig. S9), we similarly obtain values between 1.4 and 1.6 Myr. The fact that bundle number 2 contains four exposed ridges (2a-d) may even suggest a minimum ratio of 1:4 and a period of 1.6 Myr for very long eccentricity, since a fourth alternation should then be present in each bundle but is simply not exposed (i.e. it is “hidden” in the softer intervals in between the bundles). Irrespectively, it is clear that the g_4 – g_3 has a period smaller than the present-day 2.4 Myr and probably larger than 1.2 Myr. Similarly reduced periods around

1.6 Myr for the $g_4 - g_3$ cycle have been found in other cyclostratigraphic studies on Mesozoic to Paleozoic strata^{33,34} indicating chaotic planetary behaviour.

In contrast to the long and very long eccentricity cycle, the expression of climatic precession and short eccentricity cycle is not clear from our weathering profile logs and may point to a significant non-linear response³⁵. Nevertheless, short eccentricity might be represented by some of the splitting-up we encountered in specific horizons, such as in 2b, 3a-b, 5a and 6a-b. Our logs are not detailed enough to resolve the precession-related cycles, with an expected thickness of approximately 10-15 cm (Supplementary Text S6).

Link to basin history, Australian BIF and climate

We are not the first to discover metre-scale variability in the Kuruman BIF. Our 405 kyr-related alternations share parallels with Beukes' 16,24 "macrocycles" previously identified in drill-core. These comprise a vertical sequence of stilpnomelane lutite, siderite- and subsequently magnetite-hematite-facies BIF occurring "on the order of 1 – 10 m". In addition, the superposed "megacycles" that were distinguished (Fig. 5 in ref. 16) show a striking resemblance to our characteristic bundles. Yet Beukes' macro- and megacycles hinge on the occurrence of thin stilpnomelane lutite beds and are linked to volcanic activity. In contrast, our cycles are determined by relative alternations in iron oxide versus iron carbonate content and are linked to eccentricity forcing. According to Beukes' observations, the stilpnomelane lutite intervals predominantly occur in the iron carbonate-rich intervals, however, we were unable to incorporate the lutites in our current lithofacies model due to their poor field exposure.

Our cyclostratigraphic correlations (Fig. 2) further have direct consequences for the Griqualand West basin history. Previous studies^{16,24} have temporally linked 200 m of Kuruman BIF stratigraphy (and its characteristic megacycles) in the Kuruman - Daniëlskuil platform area to more than 600 m of Kuruman BIF in the southern basinal part (e.g. Fig. 10 -11 in ref. 16). However, we observed the same cycle thicknesses and characteristic pattern in the lower 200 m of Kuruman BIF in the southern Prieska section, implying that (1) accumulation rates were essentially the same as in the northern Kuruman - Daniëlskuil region and that (2) the much larger thickness in the south is likely due to prolonged sedimentation of Kuruman BIF in that area or, alternatively, by condensation or erosion in the northern platform region.

The 140-metre-thick and roughly time-equivalent^{22,36} Dales Gorge Member BIF (Hamersley Basin, Western-Australia) exhibits similar lithological variations²⁴ for which a Milankovitch origin has now become a plausible scenario. Its characteristic 17 "BIF-S macrobands" comprise iron oxide-dominated "BIF" and silicate- and carbonate- dominated "S" or shale bands^{5,15,37,38} between 2.3 – 15 m and 0.6 - 5.5 m thick, respectively, and have been correlated over the entire outcrop area. Moreover, wavelet analysis on magnetic susceptibility drill-hole data³⁹ has revealed clear periodic signals in the 5-6 m and 15 - 20 m range associated with the macrobanding. These results hint at the presence of similar cycles as those observed in the Kuruman BIF. If interpreted in the same way, the very regular, 15-cm-thick Calamina cyclothem¹⁵ in the Dales Gorge Member has the expected thickness of a

precession-related cycle. This may be an important extra argument for our preferred interpretation of the Kuruman BIF cyclostratigraphy.

At this stage, we can only speculate about potential climate mechanisms for Milankovitch forcing of BIF. The dominance of eccentricity hints at a low-latitude climate control. Monsoonal systems are known to respond strongly to precession-eccentricity forcing⁴⁰, with eccentricity modulating the precession amplitude, and were likely present during the Phanerozoic^{41,42} and Proterozoic^{43,44} as well. Recently, ca 5-metre-scale variations in Fe-Nd isotopes from the Dales Gorge Member were linked to oscillations in riverine versus hydrothermal (i.e. marine) iron⁴⁵, parallel to the S – BIF alternations, respectively. Continental runoff and ocean circulation are both mechanisms that can be strongly dependent on monsoonal intensity. Going one step further, monsoonal-enhanced iron or nutrient supply could have triggered photosynthetic or photoferrotrophic activity in the ocean's photic zone, leading to increased iron oxide production and accumulation on the seafloor. Alternatively, nutrient availability could have stimulated biological productivity, organic carbon production and subsequent formation of iron carbonates in the sediment via dissimilatory iron reduction¹⁰. However, the phase relations between precession, eccentricity and the chemical alternations in the Kuruman BIF are still unknown, yet they are crucial for any first-order climate interpretation.

We have demonstrated that Milankovitch-induced climate cycles exerted a major control on the deposition of the early Paleoproterozoic Kuruman BIF. The fact that this primary signal is still present within the stratigraphy has direct implications for BIF depositional models, and encourages the use of BIFs as climate proxy for the early Earth's pre- and syn-oxygenated environment. We have further shown that our cyclostratigraphy combined with high-precision U-Pb dating allows for basin-scale correlations for this time period with a much higher temporal resolution (i.e. 10^5 yr instead of 10^6 yr) and which may facilitate future basin analysis. Moreover, the identification of 405 kyr and approximately 1.4 - 1.6 Myr eccentricity cycles provides new geological constraints on Solar system planetary behaviour in deep-time.

Methods

Sections and logging

During a three-week reconnaissance fieldwork, we selected five suitable outcrops for logging the observed regular alternations in the weathering profile of the Kuruman BIF. To demonstrate the lateral continuity of the pattern, we distributed them spatially over a distance of 250 kilometres, along a N-S transect between the towns of Kuruman and Prieska. In each section, logging was done along trajectories (subsections) where the alternations were most clearly expressed, i.e. on hill slopes that were neither too steep (e.g. vertical walls created by streams) nor gentle (e.g. at the very bottom or top part of a hill, where the exposure is typically poor). Thickness measurements of the different intervals were done with a Jacob staff and at a decimetre to metre resolution, yet some distinct features at the centimetre-scale were reported as well if they were laterally consistent over 50 m or more. Note that there was some ambiguity in defining the boundary between subsequent beds, because the changes in relief were often gradual rather than sharp. Individual logs of the

subsections were subsequently combined into a composite log representative for an entire section.

Relief grading

For each composite section, we subsequently ranked the logged intervals in terms of their “relief”. The most deeply weathered, soft intervals were given a value of 0 and the most prominent, well-exposed ridges a value of 5. We did the ranking visually at a location where we had a good overview on the entire section. For the Prieska section this was not possible because its four subsections were relatively widely spaced, so here the grading was done three times: for a bottom, top and overlapping section. First, ranking was done independently by three people using only whole numbers (i.e. 0, 1, 2, 3, 4 or 5), and these rankings were subsequently compared. Although this method comes with a level of subjectivity, individual results turned out to be in close agreement with one another, with a maximum difference of 1. We subsequently discussed the intervals about which there was some ambiguity in the grading, and decided to introduce 0.5 and in some cases 0.25 points to account for more subtle variations in relief which were causing the disagreement in the individual rankings. Slight modifications were additionally made based on inspection of photos from each section.

Lithological analysis

For three sections (Whitebank, Woodstock and Prieska) we added textural and mineralogical observations by taking representative samples from each interval (if possible). This was generally done at a coarse resolution i.e. metre-scale and samples usually covered 5 to 15 cm of stratigraphy. Samples of a smaller size would be too much biased by the micro- and mesobanding (high-frequency chert-iron alternations) and thus not representative for the large-scale changes in composition associated with the alternations in weathering. 24 representative samples from section Woodstock, covering bundles 2 to 4, were subsequently prepared for X-ray fluorescence (XRF) analysis using a Retsch tungsten carbide jaw crusher, Herzog mill and Leco thermogravimetric analyser. Approximately 0.6 g of dry sample were fused into glass fusion beads at 1200 °C and analysed with a ARL Perform’X sequential X-ray fluorescence spectrometer at Utrecht University. Based on our field observations and the XRF-results (Supplementary Table S1) we developed a lithological facies model (Supplementary Fig. S5).

Spectral analysis

Time-series analysis was carried out on the five composite rank series (i.e. relief listed versus depth) which were detrended and linear interpolated at 10 cm. We used the multitaper method (MTM)⁴⁶ as implemented in the R package “astrochron”⁴⁷ using three 2π prolate tapers. AR1 and LOWSPEC 23 confidence levels were determined using the functions ‘mtm’ and ‘lowspec’. Astrochron was further used for rectangular bandpass filtering (‘bandpass’) and evolutive harmonic analysis (‘eha’) to evaluate spatial frequency changes (i.e. time-depth distortion). In addition, we applied frequency domain minimal tuning⁴⁸ to the Whitebank log (Supplementary Fig. S9) using the functions “traceFreq”, “freqs2sedrate”, “sedrate2time” and “tune”.

TIMS U-Pb geochronology

Four stilpnomelane lutite shales were sampled from the Gasesa-1 and UUBH-1 drill-cores (see Supplementary Fig. S1 for drill-hole information) for zircon extraction. The “Kleine Naute shale”, a distinct marker bed at the top of the Gamohaana Formation, was sampled from the Gasesa-1 core close to the boundary with the Kuruman Formation. Since many other lutites in the Gasesa-1 core were highly weathered and their stratigraphic height with respect to the Kleine Naute was not perfectly clear, the three other shales were sampled from the new UUBH-1 core at 212.18 - 212.57 m, 130.35 - 130.54 m and 110.60 - 110.90 m core depth. The depth of the Kleine Naute shale in UUBH-1 was established at 302.19 - 306.73 m and was used for calculating the depositional rate. All samples were subsequently crushed in a tungsten mill and sieved to $<250\mu\text{m}$ before zircon concentration using the Wilfley table method⁴⁹ and zircon picking under a binocular microscope.

Once prismatic euhedral zircon grains had been extracted from the samples, these grains were annealed in a muffle furnace at 900°C for 48h. The annealed grains were then subjected to chemical abrasion⁵⁰ at 210°C for 2 times 3h in concentrated HF in 3ml Savillex beakers placed in a Parr digestion vessel. After 3h the zircon grains were inspected and the remaining fragments deemed large enough to survive another 3h partial dissolution. The grain fragments remaining after chemical abrasion were cleaned on a hotplate at 80°C in 6N HCL overnight. The grain fragments were then further cleaned in 4 rounds of 3N HNO_3 combined with ultra-sonication. The zircon crystals were then loaded into individual $200\mu\text{l}$ Savillex microcapsules, spiked with $\sim 5\text{mg}$ of the EARTHTIME $^{202}\text{Pb}+^{205}\text{Pb}+^{233}\text{U}+^{235}\text{U}$ tracer solution (calibration version 351,52) and dissolved with $\sim 70\mu\text{l}$ HF and trace HNO_3 in a Parr digestion vessel at 210°C for 48h. Following dissolution, the samples were dried down and converted to a chloride by placing them back in the oven overnight in 6N HCl. The samples were then dried down again before being re-dissolved in 3N HCl and loaded into columns for anion exchange chromatography to purify and separate the U and Pb fractions⁵³. Once purified, the U and Pb fractions were combined in cleaned 7ml Savillex beakers and dried down with trace H_3PO_4 before loading on outgassed zone refined Re ribbon filaments with a Si-Gel emitter. U and Pb measurements were made on either a Thermo TRITON thermal ionisation mass spectrometer (TIMS), or a Isotopx Phoenix TIMS machine, both housed at the University of Geneva. On the TRITON, Pb was measured in dynamic mode using an axial MasCom SEM whereas for Phoenix measurements, Pb was measured in dynamic mode using a Daly photomultiplier system. U was measured as an oxide on both machines, either in static mode using faraday cups coupled to $10^{12}\Omega$ resistors or on the same ion counting system used to measure Pb when the signal on $^{238}\text{U}^{16}\text{O}_2$ was not high enough for Faraday measurements. The $^{18}\text{O}/^{16}\text{O}$ oxygen isotope ratio in Uoxide was assumed to be 0.00205. Mass fractionation of Pb and U was corrected for using a $^{202}\text{Pb}/^{205}\text{Pb}$ of 0.99506 and a $^{238}\text{U}/^{235}\text{U}$ of 137.818 ± 0.045 (2σ)⁵⁴. All common Pb was considered laboratory blank and was corrected using the long term isotopic composition of the Pb blank at the University of Geneva (see footnote in Supplementary Table S3). All data were processed using the Tripoli and Redux U-Pb software packages using the algorithms⁵⁵. The weighted mean ages presented here are reported without the additional uncertainty associated with the spike calibration and also the decay constant uncertainties since these were unnecessary for our purposes, see the data table for ages including these sources of

uncertainty. All ages were corrected for initial ^{230}Th disequilibrium in the melt using a U/Th of the magma of 3.5 and an initial $^{231}\text{Pa}/^{235}\text{U}$ of 1.1, although adding or removing these corrections makes no difference to our results.

Depositional rate model

The stilpnomelane lutites contain a significant component of felsic volcanic material²² whereas the surrounding BIF contains almost no traces of this⁵⁶. Although there is uncertainty on the origin of the stilpnomelane lutites, the zircons within the lutites must originate from relatively instantaneous volcanic eruption events. We therefore modelled the depositional rate of the Kuruman BIF assuming that the zircons originated from 1-cm-thick, tuff-rich layers which formed instantaneously within the lutites. This assumption has almost no impact on our calculated depositional rate; the same rate is obtained by treating the whole lutite as an instantaneous event (similar to a tuff deposit).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Rhythmic alternations in the weathering profile of the Kuruman BIF.
The alternations show a consistent pattern between different sections in the Griqualand West basin. Photos are from sections Whitebank (a), Prieska (b) and Woodstock (c).

Figure 2. Weathering profile logs and cyclostratigraphic correlations.

a. Logs of the Kuruman BIF weathering profile in sections Kuruman Kop (KK), Whitebank (WB), Woodstock (WS), Daniëlskuil (DK) and Prieska (PK). The relief ranges from 0 (= deeply weathered, unexposed) until 5 (= very much protuding). Blue zones mark our proposed correlations of the characteristic ridges (labelled a-d) and bundles (labelled 1 – 8) between the sections. Bandpass filter outputs are indicated on the righthand side of each log.

¹The Kleine Naute shale marks the bottom of the Kuruman Formation. However, its stratigraphic position with respect to our characteristic cycles is inferred from correlations with drill-core, because it does not crop out in the field. ²Bundles 7 - 8 are part of the uppermost Ouplaas Member of the Kuruman Formation in the Daniëlskuil – Kuruman area (Fig. S4). ³The Prieska log only captures the bottom 200 m of the Kuruman Formation in this region (Fig. S2, S4). **b.** Detail of cycles 2 – 4 in section WS showing lithological observations (left) and XRF results (right). Yellow colors indicate carbonate-dominated intervals, blue colors the oxide-dominated (see Supplementary Fig. S3 for a complete legend).

Figure 3. Spectral analysis results.

a. MTM power spectra (three 2π prolate tapers) for the logs from sections KK, WB and WS (10 cm linear interpolated; detrended) with AR1 background, 90, 95 and 99% confidence levels and peak labels in metres. Blue zones indicate the two areas of enhanced spectral power that are linked to the characteristic alternations and bundles. The peaks at 1 - 3 m are considered artefactual harmonics (Supplementary Fig. S7). **b.** EHA amplitude (3 2π ; 30 m window) and MTM power spectrum (top) for the log of section WB (left). White arrows mark the frequency shift of the two main high amplitude components between cycle 3b and 5a (mean periods are indicated in metres).

Figure 4. U-Pb zircon ages and depositional rate.

a, Concordia diagram showing the concordant high-precision U-Pb TIMS results and the calculated ages. The grey band represents the uncertainty on the Concordia curve due to the decay constant uncertainties. The ellipses represent the U-Pb isotopic data and 2σ uncertainty for individual chemically abraded zircon fragments, and the colours represent the different samples. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages are given for each sample, either as a weighted mean or from an individual analysis, along with the depth in metres in the UUBH-1 core. Left: schematic representation of sample depth (stilpnomelane lutite L1 – L4) and extent of the Kuruman Formation (in grey) in the UUBH-1 drill-core (see Methods). **b**, Depositional rate model for the Kuruman BIF with 97.5% confidence intervals indicated.