



Towards an astrochronological framework for the lower Paleoproterozoic Kuruman and Brockman Iron Formations

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Abstract

Recent evidence for astronomical-induced cycles in banded iron formations (BIFs) hints at the intriguing possibility of developing astrochronological, i.e. precise time-stratigraphic, frameworks for the earliest Proterozoic as also reconstructed for parts of the Mesozoic and Paleozoic. The Kuruman Iron Formation (IF) (Griqualand West Basin, South Africa) and Dales Gorge Member of the Brockman IF (Hamersley Basin, Western Australia) are of special interest in this regard, given their inferred temporal overlap at *ca.* 2.47 Ga and similar long-period orbital eccentricity imprint. This suggests that these two BIFs may be correlated on the basis of their large-scale cycle patterns and using additional radio-isotopic age constraints.

To examine the possibility of establishing such a framework, we generated and analysed several high-resolution proxy records from both drill-core and outcrop, combined with high-precision U-Pb dating of zircon from interbedded shale horizons. Time-series analysis of these records yields a variety of spectral peaks, of which a prominent ~5 m and ~16 m cycle can be linked to the basic stratigraphic alternations and bundling as observed in the field. New and revised $^{207}\text{Pb}/^{206}\text{Pb}$ ages calculated from the U-Pb data of the Dales Gorge Member and Kuruman IF, respectively, indicate a comparable average sedimentation rate of 10 to 12 m/Myr for both units. Based on this depositional rate, we attribute the ~5 m cycle to the long (~405 kyr) orbital eccentricity cycle. More tentatively, we interpret the ~16 m cycle as the very long (presently ~2.4-Myr) eccentricity cycle, having a reduced period of ~1.3 Myr due to chaotic behaviour in the solar system. Other identified cycles (~560 kyr, ~700 kyr and ~1.8 Myr) can be explained in terms of weaker orbital eccentricity components and/or as harmonics and combination tones of these cycles resulting from nonlinear responses.

An initial attempt to establish cyclostratigraphic correlations between the Kuruman IF and Dales Gorge Member solely based on their characteristic cycle patterns proved unsuccessful, which may be due to a difference in the recording of the astronomical signal between different depositional environments. Next, we used the zircon ages to first constrain correlations at the scale of the ~16 m cycle, followed by a correlation of the basic ~5 m cycles. The resultant framework remains problematic and debatable at the individual ~405 kyr cycle-level, but provides a starting point for future studies. Particularly, our findings highlight the need for further investigations into how Milankovitch forcing influenced BIF sedimentation and paleoenvironmental conditions at a time when the Earth and solar system behaved fundamentally different from today.

Introduction

Astronomical age models based on the calibration of sedimentary cycles to astronomical target curves of precession, obliquity, eccentricity and/or insolation have now been constructed for the entire Cenozoic (Gradstein et al., 2020; Hinnov, 2018; Hinnov and Hilgen, 2012; Westerhold et al., 2020). Due to their high resolution, these age models or astrochronologies have been key to solving fundamental research questions concerning the astronomical origin and pacing ('Milankovitch forcing') of e.g. ice ages and hyperthermals, and associated nonlinear feedbacks within Earth's climate system (Hays et al., 1976; Hilgen, 1991; Imbrie et al., 1984; Sexton et al., 2011; Westerhold et al., 2020; Zachos et al., 2010). In addition, the development of very long, tuned paleoclimate records has enabled us to differentiate the contribution of the Milankovitch 'Grand cycles', which have periodicities in the order of millions of years, from other forcing mechanisms such as tectonics and volcanism that operate on the same time scale (Boulila et al., 2012; Martinez and Dera, 2015; Olsen et al., 2019). Similar astrochronologies have also been developed for parts of the Mesozoic (e.g. Batenburg et al., 2012; Huang, 2018; Ikeda and Tada, 2014; Olsen et al., 2019; Sprovieri et al., 2013) and Paleozoic (e.g. de Vleeschouwer et al., 2017; Fang et al., 2015; Sinnesael et al., 2021; Sørensen et al., 2020; Wu et al., 2013; Wu et al., 2023), yet these age models are less precisely anchored in time due to the absence of a reliable astronomical target solution prior to ~50 Ma. Instead, these 'floating' or radio-isotopically anchored astrochronologies are

principally based on identification of the long '405-kyr' eccentricity cycle, the dominant cycle in Earth's orbital eccentricity evolution whose period is regarded as relatively stable in deep time (Laskar et al., 2004; 2011) and is typically expressed in sedimentary sequences through its amplitude modulation of climatic precession.

Recently, the expression of a strong ~405 kyr cycle was detected in ancient marine deposits at *ca.* 2.47 Ga (de Oliveira Rodrigues et al., 2019; Lantink et al., 2019), in so-called banded iron formations (BIFs), deposited in the prelude to the Great Oxidation Event (GOE; Bekker et al., 2004; Holland, 2002). This raises the question whether a similar integrated stratigraphic framework and astrochronology may be developed for these lower Paleoproterozoic BIFs, namely the Kuruman Iron Formation (IF) in South Africa and the Dales Gorge Member of the Brockman IF in Western Australia. It is generally assumed that these lithostratigraphic units were deposited near-synchronously, and possibly even within the same basin, based on similarities in the succession of lithofacies and sensitive high-resolution ion microprobe (SHRIMP) $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages (Button, 1976; Cheney, 1996; Martin et al., 1998; Nelson et al., 1999; Pickard, 2003; Trendall, 1968; Trendall et al., 2004). Establishing a cyclostratigraphic framework would, for the first time, allow their relative timing to be determined much more precisely, and as such, be of important value for reconstructions of paleogeography and basin evolution (Beukes and Gutzmer,

2008; Knoll and Beukes, 2009) as well as environmental redox changes during this critical period of Earth history (e.g. Anbar et al., 2007; Gumsley et al., 2017; Kendall et al., 2010).

Here, we combine cyclostratigraphic analysis and high-precision U-Pb dating of zircon using chemical abrasion isotope dilution thermal ionisation mass spectrometry (CA-ID-TIMS) for the Kuruman and Dales Gorge Member BIFs. Our goal is to examine their potential for establishing high-resolution (405 kyr cycle-scale) correlations using the inferred eccentricity-related cycle patterns. We begin our investigation by introducing several new, high-resolution proxy records from both stratigraphic units. For the Kuruman IF, we use bulk iron-manganese ratio (Fe/Mn) obtained via X-ray fluorescence (XRF) core scanning and magnetic susceptibility logs from a recent drill-core. For the Brockman IF, we use outcrop weathering profile 'verticality' logs (i.e., relief profiles), and ferric oxide and carbonate mineral abundances from existing drill-core. These records are then subjected to detailed cyclostratigraphic study focusing on the regular metre-scale alternations, building upon and refining the results of Lantink et al. (2019) and de Oliveira Rodriguez et al. (2019). Next, we present new and improved $^{207}\text{Pb}/^{206}\text{Pb}$ ages obtained from zircon found within shale rich layers in the Dales Gorge Member as well as the Kuruman IF, and discuss the possible Milankovitch origin of observed cycles in the depth domain. We subsequently examine potential cyclostratigraphic correlations between the two BIF units, starting from their characteristic cycle patterns as expressed in the weathering profile. Finally, we discuss the implications of our correlation exercise and the resulting astrochronological framework for how the different BIF depositional environments responded to the astronomical forcing.

Geological setting and stratigraphy (Section reference 1)

The most extensive Precambrian BIF successions were deposited during the transition from the Archean to Proterozoic between approximately 2.6 to 2.4 Ga. These iron- and silica-rich, largely chemical sedimentary deposits are exceptionally well-preserved in the Griqualand West Basin in South Africa and the Hamersley Basin in Western Australia, and extend over several hundred

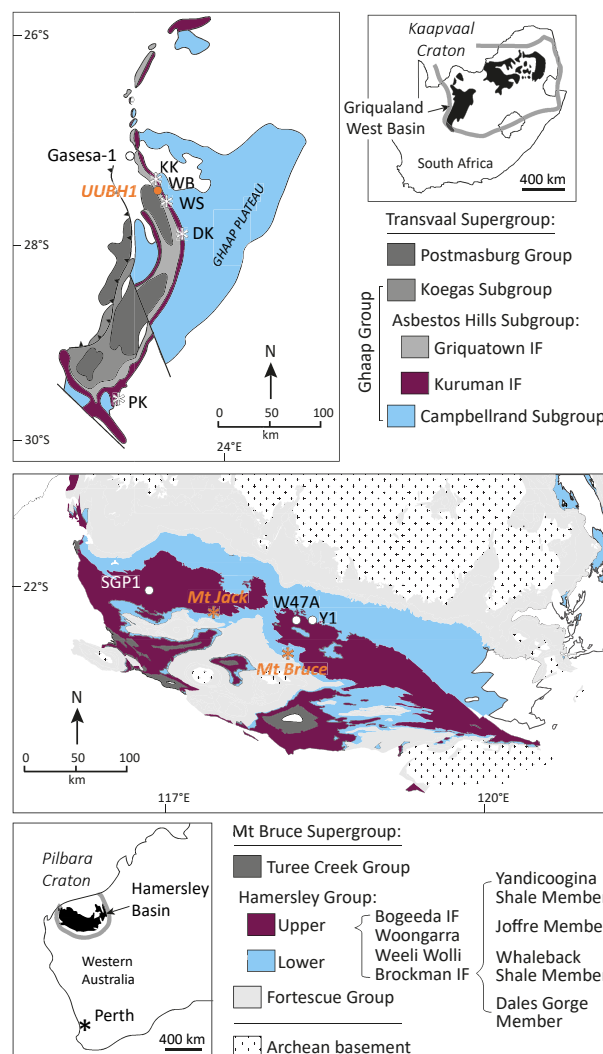


Figure 1. Geological map of the Griqualand West Basin (South Africa) and Hamersley Basin (Western Australia) and the locations of the studied sections and drill-cores of the Kuruman and Brockman Iron Formations, respectively: KK=Kuruman Kop; WB=Whitebank; WS=Woodstock; DK=Danielskuil; PK=Prieska.

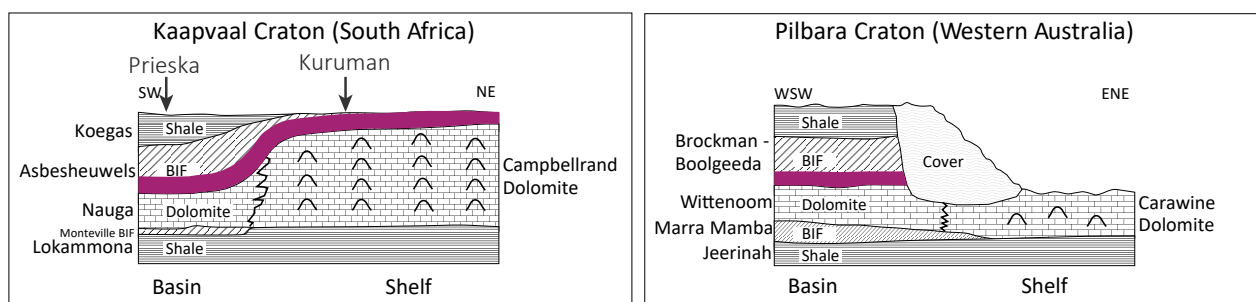


Figure 2. Schematic cross-section of the Ghaap Group on the Kaapvaal Craton (left) and Hamersley Group on the Pilbara Craton (right), showing their broadly correlative succession of lithofacies. Purple bands mark the stratigraphic intervals of the Kuruman and Dales Gorge Member banded iron formations (BIFs) that are the focus of this study. Note that the correlation of the Kuruman Iron Formation (IF) between the central Kuruman area and southern Prieska area is based on the cyclostratigraphic observations of Lantink et al. (2019) and is in disagreement with Beukes' (1980; 1983) correlations of macro- and megacycles, which imply a much higher depositional rate in the south. Figure adapted from Beukes and Gutzmer (2008).

kilometres on the Kaapvaal and Pilbara Cratons, respectively (Figure 1). In both areas, the BIF-hosting Ghaap (SA) and Hamersley (WA) Groups show remarkable similarity in age and corresponding succession of lithofacies, from relatively shallow-marine (platform) carbonates, carbonaceous and black shales to deeper-marine iron formations of the Kuruman and Brockman IFs, respectively. In particular in the Griqualand West Basin, such a shelf-to-basin facies transition is also well preserved in a lateral sense, from the central Ghaap plateau to Prieska area in the south (Figure 2 and Figure A1). (Beukes, 1980; 1983; Beukes and Gutzmer, 2008; Knoll and Beukes, 2009). The strong lithostratigraphic correlation between the Ghaap and Hamersley sequences, combined with paleomagnetic support for a Pilbara-Kaapvaal supercraton around that time, suggests that deposition may have occurred in a single large marine depository and/or in (partly) connected basins (Beukes and Gutzmer, 2008; Cheney, 1996; Martin et al., 1998) at low paleolatitude (de Kock et al., 2009; Gumsley et al., 2017).

The stratigraphy of the Kuruman IF as visible in outcrop (Figure 3a) is characterised by a pattern of regular alternations in the weathering profile at a basic thickness scale of ~5 m, and a larger-scale bundling of around ~16 to 22 m. This characteristic pattern was laterally correlated over 250 km, from Kuruman Kop to Prieska (Figure 1) in Lantink et al. (2019). The alternations partly correspond to the 'stilpnomelane lutite – BIF macrocycles' of Beukes (1978, 1980) described from drill-core (Figures A1 and A2), who originally proposed a volcanic-biogenic origin. Based on evidence from high-precision U-Pb dating, Lantink et al. (2019) attributed the alternations to the long (~405 kyr) and very long-period (now ~2.4 Myr) eccentricity cycle of the Earth's orbit, and suggested a low-latitude climatic, possibly monsoonal, influence. A similar cycle hierarchy and same Milankovitch origin was proposed for the metre-scale BIF versus 'shale' (S) macrobanding as manifested in the weathering profile of the

Dales Gorge Member (Figure 3b and Lantink et al., 2019). Of these, alternations of seventeen Dales Gorge Member BIF macrobands (i.e., DB0 to DB16) and S macrobands (i.e., DS1 to DS16A) have been formally defined and are known to correlate within the entire Hamersley region (Figure A1) (Harmsworth et al., 1990; Trendall and Blockley, 1970). Based on sequence stratigraphic analysis, Krapež et al. (2003) and Pickard et al. (2004) have interpreted the S macrobands – 'S' being defined as shale with subordinate cherts and carbonate (Trendall, 1965) – as distal density currents linked to periods of eustatic sea level fall. In line with a dominant eccentricity and thus low-latitude climate control, Lantink et al. (2019; 2023) suggested the shales to record periods of increased runoff and organic carbon productivity caused by an intensification of the monsoon.

Materials and methods

Studied sections/cores (Section reference 2)

For our cyclostratigraphic study of the Kuruman IF and Dales Gorge Member, new proxy records needed to be generated and/or were used from a number of selected drill-cores and sections in the field. For the analysis of the Kuruman IF, high-resolution lithological, geochemical and well-log data were acquired from the new UUBH1 core drilled near section Whitebank (Figures 1 and 3a). The rationale behind the UUBH1 drilling project was to provide a stratigraphically accurate, detailed record of the Kuruman IF cyclostratigraphy to complement the more basic logs of the alternations in the weathering profile and lithology in Lantink et al. (2019). For the investigation of the Dales Gorge Member, drone-based three-dimensional (3D) photogrammetry models were generated from its outcrops within the Hamersley Range at two different locations, namely at Mount Bruce and at a section ~5 km west of Mount Jack (Figures 1 and 3b). These field sections were

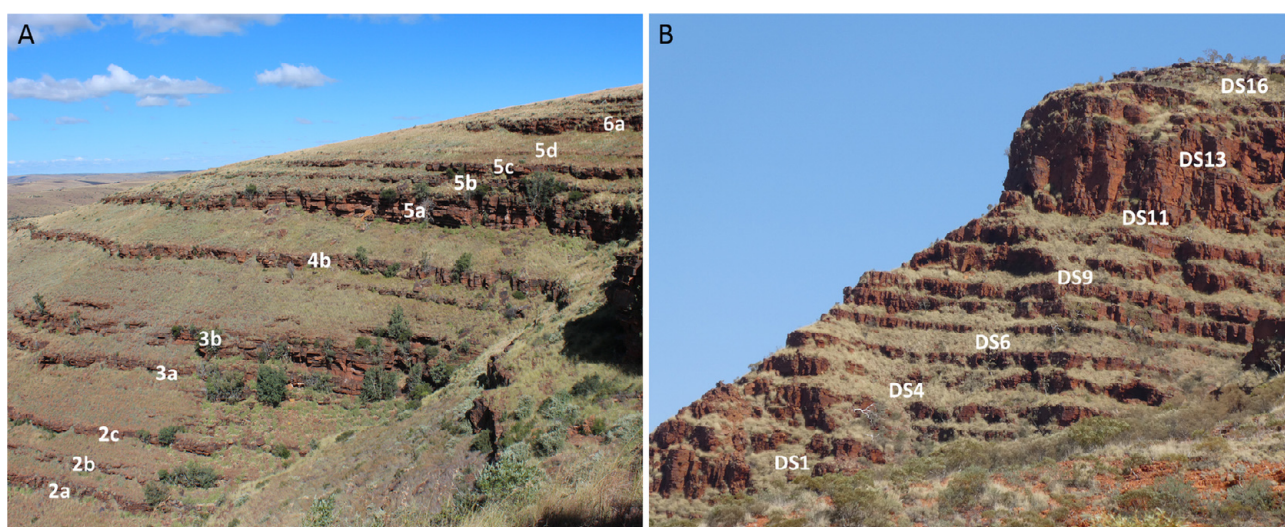


Figure 3. Regular metre-scale alternations and bundling in the weathering profile of the Kuruman Iron Formation (IF) at section Whitebank (A) and in the Dales Gorge Member near section Mount Jack (B). White labels in the image of the Kuruman IF denote the characteristic prominent banded iron formation (BIF) intervals as defined in Lantink et al. (2019). For the Dales Gorge Member, the thicker 'shale' (S) macrobands of the BIF-S macroband pattern of Trendall and Blockley (1970) are indicated.

selected for their representative pattern of the distinct metre-scale alternations in relief and relatively large distance from each other (~80 km). Based on the virtual field section models, stratigraphic logs were made of the alternations in weathering profile and a record of the outcrop 'verticality' (i.e. relief profile) was extracted. In addition, existing mineral reflectance data, made available by the Geological Survey of Western Australia (GSWA) and obtained through hyperspectral scanning of two sets of drill-core, namely DGM1 and DD98SGP001 (SGP1), were used to create high-resolution records of ferric oxide and carbonate mineral abundances. DGM1 represents a (spliced) composite section of two older cores originating from the Karijini area, namely W47A from Wittenoom and Y1 from Yampire Gorge (Figure 1); together they make up the bulk of the Dales Gorge Member 'type section', a published core photograph composite by Trendall and Blockley (1968) recently analysed for cyclostratigraphic purposes by de Oliveira Rodrigues et al. (2019) based on a greyscale scan. The SGP1 core was drilled at Silver Grass Peak located ~150 km to the west of holes W47A and Y1 and intersects the Joffe Member, Whaleback Shale Member and the upper part of the Dales Gorge Member (Figure 1).

Kuruman Iron Formation proxy records core UUBH1

Drilling and on-site logging

The UUBH1 core was drilled ~15 km west of Kuruman town at Fairholt farm (27°28'44.4" S, 23°19'13.0" E), using NQ (47.6 mm core diameter) diamond casing and orientation drilling (~10° off vertical to the northeast, perpendicular to an overall stratigraphic dip of 7° southwest) from September to November 2017. Retrieved core material was carefully checked on a daily basis to ensure the correct stratigraphic order was maintained during drilling. In addition, a schematic lithological log was made (Figure A2) according to the same lithological facies ranking as used in Lantink et al. (2019), i.e., 0=stipnomelane lutite; 1=siderite; 2=siderite-magnetite; 3=magnetite-siderite; 4=magnetite- chert 'zebra facies'; 5=magnetite. A complete succession of the Kuruman IF, from the lower Griquatown IF into the upper Gamohaan Formation, was intersected between 51.31 m and 327.15 m depth with only a minor (~1.3 m) interval of core loss between depth markers 256.33 and 259.03 m. Downhole geophysical logging was carried out after completion of the drilling and yielded magnetic susceptibility, natural gamma ray and density logs with a depth resolution of 1 cm. The core was subsequently transported to the Department of Geology, University of Johannesburg, where the core was cut in half and one archive half was kept for permanent storage. The other (working) half core was shipped to the Netherlands and is currently stored at the Geo-repository of the Department of Earth Sciences, Utrecht University.

XRF core scanning and calibration

To obtain a high-resolution chemical record of the Kuruman and upper Gamohaan Formations, X-ray fluorescence (XRF) core scanning was carried out with the Avaatech core scanner at the Royal Netherlands Institute for Sea Research (NIOZ) on Texel. Prior to the analyses, the stratigraphic order of the core was again

carefully checked by comparison to the original drill-site photos. In case of shattered lithology, true stratigraphic thicknesses were also estimated from the photos and/or drill-core metre marks. Individual 1 m core segments were placed into split plastic tubes and were supported from underneath with foam to create a stable and even surface. The XRF analyses were carried out with a 12 x 10 mm slit dimension and 1 cm step size, on cleaned surfaces covered with a 4-µm SPEXCerti Ultralene foil to prevent any cross contamination. Calcite veins were circumvented by changing the y direction of the detector, i.e., by moving it more towards the sides of the core scanning surface. Tube energy settings, primary beam filters and measurement time were optimised for minor and trace elements while maintaining a dead time between 20 to 40% (see Table S1 for applied settings). (Supplementary data files are archived in the South African Journal of Geology repository (<https://doi.org/10.25131/sajg.127.0005.sup-mat>)). Spectral data were processed using bAxil spectrum analysis software developed by Brightspec. Eight external reference standards (GSR-4, GSR-6, GSD-10, JSd-1, JSd-3, MESS 3, SARM 2, and SARM 3; see Hennekam et al., 2019) were scanned every two weeks and indicated a constant performance (i.e., no statistical difference between concentrations in standards and intensities measured) of the XRF core scanner during the entire duration of the experiment of ca. two months.

To convert the raw core scanner data (intensities) to element concentrations, a large subset of discrete samples was selected and prepared for bulk-rock quantitative wavelength dispersive XRF analysis. About 100 samples of ~10 cm thickness and spaced at 1 metre intervals were powdered and homogenised using a Retsch tungsten carbide jaw crusher and Herzog mill. Approximately 0.6 g of dry rock powder was fused into glass beads at 1200°C and analysed with an ARL Perform'X sequential XRF spectrometer at Utrecht University. For the calibration we used the multivariate log-ratio approach of Weltje et al. (2015) as implemented within the AvaXelerate software package of Bloemsma (2015). This resulted in a much cleaner (i.e., less noisy) pattern for many of the elements of interest (in particular, Fe, Mn and Al) and high R² values in the corresponding cross-plots with the bulk-rock XRF reference values (Figure S1).

XRF-core scanning depth scale

Individually scanned core segments were combined into a single XRF-core-scanning composite record by precisely determining the fit between successive intervals. For this purpose we used the high-resolution photos that were taken from every interval when placed inside the scanner (Figure S2). To enable comparison to the well log data, this composite depth record was subsequently recalibrated by matching the positions of the distinct shale layers within the XRF core scanning records (peaks in Zr, Al, K etc.) to the depths of their corresponding peaks in the downhole natural gamma ray signal. This yielded a stratigraphically accurate, natural gamma ray-based corrected depth scale for the XRF core scanning data, which is presented in the main figures and was used for time-series analysis. No further stratigraphic dip corrections were made because of the very minor (~3°) offset from drilling

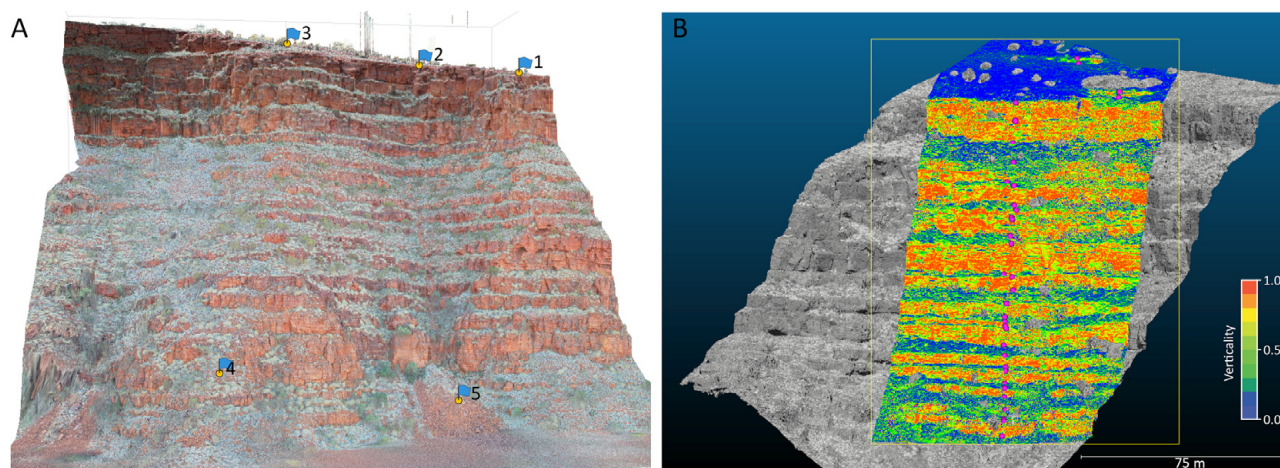


Figure 4. Examples of photogrammetry models constructed for the Dales Gorge Member field sections using an unmanned aerial vehicle. **(A)** Textured 2.5D mesh of section Mt Jack East with the position of the ground control point markers indicated by the blue flags. Marker 4 is positioned in the lower part of DB0 and marker 3 is placed at the base of DB16, corresponding to a stratigraphic thickness of ~133 m. **(B)** Dense point cloud of section Mt Bruce East, slightly rotated with respect to the original orientation to correct for stratigraphic dip. The purple dots in the yellow box indicate manually selected boundaries between successive ledge-forming banded iron formation (BIF) and slope-forming 'shale' (S) intervals that were used for measuring layer thickness and creating a stratigraphic log. The lowermost dot marks the base of DB4 and the uppermost dot marks the top of WB1, corresponding to a stratigraphic thickness of ~128 m. Intervals with colour gradient indicate the sections from which 'verticality' scalar values were extracted and averaged out horizontally to create a representative verticality record.

perpendicular to the bedding, yielding a thickness change of only 0.15%.

Dales Gorge Member field logs and core proxy records *3-D outcrop models and verticality profiles*

Since the hill exposures of the Dales Gorge Member turned out to be too steep for manual logging of the basic lithology and weathering profile, 3D photogrammetry models were constructed for the Mt Bruce and Mt Jack locations using an unmanned aerial vehicle (i.e. drone) (Figure 4 and Figure S3). To limit the model size but at the same time maintain enough stratigraphic detail, we concentrated for the Mt Bruce section on two narrower subsections located on its northeastern face, namely 'Mt Bruce West' and 'Mt Bruce East', that are representative for the upper and lower part of the Dales Gorge Member stratigraphy, respectively. The same was done for section Mt Jack, which was studied at a 'Mt Jack East' and 'Mt Jack West' subsection. Photographs were taken manually by a 20-megapixel camera mounted on a multirotor drone (DJI Mavic 2 Pro), which was flown parallel to the outcrop surface and provided approximately 70% horizontal overlap between successive photos. Each outcrop area was photographed from different heights and camera angles (at 0, 45 and 90°) to provide complete coverage and to aid alignment during processing.

To ensure correct stratigraphic thicknesses were maintained in the photogrammetric model, one to three ground control points (GCPs) were placed at the base and top of each subsection (apart from at Mt Jack West) and surveyed using an Emlid Reach RS+ GNSS receiver ('rover'). Raw GNSS measurements of the rover and a second Emlid receiver ('base

station') were processed using the post-processing package RTKLIB and provided centimetre accuracy of the GCP locations relative to the base station. GCP positions were then used to optimise camera positions during the digital 3D model building as done in Agisoft Metashape, yielding less than 0.1% error in the z direction (Figure S3).

High-resolution dense point clouds were subsequently imported into the visualisation and interpretation software Cloudcompare. After applying a stratigraphic dip correction (using 'matrix transformation'), a simple log was made from the individual thicknesses of alternating ledge-forming and slope-forming intervals (using 'point picking'). In addition, a quantitative record of the outcrop's verticality (using 'compute geometrical features') was extracted along representative sections or slices, by compressing and averaging the computed verticality point cloud in the y/x relative to z direction. Individual verticality records and corresponding logs were subsequently combined into a single Mt Bruce and Mt Jack composite (Figure S4).

HyLogger records cores DGM1 and SGP1

To complement our analysis of the Dales Gorge Member outcrop data, we used existing mineral reflectance data from cores DGM1 and SGP1. The mineral reflectance data were collected by the GSWA in 2018 using the HyLogger spectral scanner at the Perth core library (Hancock and Huntington, 2010). From the two datasets, the pattern of total ferric oxide mineral abundance (i.e., hematite and goethite), as well as carbonate mineral abundance (i.e., siderite, ankerite, dolomite, calcite), was found to reflect the characteristic macroband pattern of the Dales Gorge Member

particularly well upon inspection in 'The Spectral Geologist' (TSG) visualisation programme. With help from the GSWA, these proxy records were subsequently extracted using TSG from the visible near-infrared and thermal infrared range, respectively, at cumulative 8 mm bins corresponding to the scanner's original step size. From these records, we then removed all intervals that yielded a 'NULL' response, meaning where the ferric oxides and/or carbonates signal was masked off because of interference with other minerals having similar-looking absorption spectra, followed by a resampling (piecewise linear interpolation) at 1 cm intervals.

Note that the ferric oxide and carbonate mineral abundances constitute interpreted, relative weight percentage (wt%) and should be regarded in a purely qualitative way, since only a subset of minerals (i.e. those present in the TSG library) was included in the determination of the total wt%, while minerals not visible in the targeted spectral range, as well as aspectral minerals such as magnetite, were excluded. In addition, note that we have applied some corrections to the stratigraphic (height) scale of the DGM1 HyLogger mineral records based on a comparison with the original core photographs of the Dales Gorge Member type section as presented in Trendall and Blockley (1968) (Section reference 2). Specifically, we have removed ~1.14 cm of scanned stratigraphy in between 9.544 and 9.552 m height (corresponding to the uppermost part of core Y1 and lowermost part of core DGM1 as present in tray three rows b and c) because this part was not present in the original photo composite. Similarly, we have excluded the topmost ~5.58 m of the DGM1 HyLogger dataset (above 145.072 m height) because we could not establish a match with the original type section core photos.

Time-series analysis

We combined visual inspection with time-series analysis of selected proxy records to investigate the presence and expression of large-scale (>metre-thick) cycles in the stratigraphy of the studied Kuruman and Brockman IF sections. For the analysis of the Kuruman IF we focused on the (log-transformed) iron-manganese ratio as derived from XRF core scanning of core UUBH1 and on the magnetic susceptibility record as derived from downhole geophysical logging (Section reference 4). For the Dales Gorge Member we used the composite verticality records of the Mt Bruce and Mt Jack sections and the (log-transformed) ferric oxide and carbonate mineral abundance records of core DGM1 as derived from the HyLogger dataset.

Time-series analysis of all proxy records, including record preparation, spectral analysis, statistical hypothesis testing and bandpass filtering, was performed using the Acycle package of Li et al. (2019) and Astrochron package of Meyers (2014). Acycle was used to detrend records by subtracting a 35% locally weighted scatter-plot smoothing (LOWESS) curve, after which initial spectral analysis was carried out using the Lomb-Scargle (L-S) method (Lomb, 1976; Scargle, 1982) on original depth series. Astrochron was subsequently used to conduct multi-taper method (MTM) spectral analysis (Thomson, 1982) on linearly interpolated series at 10 cm intervals and using a time-bandwidth product of 3, unless otherwise indicated in the

respective figures. Calculation of 90, 95 and 99% autoregressive noise confidence levels was based on the locally-weighted regression spectral background estimation (LOWSPEC) method of Meyers (2012). Gaussian bandpass filtering (in Acycle) was used to isolate individual power spectral components of interest for visual comparison with the original proxy records in the stratigraphic (depth) domain. Precise individual bandpass filter widths are provided in the respective figures.

CA-ID-TIMS zircon dating

To obtain accurate and precise U-Pb zircon ages for the Dales Gorge Member, several of the shale macrobands as exposed in the gorges of the Karijini National Park were sampled for zircon extraction. The two shale samples used in this study are DS1 and DS9, which come from the Wittenoom Gorge type section as illustrated in Figure 4 of Trendall and Blockley (1970) and represent repeats of samples previously collected by A.F. Trendall (e.g., Trendall et al., 2004). The DS1 sample was collected over the entire width of the upper stilpnomelane-rich shale and corresponds to an approximate height of 16.2 m in the DGM1 type section core. The DS9 sample comes from the upper stilpnomelane-rich shale band of this macroband interval, corresponding to a height of around 68.6 m in core DGM1.

In an attempt to generate additional and more precise age constraints from the Kuruman IF, quarter core samples were taken from the stilpnomelane-rich shales at 110.75 m, 130.44 m and 212.38 m depth in UUBH1, corresponding to the lutite 4, 3 and 2 intervals which had previously been dated in Lantink et al. (2019) using material from the other half core left in Johannesburg. All samples were subsequently processed for zircon extraction. Following separation of euhedral zircon crystals, the grains were chemically abraded (Mattinson, 2005; Widmann et al., 2019) to remove the effect of decay-damage-related Pb loss and dated using CA-ID-TIMS techniques identical to those outlined in Lantink et al. (2019).

Depositional rate modelling was conducted using the R package Bchron (Haslett and Parnell, 2008) with concordant weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages or single grain $^{207}\text{Pb}/^{206}\text{Pb}$ ages depending on how many concordant analysis were found in each sample. For the lower Brockman IF, a third recently derived CA-ID-TIMS age from a shale close to the base of the Joffre Member at 371.2 m depth in core SGP1 (Lantink et al., 2022) was included in the calculation of the depositional rate, together with the new ages from DS1 and DS9. For this purpose, a single depth scale for these three samples had to be created, which we did by correlating the HyLogger patterns of the SGP1 and DGM1 cores. This yielded a corresponding virtual depth of 494.5 m for DS9 and 546.9 m for DS1 below the 371.2 m shale in SGP1. A slightly updated depositional rate model was established for the Kuruman IF based on additional concordant zircon analyses obtained for the shales at 111 m and 212 m depth in core UUBH1.

Results (Section reference 3)**Cyclostratigraphic analysis of the Kuruman Iron Formation** (Section reference 4)

For our cyclostratigraphic study of the Kuruman IF we focused on the iron-manganese ratio (Fe/Mn) and magnetic susceptibility (MS) signal as the two key proxies. These records were selected from the XRF core scanning and geophysical logging data sets as obtained for the UUBH1 core, respectively (Dataset S1). We chose these two proxies because they proved to most accurately reflect the characteristic cycle pattern of the Kuruman IF as described from outcrop (Lantink et al., 2019). Note, however, that the inverse of manganese (1/Mn), and ratio of iron over aluminium (Fe/Al) (Figure S5), show an almost identical pattern to the Fe/Mn record, and that this pattern is also reflected in our lithofacies rank series (Figure A2). Variations in Fe/Mn (or 1/Mn) are considered mainly a proxy for relative changes in carbonate concentration, given that Mn in the Kuruman IF is primarily bound to the carbonate mineral fraction (ankerite, siderite) (Oonk et al., 2017). Variations in Fe/Al are considered a proxy for variations in detrital silicate fraction, while the MS signal is largely controlled by abundance of magnetite (Cowan and Cooper, 2009). Below, we will first describe how the characteristic cycle pattern of the Kuruman IF was recognised in the selected UUBH1 core proxies and compares to the original field logs of Lantink et al. (2019), before proceeding to a more detailed examination of the cyclostratigraphy using time-series analysis.

Visual identification

The Fe/Mn and MS records of core UUBH1 show distinct regular alternations throughout the stratigraphy of the Kuruman IF (100 to 302 m depth) and upper Gamohaan Formation (302 to 327 m depth) that, upon initial inspection, seem to occur on two principle thickness scales. First, large amplitude swings can be distinguished at a thickness scale of about 5 m, which are particularly evident in the log(Fe/Mn) record, and below a depth of ~170 m (Figure 5). The maxima of this basic ~5 m-scale alternation correspond to intervals which are relatively rich in iron oxides, hereafter referred to as 'BIF', while the minima represent intervals relatively rich in iron carbonate and stilpnomelane lutite. These alternations, in turn, are grouped into larger-scale bundles composed of one to three more pronounced ~5 m-scale maxima, occurring at an approximate spacing of 15 to 20 m.

The more pronounced ~5 m-scale BIF intervals and bundles expressed in the normal Fe/Mn record can be readily identified as the characteristic cycle pattern observed in the Kuruman IF weathering profile by Lantink et al. (2019), when compared to the original field logs of Whitebank and Woodstock (Figure 5). The strongest and thickest Fe/Mn peaks – i.e., the three maxima at 260 to 275 m depth; followed by two maxima at 240 to 250 m; followed by a single pronounced interval at 215 m; and then four alternations from 180 to 200 m with an anomalously thick and prominent zone at 200 m – bear a remarkable resemblance to the characteristic sequence of indurated BIF intervals labelled as cycles 2abc, 3ab, 4b and 5abcd. Recognising this link, the identification of the other previously defined BIF intervals –

i.e., 1abc at the base of the Kuruman IF; 2d and 4a; and 6abc, 7a, 7bc and 8a in the upper part – becomes relatively straightforward. One notable exception is BIF 6a, which is rather poorly developed in the Fe/Mn record around 170 m depth, but nevertheless manifested in the MS record (Figure 5), and to a moderate degree in the Fe/Al record (Figure S5).

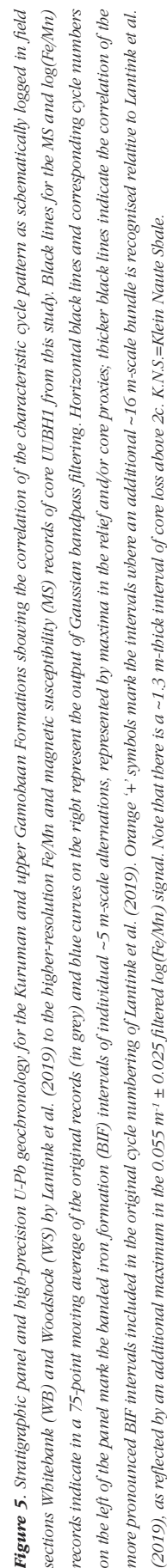
When we correlate this characteristic pattern of pronounced BIFs between the core and field logs (see thick correlation lines in Figure 5), additional more subtle Fe/Mn maxima at a regular ~4 to 5 m spacing can be distinguished in the relatively iron oxide-poor intervals separating bundles 1 to 6. These weaker ~5 m-scale 'BIF' intervals – which we indicate with 1a.0, 1d, 2e, 3c, 3d, 3e, 4c, 4d, 5a.2, 5e and 6a.2 – are only partially expressed in the (logs of the) weathering profile at Woodstock and Whitebank. Given their clear manifestation in the core data, however, we can now add them to the original Lantink et al. (2019) cycle numbering and our correlations between the field logs and core UUBH1 (see thinner horizontal lines in Figure 5).

Taking a second, closer look at our established field-to-core framework reveals that, due to a different expression of several of the 'weaker' BIF intervals, the core proxy records exhibit a somewhat deviating bundling pattern compared to the general pattern observed in outcrop. For example, in both the Fe/Mn and MS records, 'BIF' 1d is substantially more pronounced than in the weathering profile logs, which results in a less clear definition of bundles 1 and 2; note, incidentally, the distinct semi-5 m-scale variability present in this lower part of the Kuruman IF. In addition, 'BIF' intervals 3d and 3e are slightly more pronounced in the log(Fe/Mn) record than in the field and much more pronounced in the MS signal, pointing to the presence of an additional 'BIF' bundle in between 3 and 4. Note also, however, that the MS record shows a notoriously different bundling pattern than the log(Fe/Mn) record around this stratigraphic interval, with 3a and 3b seemingly forming part of two separate bundles.

Spectral analysis and bandpass filtering (Section reference 5)

To examine this apparently more complex bundling pattern of the Kuruman IF in more detail, we move on to time-series analysis. In Figure 6, the results of L-S and MTM spectral analysis are presented for the log(Fe/Mn) and MS records, showing high concentration of power around three frequency bands, namely at ~4.5 to 6.5 m, ~14 to 25 m and ~30 to 50 m. More specifically, the log(Fe/Mn) MTM spectrum shows a dominant peak at 15.8 m and strong peaks at 5.6 m, 22.8 m and 46 m, exceeding both the 99% LOWSPEC significance level and 90% harmonic F-test confidence level (Figure 6). For the MS record we find essentially the same results, except that a strong 22.8 m and 46 m peak are absent in its corresponding MTM spectrum. Instead, additional significant peaks (satisfying both the required LOWSPEC and harmonic confidence levels; Meyers, 2012), are observed at 8.8 m and 11.4 m.

Next, we use bandpass filtering to extract these main low-frequency cycles from the log(Fe/Mn) and MS records. For extracting the ~4.5 to 6.5 m components, we applied a wide (Gaussian) filter bandwidth centred around 5.3 m which, as



expected, picks up each of the previously identified abc-alternations (Figure 5). Furthermore, an additional filtered ~5 m cycle is identified in the relatively thick interval between 5a.2 and 5b ('5a.3') in the filtered log(Fe/Mn) record, but this cycle is not picked up in the filtered MS record.

For extracting the ~14 to 25 m components from the log(Fe/Mn) record, we applied a narrow filtering around 15.6 m and 22.7 m to isolate the individual spectral peaks, and a broad filtering around 18.2 m to look at their combined expression (Figure 5). As shown in Figure 5, each of the previously identified bundles, including the weak 3c to 3e in between bundles no. 3 and 4, are followed by the filtered ~16 m cycle, which furthermore places additional cycles in between bundles no. 1 and 2 (i.e., around 1d) and around bundles no. 5 and 6 (i.e., around 5a, 5c, 6a and 6c). These '~16 m-scale' bundles are also picked up by the broad ~18 m filter, which identifies 1d to 2a, 3d to 3e, and 6a as relatively weak additional ~16 m cycles (see orange plus symbols in Figure 5). In contrast, the filtered ~23 m cycle only follows the more pronounced BIF bundles 1 to 5a, coinciding with distinct ~18 m filter maxima, and shows minima around 1d, 3d or 3e, and 6a, coinciding with weak ~18 m filter maxima. Thus, two simultaneously occurring cycles with periodicities of ~16 m and ~23 m appear to determine (largely) the characteristic bundling of ~5 m-scale BIF intervals in this main part of the Kuruman IF stratigraphy (i.e., below 170 m core depth).

These results overlap with but also differ from those of Lantink et al. (2019), where similar MTM power spectra were generated for weathering profile logs, with dominant periodicities around ~4.3 to 6.3 m and ~16 m to 22 m. However, in that study, the ~16 m and ~22 m components were attributed to a single cycle resulting from an upward change (decrease) in depositional rate, as a stronger amplitude was observed for the ~22 m cycle in the lower part of the Kuruman IF versus a stronger ~16 m cycle amplitude in the upper part from 4ab upwards. This interpretation was supported by a parallel upward shift in the dominant wavelength associated with the basic abc-alternations from ~6 m to ~4.5 m. However, no such a distinct trend is observed here in the amplitude or thickness of the filtered ~5 m cycle in the log(Fe/Mn) and MS records, nor do we see any changes in the amplitude of the filtered ~16 m or ~23 m cycles, between 170 m to 320 m core depth.

Bandpass filtering of the ~46 m peak in the log(Fe/Mn) record (Figure 6) indicates a link with the phasing of the ~16 m and/or ~23 m cycle (Figure 5). More specifically, we note that maxima in the filtered ~47 m cycle coincide (roughly) with maxima in the filtered ~23 and ~16 m cycles when they are in phase, i.e., occurring every second ~23 m- and every third ~16 m-scale maximum, in accordance with their 2:3 frequency ratio. Conversely, minima in the filtered ~47 m cycle occur during intervening maxima in the ~23 m cycle and showing an out-of-phase (opposite phase) relation with the ~16 m cycle.

Lastly, we use bandpass filtering for locating the origin of the moderately strong ~9 m and ~11.5 m peaks as present in the MTM spectrum of the MS record. As shown in Figure 5, the filtered ~9 m curve reveals largest amplitude around bundle 6, placing its successive maxima around 6a, 6b, 6c and 6d, which

are also partially followed by the ~11.5 m filter. Lower down in the stratigraphy, the filtered ~11.5 m cycle also picks up BIF intervals 5a and 5a.2, the relatively thick 4b, and the slightly more pronounced 2a and 2c relative to 2b. Both the filtered ~9 m and ~11.5 m cycles exhibit a minimum around the pronounced MS minimum in between 3a and 3b. This minimum is further recognised as a minimum in the filtered ~16 m MS cycle; note that in the filtered ~16 m log(Fe/Mn) signal this minimum is located higher, that is, above 3b.

Cyclostratigraphic analysis of the Dales Gorge

Member (Section reference 6)

Visual identification

The cyclostratigraphy of the Dales Gorge Member as reflected in and correlated between the logs and verticality profiles of the Mt Bruce and Mt Jack sections (Figure 7) shows clear similarities but also differences with the Kuruman IF. In the first place, regular alternations are visible between well-exposed ridges or cliffs and more weathered, low-relief intervals which occur at a similar basic thickness scale of about ~5 to 7 m in the lower two-third part of the stratigraphy. The alternations are associated with the formal 'BIF-S macrobanding' of Harmsworth et al. (1990) and Trendall and Blockley (1968) and have been labelled accordingly (Figure 7). However, they are not completely the same, given that our 'BIF' and 'S' intervals are based on relief and not lithology, resulting in more gradual transitions and somewhat thicker S intervals. Still, the relative thickness proportion of the cliff forming 'BIF' versus slope-forming 'S' units in the Dales Gorge Member is larger than in the Kuruman IF hill exposures, creating a more staircase-like weathering profile with steeper slopes in case of the former.

Secondly, similar to the Kuruman IF, we observe a regular larger-scale variation or bundling of ~15 to 20 m-thickness, most clearly developed in the interval from BIF macrobands DB1 to DB12; this bundling is manifested by the occurrence of relatively thicker S macrobands, i.e., DS4, 6, 9 and 11. However, the number of BIF-S alternations in each bundle in the Dales Gorge Member is less than the characteristic three to four BIF intervals per large-scale bundle observed in the Kuruman IF, with alternating groups of either three or two BIF macrobands instead (namely DB1 to 3, DB4 and 5, DB6 to 8, and DB9 and 10). In the bundles comprising just two BIF-S macroband alternations, one of the two BIF intervals is ~1.5 times thicker than its neighbour and occurs adjacent to a thicker (~3 to 5 m) S interval.

An apparently different bundling pattern is observed in the lowermost part (DB0) and upper one third part (DB12 to 16) of the Dales Gorge Member (Figure 7). These intervals are characterised by a larger absolute as well as relative proportion of BIF versus S units in terms of stratigraphic thickness, with BIF macrobands that are at least 1.5 to more than two times thicker than is the case for the 'basic' BIF-S alternations in the central part of the Dales Gorge Member. The very thick (~12 to 13 m) DB0 at the base of the Brockman IF seems to represent a single BIF bundle on its own, while also showing some affinity with the next BIF interval above (DB1), due to its more pronounced upper part and the relatively thin shale DS1 separating it from

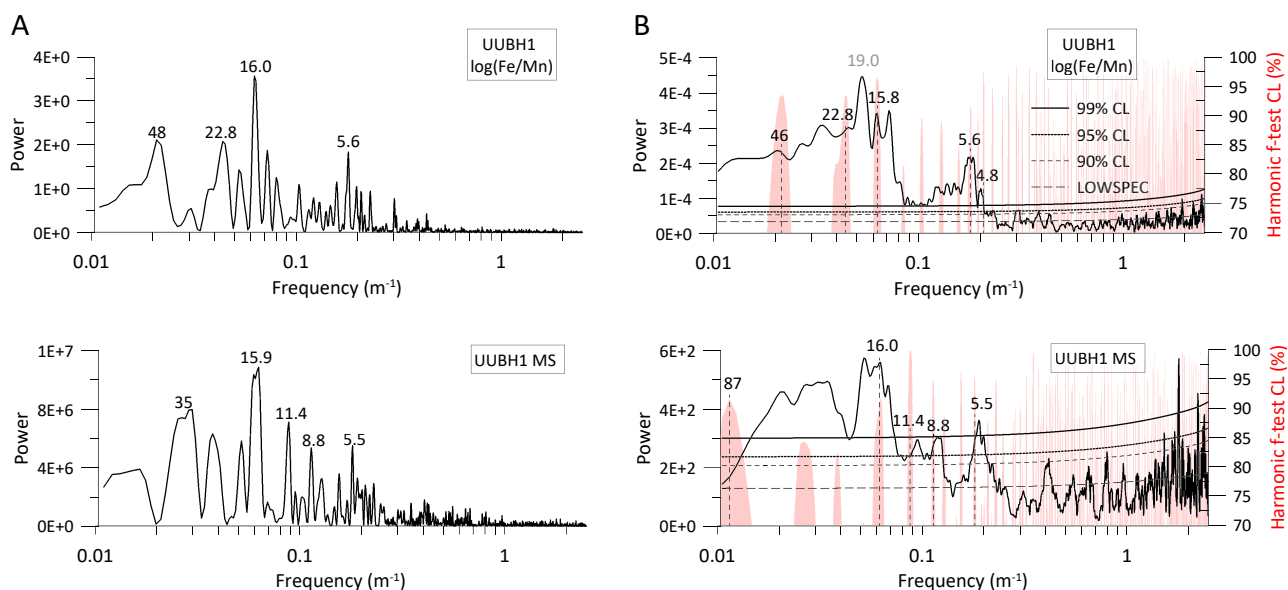


Figure 6. Spectral analysis results for the Kuruman Iron Formation. **(A)** Lomb-Scargle (L-S) power spectra of locally weighted scatter-plot smoothing (LOWESS) detrended log(Fe/Mn) and magnetic susceptibility (MS) depth records. Peak labels of prominent spectral peaks are indicated in metres. **(B)** Multi-taper method (MTM) power spectra of the records in (A) after applying a 0.1 m interpolation, with locally-weighted regression spectral (LOWSPEC) background estimation and harmonic F-test results (in red). Peak labels in black correspond to the positions indicated by the vertical dotted lines and represent significant spectral peaks according to the requirements of Meyers (2012), i.e., satisfying both the 90% LOWSPEC confidence level and 90% harmonic F-test confidence level; for the peak label in light grey the latter is not the case.

DB1 (compared to the thicker S intervals DS4, DS6 etc.). Similarly, the four ~5 m-scale 'cherty BIF'-S alternations of the Colonial Chert Member below DB0 do not show an obvious bundling, albeit that the upper two beds are slightly more pronounced and demonstrate some affinity with DB0 due to the relatively thin interstitial S interval CS6. Above DB12, the separation of DB13 to 15 from DB16 to 16A by the thicker S interval DS16 looks like a continuation of the characteristic 'two-three-two' BIF grouping observed in the middle part of the Dales Gorge Member, but occurs here at a larger thickness scale of ~25 to 30 m instead of ~16 m. In addition, DB12 and DB13 show a slight affinity to each other due to the relatively thin DS13 and the more pronounced and thicker lower part of DB13.

Further insight into the internal structure of the thicker BIF macrobands can be gained if we look more closely at the verticality profiles and their correlative HyLogger mineral records from cores DGM1 and SGP1 (Figure 8). Particularly in the ferric oxide abundance record, a clear subdivision is noticeable in several of the thicker BIF intervals, indicating that they consist of a merged (partially) double ~5 m-scale BIF-S alternation. This is particularly evident in DB12, whose ferric oxides signal reveals two distinct ~5 m-scale maxima and a pronounced minimum halfway in between, indicating a weakly developed S layer at that position. In this way, DB12 looks somewhat analogous to the double BIF macroband DB16 and 16A, which is separated by a very weak shale DS16A, although their individual BIF-S alternations are significantly thicker (~7 m in DGM1 and SGP1; 8 to 9 m at Mt Bruce) than those in DB12. A partial splitting-up of BIF intervals is further noticeable in DB13, DB15, DB9 and to some extent in DB4. For DB13

and 15, the subdivision as seen in the verticality and ferric oxides profiles is more asymmetric, with a second upper 'BIF' maximum that is relatively weaker and thinner (~3 to 4 m).

At comparable thickness scale, we note in several of the thicker S macrobands the occurrence of an additional faint 'BIF' or verticality maximum (Figure 8). In particular, the slightly more prominent bed within DS6 of the Mt Jack verticality profile occurs at the same spacing i.e. the same thickness scale of the basic ~5 m-scale alternations in DB6–8 above. However, the spacing of two conspicuous 'BIF' beds in DS11 is again thinner (1.5 to 2 m), indicating variability at the sub-macroband level as can also be seen in between CB4 and CB6 of the Mt Jack log. In general, this sub- or semi-5 m-scale variability seems to be more strongly developed in the carbonate record of core DGM1 (Figure 8). Note furthermore that the positions of the carbonate minima associated with the ~5 m-scale BIF-S variability are generally somewhat offset from those in the ferric oxides record, as can for instance be seen by a more symmetric subdivision of DB15 and different position of DS16A within DB16–16A (Figure 8).

Spectral analysis and bandpass filtering (Section reference 7)

Spectral analysis was carried out on all four Dales Gorge Member proxies to independently test for cyclicity associated with the observed metre-scale BIF-S alternations and bundling. The resultant L-S and MTM spectra of the Mt Jack and Mt Bruce verticality records both show dominant spectral power concentration around 7 m and strong peaks around 3.5 m, 4.9 to 5.4 m and 9 m, each exceeding the 99% LOWSPEC and 90% harmonic confidence level (Figure 9). In the MTM spectrum of

the Mt Bruce record, additional ~18 m and 29 m peaks are identified as significant (reaching 90 to 95% LOWSPEC confidence). A similar L-S spectrum is obtained for the DGM1 ferric oxides record, except that all longer-wavelength periodicities are ~10% thinner (e.g., the ~18 m peak is now ~16 m) and generally have higher significance levels than in the verticality spectra. MTM analysis of the ferric oxides record yields a relatively noisy spectrum, but confirms statistical significance of previously identified main spectral components (~5 m, ~7 m, ~9 m, ~16 m) in addition to peaks around ~10 to 13 m and ~45 m. A somewhat cleaner (less noisy) spectrum is obtained for the DGM1 carbonates record, with main peaks around 2.5 m, 4.5 m, 6.8 m, 8.5 m, ~16 m and ~23 m.

For all four Dales Gorge Member proxies, bandpass filtering was again used to isolate the most prominent cyclical components and compare their filter outputs to the original records (Figures 7 and 8). First of all, extraction of the very strong ~7 m cycle in the verticality and ferric oxides records shows that it follows the majority of individual BIF-S macroband alternations 1 to 11 reasonably well. In particular, the filtered ~7 m cycle shows a clear correspondence with the relatively (~1.5 times) thicker BIF macrobands DB1 to 3, DB4 and DB9 (and adjacent thicker S intervals DS4 and DS9). The filtered ~5 m cycle, on the other hand, closely tracks the thinner BIF-S alternations 5, 6 to 8, 10 and 11, as well as the four cherty BIF-S alternations of the Colonial Chert Member. Thus, the combination of a ~7 m and ~5 m cycle seems to be responsible for the basic BIF-S alternations characteristic of the lower two-third part of the Dales Gorge Member. In addition, the ~5 m filtering places an additional cycle in each of the thicker S intervals (DS6 and 11) or at the transition from thick S to thicker (~7 m) BIF interval (DS4 to DB4 and DS9 to DB9). The maxima of these filtered additional ~5 m cycles coincide with minima in the filtered ~7 m cycle in these intervals. Hence bandpass filtering confirms the possibility of an additional ~5 m-scale weak 'BIF' maximum in the thicker S macrobands (see orange plus symbols in Figures 7 and 8).

Besides the ~5 m and ~7 m cycles, bandpass filtering around ~9 m reveals a correspondence to the ~2 times thicker BIF-S alternations as characteristic of the upper one third of the Dales Gorge Member stratigraphy, as well as with DB9. In particular, the filtered ~9 m cycle follows the thicker and more pronounced lower parts of DB13 and DB15. In addition, the ~9 m filtering picks up the double BIF macroband DB12, placing a maximum in the middle that counteracts the minimum in the filtered ~5 m cycle at that position. However, note that the minima in the filtered ~9 m cycle correspond to the upper and lower edge of DB12, while DS12, DB12 and DS13 are better matched by the more broadly filtered ~11.5 m cycle (Figure 8). In the ferric oxides record, the prominent parts of DB13 to 15 and/or their adjacent S intervals are also picked up by the filtered ~7 m cycle. Moreover, the thick and double BIF interval DB16 to 16A is identified as a double (filtered) ~9 m cycle, as well as a double ~7 m cycle, while it is identified as three (filtered) ~5 m cycles. At the base of the Dales Gorge Member, the characteristic strong-weak-strong pattern of DB1, 2 and 3 is picked up by both the ~9 m and ~11.5 m filters.

Filtering of the strong ~16 m cycle shows that, as for the Kuruman IF, this cycle follows the characteristic bundling of two or three BIF-S alternations in the majority of the Dales Gorge Member stratigraphy. In Figures 7 and 8, both the filtered ~16 to 18 m cycle (using a narrow filter bandwidth) and ~18 to 20 m cycle (using a broad filter bandwidth) track each of the thicker S macrobands defining the bundles, including DS13. Note also that all of these thicker S intervals are typically associated with minima in the filtered ~9 m cycle and ~7 m cycle, whereas, as emphasised earlier, they are associated with maxima in the filtered ~5 m cycle. In the basal part of the Dales Gorge Member, however, the ~16 m filtering does not follow the characteristic group of three BIF macrobands DB1 to 3: here, the filtered ~16 m cycle minimum is situated higher, around DB1–DS2 instead of DS1, while the next filtered ~16 m maximum below is placed around the top part of DB0. This appears to explain the apparent merging or affinity of DB1 with DB0. Secondly, the very thick bundle DB13 to 15 higher up in the stratigraphy is identified as a double rather than single ~16 m cycle.

This thicker bundle in the upper part of the Dales Gorge Member seems to be largely responsible for the lower-power cycles in the ~20 to 29 m range (Figure 9). As visible in Figures 7 and 8, their correspondingly filtered curves identify bundle DB13 to 15 (but also DB11–12 and DB16–16A) as a single cycle and generally exhibit largest amplitude in this upper interval. More specifically, the ~27 to 29 m cycle as present in the Mt Bruce and Mt Jack spectra seems the consequence of the relatively thicker upper macrobands in these two field sections compared to in core DGM1, where this cycle has a shorter wavelength of ~20 to 25 m according to the spectral analysis (Figure 9). In the carbonates abundance record of core DGM1, the filtered ~22 m cycle shows a relatively constant amplitude throughout the stratigraphy, i.e. also in the lower and middle part of the Dales Gorge Member, indicating that DS1, DB4 and DB8 are successive (filtered) ~22 m cycle minima (Figure 8). In the ferric oxides record, the expression of the ~22 m cycle is more subtle, as revealed by amplitude variations of the broadly filtered ~18 to 20 m cycle (~16 m-scale bundling) (Figure 8).

U-Pb ages and sedimentation rate

Concordant high-precision U-Pb TIMS data were obtained from the targeted stilpnomelane-rich shale intervals of the Dales Gorge Member (DS1 and DS9 upper), as well as from the Kuruman IF, allowing for a more robust assessment of their relative timing than was hitherto possible based on available U-Pb SHRIMP ages of the Dales Gorge Member (Nelson et al., 1999; Trendall et al., 2004; Wingate et al., 2021a; 2021b). The calculated $^{207}\text{Pb}/^{206}\text{Pb}$ ages derived from shale DS1 and DS9 upper are $2\,482.1 \pm 1.9$ Ma (2σ) and $2\,477.8 \pm 0.9$ Ma, respectively (Figure 10) corresponding to 13.9 m and 64.9 m height in the DGM1 core. These ages constrain the depositional time frame of the Dales Gorge Member to the lower circa three quarters of the Kuruman IF, whose onset is estimated at $2\,484.6 \pm 0.34$ Ma, reflecting the previously acquired TIMS U-Pb age for the basal Klein Naute Shale of Lantink et al. (2019). Our TIMS ages for DS1 and DS9 are also consistent with but more

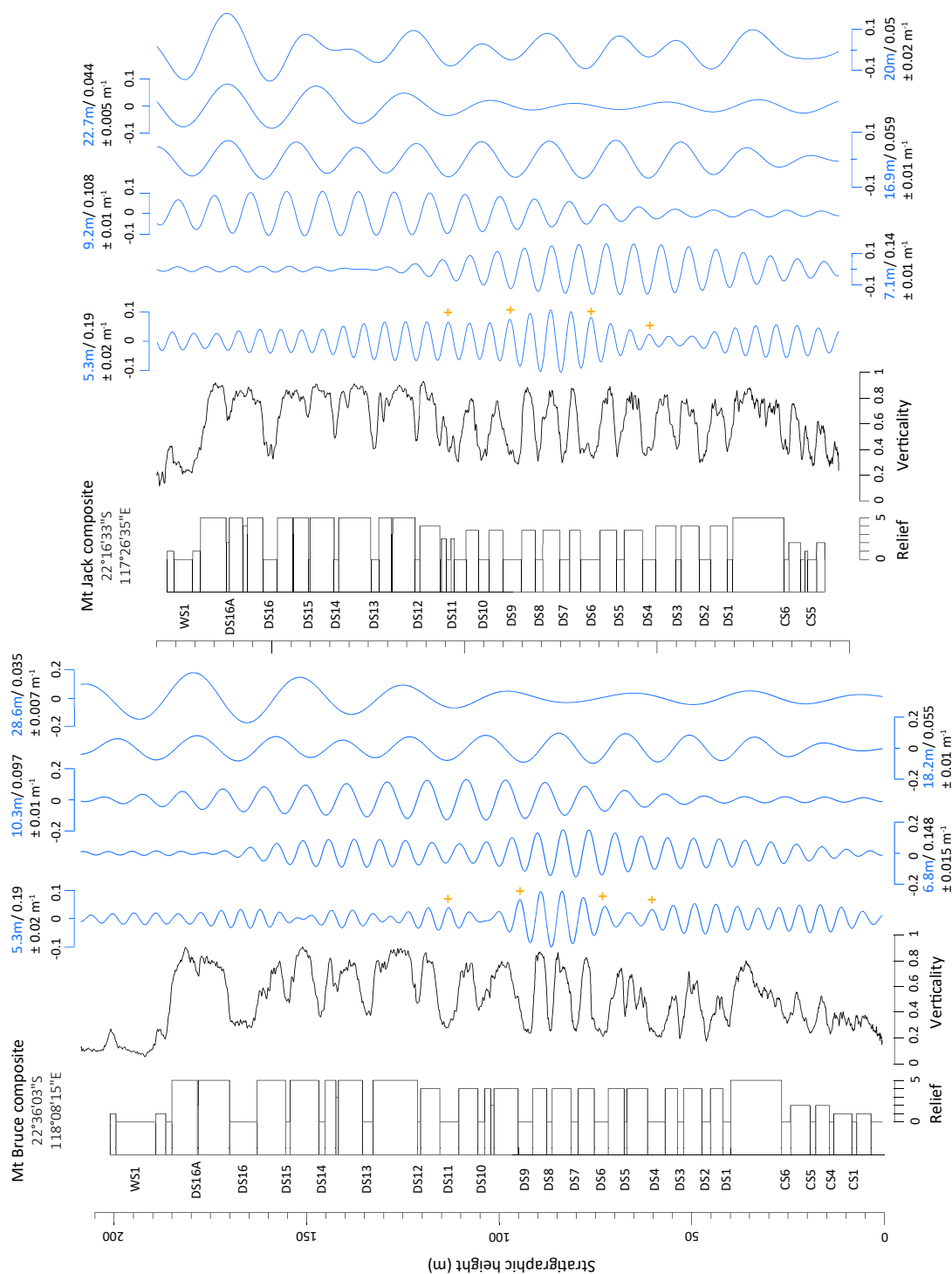


Figure 7. Composite relief logs and verticality profiles for the Mt Bruce and Mt Jack field sections with corresponding bandpass filters in blue. Indicated on the left of the schematic columns are the 'shale' (S) macroband numbers of the characteristic Banded Iron Formation (BIF)-S macroband alternations of the Dales Gorge Member (DS1-16A), the underlying Colonial Chert Member (CS1-6) and overlying Whaleback Shale Member (WS1), according to the nomenclature of Harnsworth et al. (1990). Macroband numbers of the BIF intervals follow that of the underlying S macroband. DS1 (Dales Gorge Member BIF) occurs below DS1 (Dales Gorge Member S1) and defines the base of the Broedman Iron Formation. Orange '+' symbols mark the thicker S intervals where an additional ~5 m cycle maximum is recognised by the filtering coinciding with minima in the (filtered) ~7 m and ~16 m cycle.

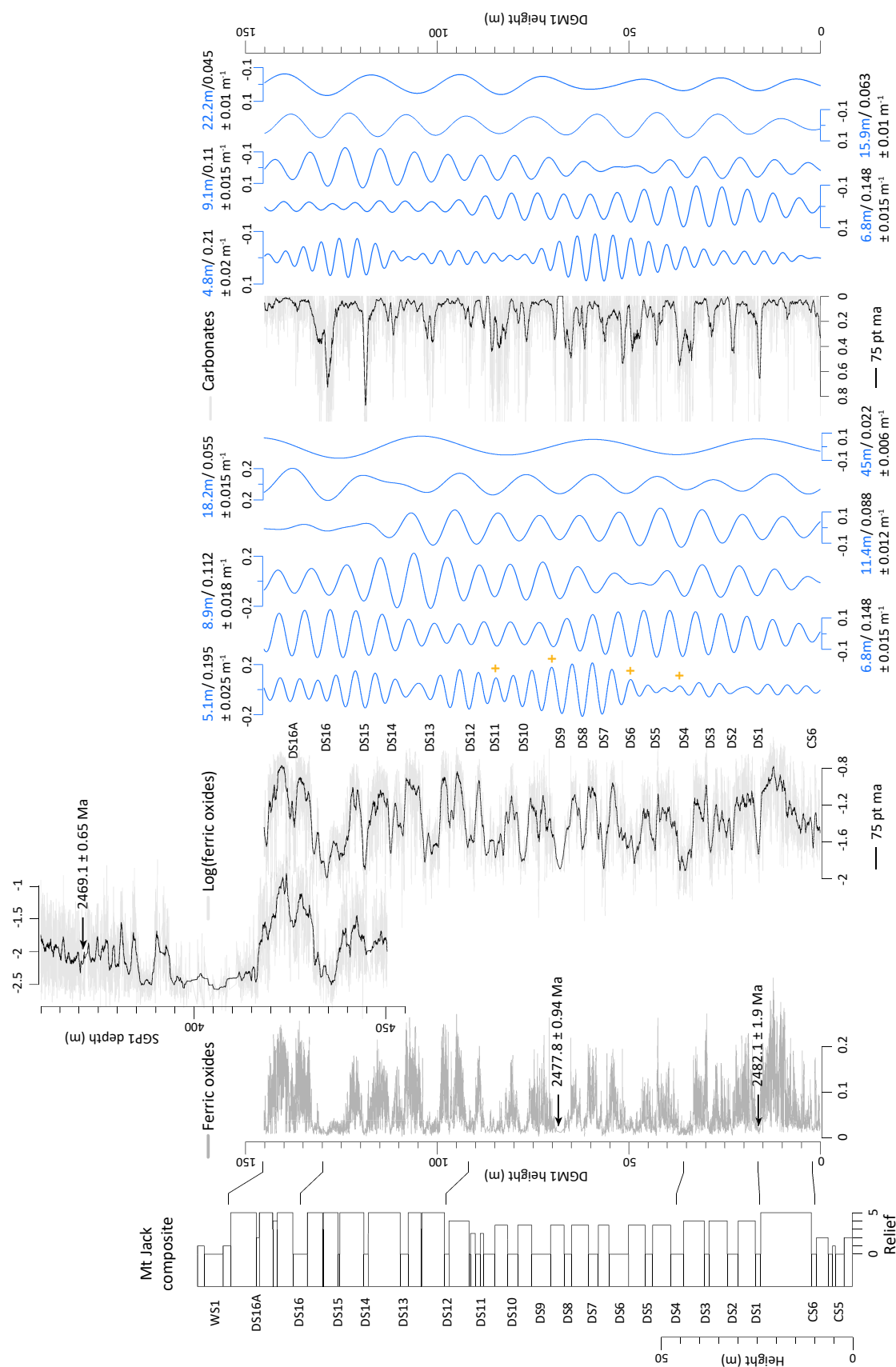


Figure 8. Stratigraphic panel and high-precision U-Pb geochronology for the Dales Gorge Member showing the correlation between the characteristic banded iron formation-shale' (BIF-S) macroband alternations of the Mt Jack log to the ferric oxide and carbonate mineral abundance data from cores DGM1 and SGPI. Results of Gaussian bandpass filtering (in blue) and a 75-point moving average (in black) are given for the log(ferric oxides) and carbonates records. Orange '+' symbols mark the thicker S intervals where an additional ~5 m cycle maximum is recognised by the filtering coinciding with minima in the (filtered) ~7 m and ~16 m cycle.

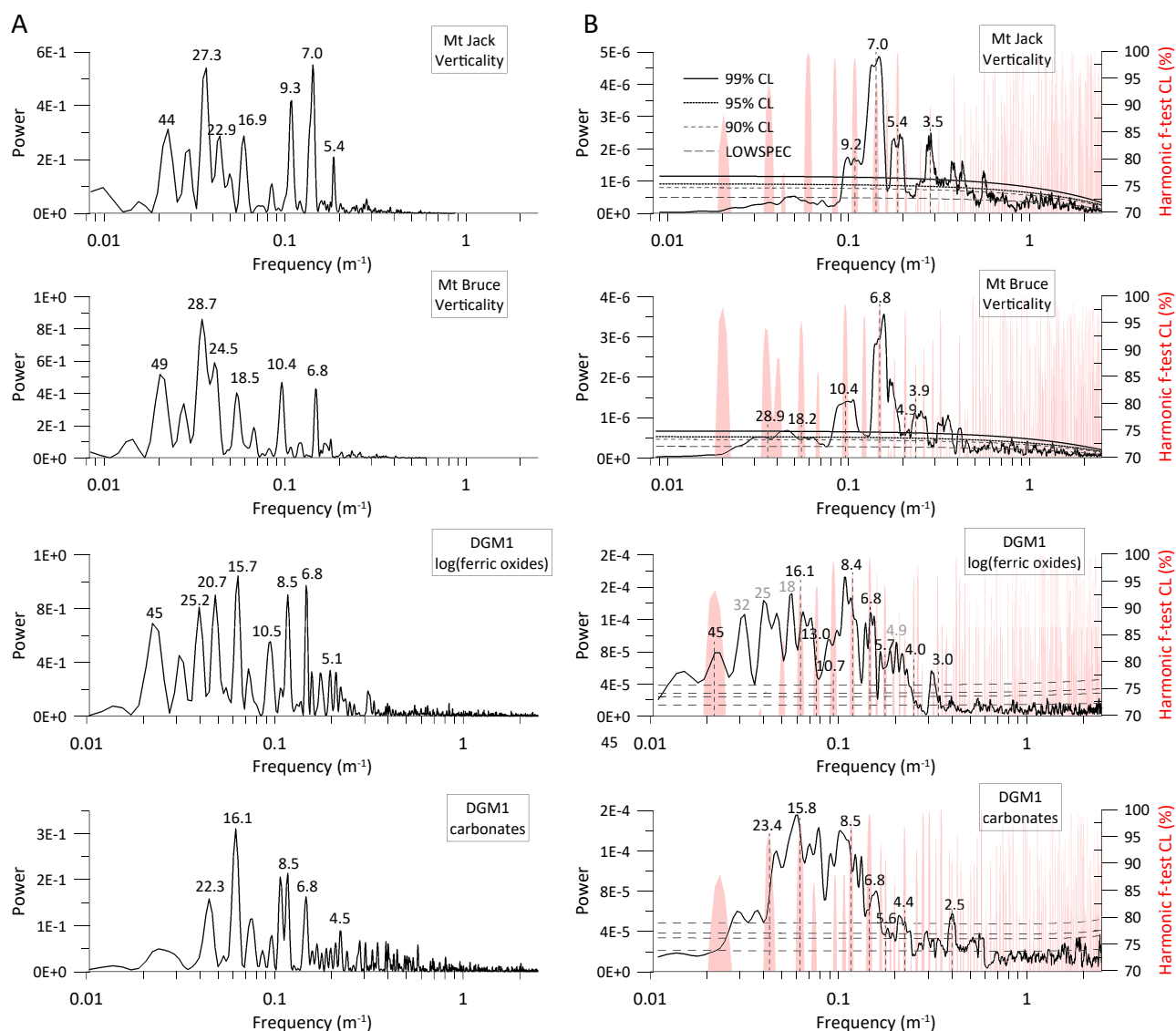


Figure 9. Spectral analysis results for the Dales Gorge Member. **(A)** Lomb-Scargle (L-S) power spectra of locally weighted scatter-plot smoothing (LOWESS) detrended verticality profiles (Mt Bruce and Mt Jack) and mineral abundance data (core DGM1). Peak labels of prominent spectral peaks are indicated in metres. **(B)** Multi-taper method (MTM) power spectra of the records in (A) after applying a 0.1 m interpolation, with locally-weighted regression spectral (LOWSPEC) background estimation and harmonic F-test results (in red). The spectrum of the log(ferric oxides) is based on a 5 cm interpolated record and was made with a time-bandwidth product of 2 instead of 3. Peak labels in black correspond to the positions indicated by the vertical dotted lines and represent significant spectral peaks according to the requirements of Meyers (2012), i.e., satisfying both the 90% LOWSPEC confidence level and 90% harmonic F-test confidence level; for peak labels in light grey the latter is not the case.

precise than recent SHRIMP analyses from a larger population of zircon from the same samples (Wingate et al., 2021a; 2021b). In addition, revised $^{207}\text{Pb}/^{206}\text{Pb}$ ages were calculated for the shales at 212 m and 111 m depth in core UUBH1 (lutites 2 and 4 of Lantink et al., 2019) from adding new concordant zircon analyses to the weighted mean age of each sample. This yielded slightly older and significantly more precise ages of 2476.9 ± 0.9 Ma and 2464.8 ± 0.77 Ma, respectively (Figure 10), compared to the results of Lantink et al. (2019).

Importantly, our new zircon ages indicate an almost identical accumulation rate for the Dales Gorge Member and Kuruman IF. An average accumulation rate of 10 to 13 m/Myr (~ 1 to

35 m/Myr, 95% C.L.) is estimated for the Dales Gorge and overlying Whaleback Shale Member (Figure 11), which includes a third, recently established TIMS zircon $^{207}\text{Pb}/^{206}\text{Pb}$ age from a shale at 371 m depth in core SGP1 of 2469.1 ± 0.65 Ma (Lantink et al., 2022). Likewise, our updated depositional rate model for the Kuruman IF suggests an average accumulation rate of 10 to 12 m/Myr (~ 1 to 30, 95% C.L.) for the time interval corresponding to the Dales Gorge Member, which decreases slightly with increasing stratigraphic height. Thus the U-Pb geochronology appears to be consistent with a common or shared origin for the in thickness-matching cycles of Kuruman IF and Dales Gorge Member described in (Section references 4 and 6).

Time calibration of the observed cycles and possible origin (Section reference 8)

The goal of this study was to examine the possibility of a correlation between the Kuruman IF and Dales Gorge Member based on their inferred long-period eccentricity related cycle pattern. As such, we must first turn to the question of whether such a Milankovitch control is a plausible explanation.

Astronomical interpretation of the basic alternations and bundling (Section reference 9)

As previously discussed in Lantink et al. (2019), we find it difficult to imagine a phenomenon other than astronomical forcing that can explain the periodic nature, hierarchical ordering and vast lateral continuity of the observed metre-scale alternations in the Kuruman IF and Dales Gorge Member. The regular nature of the stratigraphic cycles and observed amplitude-modulation relationship at two main thickness levels (in particular, ~16 m-thick 'bundles' of ~5 m-scale BIF-S alternations) over a stratigraphically extensive (≥ 150 m-thick) interval makes alternative paleoenvironmental causes (e.g. tectonic or autoregressive 'red' noise) unlikely, while the lateral extensiveness of the patterns argues against autocyclic controls. The lateral continuity of the alternations in the Kuruman IF spans at least 250 km (Lantink et al., 2019). Similarly for the Dales Gorge Member, a lateral continuity of ~150 km of the characteristic BIF-S macroband pattern is indicated by the four localities targeted in the current study (Figures 1, 4, 7 and 8). However, this continuity may in fact be extended to almost 500 km knowing that the classical BIF-S macroband pattern of the Dales Gorge Member can be laterally traced over the full west-east extent of the Hamersley Basin (Harmsworth et al., 1990; Trendall and Blockley, 1970).

For the Kuruman IF, independent support from U-Pb dating was already provided in Lantink et al. (2019) for the hypothesis that the main ~5 m-scale iron oxide ('BIF') versus carbonate-shale cyclicity represents the stratigraphic expression of the long (~405 kyr) eccentricity cycle (Section reference 1). Our updated, slightly higher sedimentation rate established here for the lower half of the UUBH1 core (Figure 11) seems in even better agreement with this interpretation. When assuming a sedimentation rate of 12 m/Myr, we obtain a period of 467 kyr for the main 5.6 m peak, and a period of 400 kyr for the weaker but also significant peak around 4.8 m, as present in the log(Fe/Mn) MTM spectrum (Figure 6). Note that the average wavelength of the 405 kyr-related cycle in the Kuruman IF is estimated to be closer to 4.8 m than to 5.6 m, since a mean thickness of 5.1 m is obtained when counting the number of (filtered) ~5 m-scale alternations in the interval from 1a to 5d (i.e., 23 cycles in 117 m of stratigraphy). This implies that the 5.6 m periodicity as derived from spectral analysis is biased towards longer wavelengths, probably due to relatively thicker and more prominent alternations in the BIF-dominated intervals which contribute more to the amplitude of the power spectrum than the relatively thinner alternations in the carbonate- and shale-dominated intervals.

For the equivalent (i.e., ~5 m-scale) BIF versus S cyclicity in the Dales Gorge Member, a sedimentation rate of 12 m/Myr for the lower Brockman IF (Figure 11) yields a period of 408 kyr if the average 4.9 m wavelength (peak) in the DGM1 ferric oxides record is selected (MTM spectrum; Figure 9). Again, the calculated period based on the U-Pb-derived sedimentation rate is remarkably close to that of the 405-kyr long eccentricity cycle. Thus, as for the Kuruman IF, the cyclostratigraphic and U-Pb dating results are in mutual support of a long eccentricity origin for the ~5 m-scale cyclicity in the Dales Gorge Member. Note that this interpretation is different from that of de Oliveira Rodrigues et al. (2019), who also suggested a link between the BIF-S macrobanding and the 405 kyr eccentricity cycle in their 'Timescale 1', but reported a cycle thickness of 8 m (instead of ~5 m), based on the average thickness of 17 BIF-S pairs as determined from a greyscale scan of the type section core. However, our cyclostratigraphic results indicate that the combination of a ~5, 7 and 9 m cycle explains the characteristic BIF-S macroband pattern in the Dales Gorge Member (Section reference 6).

In addition, our results for the Dales Gorge Member question the recent work of Zhou et al. (2022), who applied the Bayesian inversion method of Meyers and Malinverno (2018) to a 2 m-thick section (of DB12) from the greyscale record used in de Oliveira Rodrigues et al. (2019). However, Zhou et al. (2022) assumed a maximum sedimentation rate 'prior' of 3 m/Myr, which is lower than the average rate reported in Lantink et al. (2019) and as confirmed by this study. As a consequence, these authors obtained an estimated total duration of 1.2 Myr for the studied interval by interpreting Calamina cyclothem variability of ~10 to 15 cm-thickness – a likely candidate for the expression of climatic precession (Lantink et al., 2019; 2022; 2023) – as short (~100 kyr) eccentricity. This implies that the precession frequency, Earth-Moon distance and length-of-day estimated by Zhou et al. (2022) are likely based on a fundamentally incorrect Milankovitch interpretation.

Subsequently, it was argued in Lantink et al. (2019) that the apparent '~16 to 22 m' cycle responsible for the bundling of the ~5 m cycles in the Kuruman IF is a most logical candidate for the very long (now ~2.4 Myr) eccentricity cycle ('Hypothesis 2' of Lantink et al., 2019). The unstable '~2.4 Myr' eccentricity cycle is the strongest eccentricity component after the 405 kyr and short (~100 kyr) eccentricity cycles (e.g. Laskar et al., 2004), and is also denoted as the 'Mars-Earth' $g_4 - g_3$ cycle, where g_i terms refer to the fundamental frequency of the rotation of the orbits of Mars ($i = 4$) and Earth ($i = 3$) on their respective orbital planes. Given the prominent expression of the 405 kyr cycle in the Kuruman IF weathering profile, it was therefore argued that a similarly strong imprint of the $g_4 - g_3$ eccentricity cycle would be expected, in case of a nonlinear response and associated power transfer from the domain of climatic precession (the inferred primary insolation driver) to its longer-period amplitude modulating cycles of eccentricity. The observed 1:3 to 1:4 ratio between the inferred 405 kyr- and ($g_4 - g_3$)-related cycles was attributed to a reduction in the period of $g_4 - g_3$ to ~1.2 and 1.6 Myr due to chaotic diffusion (Lantink et al., 2019; Laskar, 1990), as also observed in the Mesozoic (e.g. Ma et al., 2017; Olsen and Kent, 1999).

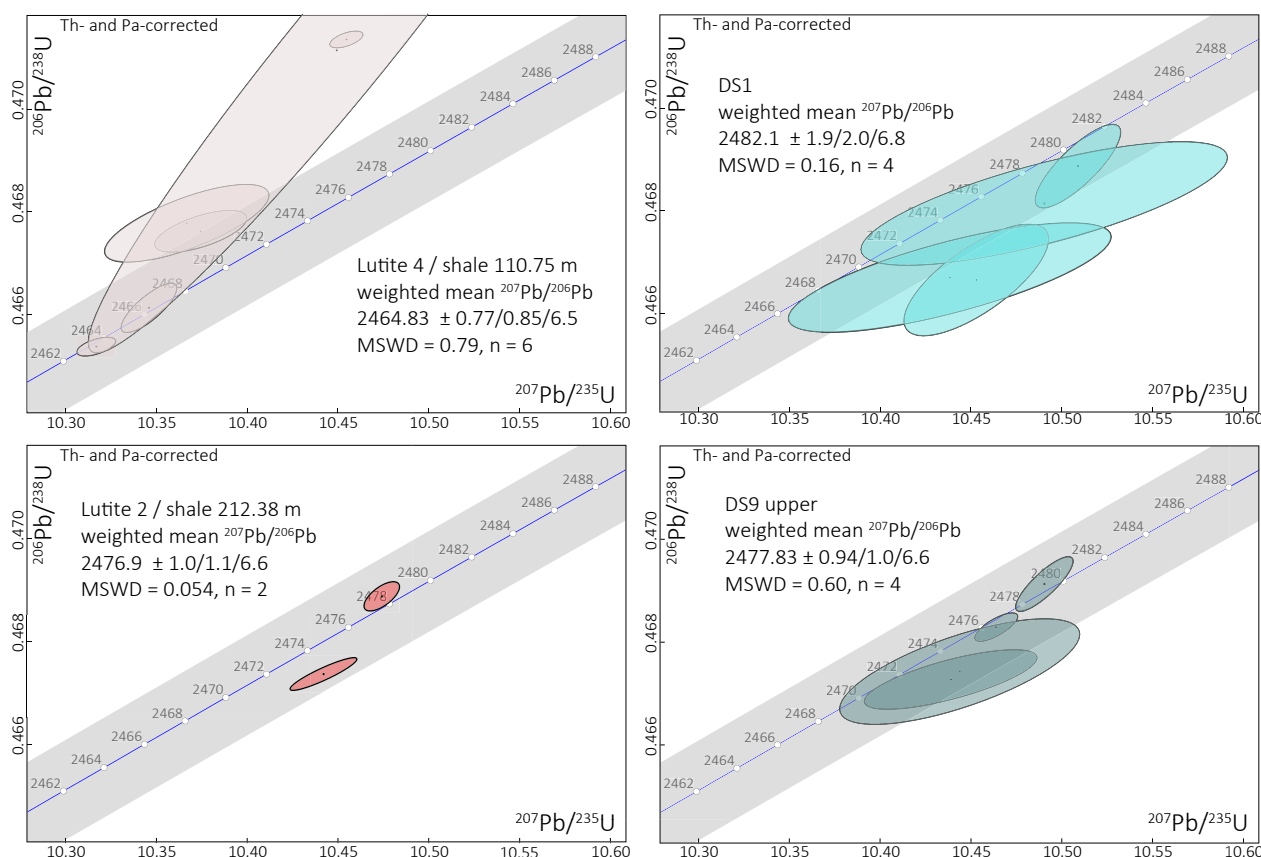


Figure 10. Concordia diagrams showing the concordant high-precision U-Pb thermal ionisation mass spectrometry (TIMS) dating results and the calculated $^{207}\text{Pb}/^{206}\text{Pb}$ ages for DS1 and DS9 (Dales Gorge Member) and shales 212 m and 111 m (Kuruman Iron Formation). The grey band represents 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. MSWD=mean square of the weighted deviates.

Unlike the $g_4 - g_3$ cycle, the period of the 405 kyr ($g_2 - g_5$) cycle – arising predominantly from the secular orbital motions of Venus ($i = 2$) and Jupiter ($i = 5$) – has been considered relatively stable in deep time (e.g. Hoang et al., 2021; Laskar, 1993; Laskar et al., 2004, 2011). Accordingly, this cycle may (when clearly expressed in the stratigraphy) be used for time calibration of other (longer-period) cycles. Lantink et al. (2019) related the 4.5 to 6.1 m cycle as seen in the evolutive harmonic spectrum of the Whitebank section to the 405 kyr eccentricity cycle to obtain a period between 1.4 and 1.6 Myr for the single larger-scale cycle associated with the bundling. However, based on our more detailed cyclostratigraphic account of the Kuruman IF and Dales Gorge Member (Section references 5 and 7), now at least two cycles appear to be involved in the bundling in both stratigraphic units, of which the dominant cycle has a period of ~16 m. Therefore, it currently seems most logical to attribute this ~16 m cycle to $g_4 - g_3$. Using the established mean thickness of the 405 kyr-related cyclicity in both successions, the ~16 m cycle converts to a mean period of ~1.3 Myr (Table 1), i.e., shorter than initially estimated by Lantink et al. (2019). More precisely, we estimate a period of 1.27 ± 0.05 Myr for the Kuruman IF, based on counting between 21 and 23 (interpreted) 405 kyr-related cycles and seven filtered ~16 m cycles in the interval from BIF 1a to 5c.

Milankovitch origin of other long-period cycles? (Section reference 10)

Starting from our preferred astronomical explanation of the prominent ~5 and ~16 m cycles, the interpretation of the remaining long-period cycles in the Kuruman IF and Dales Gorge Member spectra from a Milankovitch perspective is less certain and hence becomes more speculative. While there are potential candidates for the ~7 and 9 m cycles in terms of periodicity (Table 1; $(g_2 - g_5) - (g_4 - g_3)$ and $(g_2 - g_1)$ with respective periods of ~560 and 700 kyr), the amplitudes of these cycles in Earth's eccentricity evolution as observed in astronomical solutions (Laskar et al., 2004; 2011; Zeebe, 2017; Zeebe and Lourens, 2022) are much weaker than what we observe in our spectra. Furthermore, there is no obvious candidate to explain the ~23 m cycle in case we attribute the ~16 m cycle to the very long ($g_4 - g_3$) eccentricity cycle. Alternatively, it is possible that the ~23 m rather than the ~16 m cycle is related to $g_4 - g_3$, in which case the ~16 m cycle could reflect the ~1.2 Myr obliquity amplitude modulation cycle instead (Table 1; $s_3 - s_6$). However, the evidence so far argues for a dominant precession and eccentricity control (Lantink et al., 2019; 2023).

Moreover, we know from the more recent geological past that a nonlinear climate response to the astronomical forcing can result in combination tones and harmonic cycles (e.g. an ~80 kyr double obliquity cycle in the Pleistocene, see Huybers, 2009; Huybers and Wunsch, 2005; Marino et al., 2009; Raymo and Nisancioglu, 2003; Ruddiman et al., 1989), while these may also result from time-depth distortions during registration of (astronomical) cycles in the sedimentary archive (e.g. Herbert, 1994; Meyers, 2019; von Dobeneck and Schmieder, 1999; Weedon, 2003; Westphal et al., 2004). Indeed, the ~7 and 9 m could reflect combination tones arising from nonlinear coupling of the ~5 and 16 m and the ~16 and 23 m cycles ($1/5 - 1/16 \approx 1/7$ and $1/16 + 1/23 \approx 1/9$), while the ~9 m cycle can also be partly explained as a harmonic of the ~16 m cycle (see bandpass filters in Figures 7 and 8) or a difference tone of the ~5 and 11.5 m cycle ($1/5 - 1/11.5 \approx 1/9$) (Table 1). Similarly, the ~2.5 and 3.5 m cycles may result from true harmonics of real eccentricity cycles (e.g., $2(g_2 - g_3)$; Hilgen et al., 2020; Laskar, 2020) and from nonlinear responses in the climate-depositional system (Figure S6). Finally, the ~45 m cycle may reflect a combination (difference) tone of the ~16 and 23 m cycles (Figures 5, 8 and Table 1).

In summary, uncertainties remain concerning the origin of several cycles involved in the characteristic cyclostratigraphic patterns of the Kuruman IF and Dales Gorge Member. Particularly enigmatic are the strong ~7 and 9 m cycle in the Dales Gorge Member (corresponding to ~1.5 to 2 times thicker BIF macrobands) and a moderately strong ~23 m cycle in the Kuruman IF (involved in the large-scale bundling), which may reflect weaker eccentricity components and/or combination tones and harmonics that result from nonlinear response within the climate-depositional system. Nonetheless, we consider the cyclostratigraphic and U-Pb evidence presented in (Section reference 3) sufficiently convincing in support of the Milankovitch interpretation of Lantink et al. (2019) for the main hierarchy of two cycles in both units, namely:

- a ~5 m cycle defining the basic 'BIF' versus 'S' alternations related to the (~405 kyr) long eccentricity cycle; and
- a ~16 m cycle dominantly responsible for the bundling of several BIF intervals (associated with the ~5 m cycle), which may reflect the expression of very long eccentricity with a period of ~1.3 Myr.

Therefore, we consider it justified to proceed in establishing a cyclostratigraphic correlation between the Kuruman IF and Dales Gorge Member, focusing on the expression and/or scale of the ~5 m and ~16 m cycles.

Establishing of a 405 kyr-scale cycle framework (Section reference 11)

Correlation option I: based on the characteristic weathering profile pattern (Section reference 12)

Cyclostratigraphic correlations between outcrops of the Kuruman IF in the Griqualand West Basin have previously been established over 250 km on the basis of the characteristic pattern in the succession of prominent BIF bundles as seen in weathering profile (i.e., 2abc, 3ab, 4(a)b, and the double (~16 m-scale) bundle 5abcd, see Lantink et al., 2019). Likewise, the correlation between the weathering profile logs and the new UUBH1 core proxy records based on identification of this characteristic pattern proved relatively straightforward in the present study (Section reference 4). Similarly, the distinctive cycle pattern seen in outcrops and cores of the Dales Gorge Member has been used for detailed correlations across the Hamersley Basin over many hundreds of kilometres. Thus, adopting the same visual approach seems a promising starting strategy for establishing the intended high-resolution correlations between the Kuruman IF and the Dales Gorge Member. To establish these correlations, we will use the log(Fe/Mn) record of the Kuruman IF, which is generally more representative for its weathering profile than the MS record. For the Dales Gorge Member, we will use the log(ferric

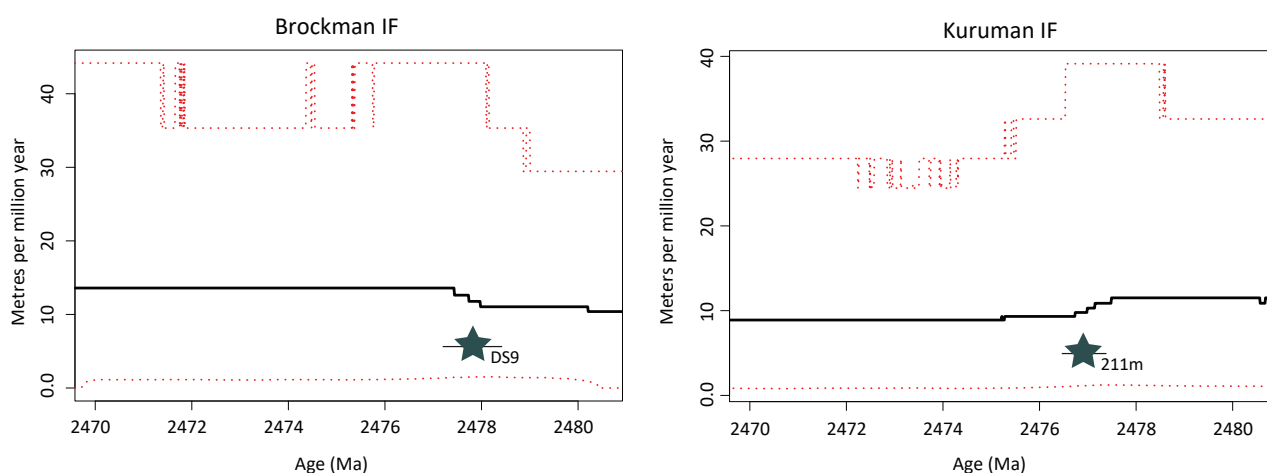


Figure 11. Bchron depositional rate model for the lower Brockman Iron Formation (IF) (left) based on the high-precision $^{207}\text{Pb}/^{206}\text{Pb}$ ages from zircon extracted from DS1 and DS9 layers and shale 371 m from core SGP1 of Lantink et al. (2022). An updated depositional rate model is also given for the Kuruman IF (right) based on improved $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages from the shales at 212 m and 111 m depth in core UUBH1. The stars indicate the age and uncertainty of the samples that plot within the figures, the other ages are just outside the limits of the figure. The red dotted lines represent the 95% confidence limits of the Bchron model.

oxides) record of core DGM1 as representative proxy, because the cycle thicknesses in that record are more similar to those in the Kuruman IF than the verticality profiles of Mt Jack and Mt Bruce.

As a starting point for our correlation, we choose bundle 2abc, the characteristic group of three prominent BIF intervals seen in the Kuruman IF weathering profile (Lantink et al., 2019). Looking at the outcrop pictures of the Dales Gorge Member (Figure 3 and 4), and the verticality and log(ferric oxides) records (Figures 7 and 8), the three well-defined alternations of roughly equal thickness DB6 to 8 bear most resemblance to 2abc, and were correlated accordingly (Figure 12). Subsequently, the most logical correlation, when focusing on the more pronounced and/or thicker BIF intervals, is to correlate 3ab to DB9 and 10, 4ab to DB11 and 12 (where 4b corresponds to the lower part of DB12), and the very prominent bundle 5abcd to DB13–15, interpreting DB13 and DB15 each as a double ~5 m cycle. To complete our scheme, we must correlate the lower bundle 1abc in the Kuruman IF to DB4 and 5, and 6ab to the very prominent DB16 and 16A at the top of the Dales Gorge Member.

However, starting from this initial correlation option I, we encounter two critical inconsistencies regarding our cyclostratigraphic and U-Pb zircon dating results. Firstly, there are no correlative ~5 m-scale BIF-S alternations in the Dales Gorge Member for the three weaker BIFs 3c to 3e in the extra ~16 m-scale bundle in between 3 and 4 of the Kuruman IF. As a consequence, 3c, 3d and 3e need to be correlated to DS11, implying a major condensed interval, for which there are no (obvious) sedimentological nor cyclostratigraphic indications. To avoid this condensed interval, or alternatively a hiatus, the correlations of the cycles above 3b can be shifted upwards by two ~5 m cycles in the Dales Gorge Member. However, this revision results in a loss of fit between the cycle patterns in the two units (Figure 12).

Secondly, correlation option I is not compatible with the U-Pb geochronology, especially when considering the ages of DS9 in the Dales Gorge Member and the shale at 212 m in core UUBH1 of the Kuruman IF. The 2σ age uncertainties associated with these ages allow for a maximum difference of 2.8 Myr between the two dated stratigraphic levels. This is in direct conflict with the at least eight ~5 m or 405 kyr eccentricity-related cycles identified in this interval in the Kuruman IF, implying a duration of 3.2 Myr (Figure 12). This implies that the Dales Gorge Member needs to be shifted upwards relative to the Kuruman IF by at least one (filtered) ~16 m cycle to make the cyclostratigraphic correlations consistent with the U-Pb results.

Correlation option IIa: most consistent with the U-Pb geochronology and characteristic pattern (Section reference 13)

We therefore explore a second, alternative correlation between the Kuruman IF and Dales Gorge Member that is both consistent with the U-Pb dates and the characteristic cycle patterns (succession of prominent BIF bundles) by shifting the Dales Gorge Member two (filtered) ~16 m cycles upwards (Figure 13). In this way, the 212 m shale and DS9 are placed within two or three ~5 m cycles from each other, which is consistent with their

mean U-Pb age difference of 1.2 Myr. From a cyclostratigraphic point of view, this two-bundle shift is required to correlate 2abc to the other group of three pronounced, roughly equal BIF macrobands in the Dales Gorge Member, namely DB1 to 3. For the remainder of the stratigraphy, we proceed by first correlating at the ~16 m bundle level, followed by linking the more prominent ~5 m-scale BIF intervals of each bundle. Accordingly, 3ab correspond to DB4 and 5, 4b to DB9 and 5a to DB12. For the upper part, we shift the Dales Gorge Member upwards by only one filtered ~16 m cycle in order for the correlation to make more sense in terms of pattern resemblance, by linking the characteristic group of three prominent BIF intervals 5bcd to DB13–15, and 6a to DB16.

Although this second correlation (option IIa) initially did not seem most logical in terms of resemblance in characteristic pattern, similarities in the expression and/or the number of prominent BIF intervals per correlated bundle are still largely maintained and are in some cases even improved (Figure 13). In particular, the correlation of 2abc to DB1–3, instead of to DB6–8 (as was the case for option I), makes sense from the perspective of the UUBH1 proxy records (as opposed to weathering profile expression), in which 2a forms part of bundle 2abc as well as showing affinity with the distinct 1d below (Figure 5). This pattern looks similar to the characteristic merging of DB1 with the top of DB0 in the Dales Gorge Member; both features are related to the somewhat higher stratigraphic position of a ~16 m-scale cycle maximum (i.e., around 1d and the top of DB0, respectively; see narrow ~16 m filter output in Figure 5). In addition, 2a and 2c are slightly more pronounced than 2b, as are DB1 and DB3, which in both cases is related to the expression of the ~11.5 m cycle in this interval (Figures 5 and 8). Moreover, higher up in the stratigraphy, the resemblance of the weak 4d followed by the very prominent, double 5a to DB11 and 12 (correlation option II) is compelling and appears to be more logical than a correlation to DS12–DB13 (according to option I), particularly when comparing the expression in the Kuruman IF weathering profile (Figure 5) with the DGM1 carbonates abundance record (Figure 8).

However, at the individual ~5 m- and ~16 m-cycle level, we also encounter several misfits if we stick to our strategy of linking the most prominent BIF intervals. In the middle section, the result of correlating 3ab to DB4 and 5 is that an additional ~5 m cycle is required in DS4, on top of an already-inferred extra cycle, as well as one additional ~5 m cycle in between 4c and 4d (Figure 13). In addition, this correlation implies that the top of DB9 correlates to the interval in between 4a and 4b in the Kuruman IF. Higher up in the stratigraphy, the consequence of linking 5b to the lower, more pronounced part of DB13 is that it requires the absence of an additional ~5 m cycle above 5a.2 ('5a.3'), but again the addition of a ~5 m cycle in between 5b and 5c, if we assume that DB13 represents a double ~5 m cycle. In addition, correlation IIa implies the absence of a second ~5 m cycle for the upper part of DB15.

Furthermore, with correlation IIa we have thus far treated bundle DB13–15 as a single ~16 m bundle, in contradiction to what is suggested by the double (filtered) ~16 m maximum around this interval. The issue is that it is still unclear whether

Table 1. Time calibrated period, relative strength and possible astronomical or nonlinear origin of the different cycles identified in the stratigraphy of the Kuruman Iron Formation and Dales Gorge Member. Representative power spectrum peaks are selected from the Lomb-Scargle (L-S) or multi-taper spectra of the UUBH1 and DGM1 core proxy records (Figures 6 and 9). Orbital cycles are written as combinations of two or more g_i frequencies or s_i frequencies for the planets $i = 1$ to 5, where g terms refer to the fundamental frequency of the precession of perihelion in the orbital plane, yielding the eccentricity cycles, and s terms refer to the fundamental frequency of the precession of the orbit's ascending node, yielding the obliquity amplitude modulating cycles. La2004 mean period and amplitude values (multiplied by 10^4) are taken from Tables 6 and 7 in Laskar et al. (2004) and Figure 4 in Laskar (2020). *Assuming $g_4 - g_3$ has a period of 1.3 Myr.

Dales Gorge Member			Kuruman Iron Formation			Astronomical			Nonlinear
Power spectrum peak (m)	Period 4.9 m = 405 (kyr)	Relative strength	Power spectrum peak (m)	Period 5.1 m = 405 (kyr)	Relative strength	g_i or s_i combination term	La2004 [-15, +5 Myr] mean period (kyr)	La2004 [-15, +5 Myr] amplitude	harmonic and/or combination tone
2.5	207	-	-	-	-	$-2g_2 - 2g_5$	203	-	harmonic 5 m
3.0–3.5	248–289	+	-	-	-	$(g_2 - g_5) + (g_1 - g_5)$	285	-	harmonic 7 m; sum. tone 5 and 16 m
4.4–5.7	363–471	+	4.8–5.6	381–445	++	$g_2 - g_5$	405	107	
6.8	562	++			-	$(g_2 - g_5) - (g_4 - g_3)$	486 / 593*	20	diff. tone 5 and 16 m
8.5	703	++	8.8	699	+/-	$g_2 - g_1$	688	18	diff. tone 16 and 23 m; harmonic 16 m; diff. tone 5 and 11.5 m
10.7 13	884 1074	+/- -	11.4	905	+/-	$g_1 - g_5$	978	28	double 5 m; thin 16 m
16.1	1331	++	15.9	1263	++	$g_4 - g_3$ (or $s_3 - s_4$?)	2369 1192	30 -	
20.7 23.4 25.2	1711 1.934 2083	+/-	22.8	1811	+	$g_4 - g_3$	"	"	double 11.5 m
45	3719	+/-	46	3653	+	-	-	-	16 and 23 m diff. tone; double 23 m

the depositional rate of the Dales Gorge Member increased somewhat in this upper part of the stratigraphy, in which case DB13 to 15 could reflect a single ~16 m bundle equivalent to DB1 to 3; or whether the depositional rate has stayed relatively constant, in which case the overall thicker (≥ 7 m) BIF macrobands in this upper part are due to a weaker expression of the ~5 m cycle. A further complicating factor is the uncertainty in the period of the 16 m-scale cycle interpreted as $g_4 - g_3$, which is inherently unstable. Resolving these uncertainties ultimately requires a more detailed investigation into the expression of sub-405 kyr eccentricity-related Milankovitch cyclicity in this interval, which is beyond the scope of the present study.

Correlation option IIb: most consistent with the ~5 m and ~16 m filtering (Section reference 14)

The discrepancies of correlation IIa with respect to the postulated number of (filtered) ~5 m and ~16 m cycles in the Dales Gorge Member can be largely resolved when considering a third, modified correlation II (option IIb) that attaches more importance to the ~5 m and ~16 m filtering of the Kuruman IF and Dales Gorge Member, than to the resemblance in cycle pattern. This results in a modified correlation option IIb, in which the cycles in the 2e to 4c interval of the Kuruman IF are shifted upwards by one (filtered) ~5 m cycle with respect to the Dales Gorge Member (Figure 14). In that case, no extra ~5 m cycles need to be assumed in DS4 and 4c–d. However, this

means that the very prominent BIF intervals 3b and 4b in the Kuruman IF are now correlated to 'shale' DS6 and to the less prominent BIF macroband DB10, respectively, in the Dales Gorge Member. Also, the weak BIF 2e is now correlated to the prominent DB4.

Similarly, shifting the correlations above double BIF 5a in the Kuruman IF to DB12 in the Dales Gorge Member by two (filtered) ~5 m cycles upwards, resolves the need for an additional ~5 m cycle between 5b and 5c, and is compatible with a second ~5 m cycle in the top of DB15. However, as a consequence, 5c is now correlated to the less prominent upper part of DB13, the weak 5e to the prominent lower part of DB15, and the less prominent 6c to the very prominent DB16A. In this way, we have arrived at a correlation that is based on a maximum alignment of the filtered ~5 m and ~16 m cycles between the Kuruman IF and Dales Gorge Member (Figure 14) by abandoning our previous strategy of trying to achieve the best possible pattern fit.

The resultant mismatch in stratigraphic expression of some correlated ~5 m-scale 'BIF' and 'S' intervals seems difficult to reconcile at first. However, the pattern misfit can be potentially explained by taking the marked differences in the cyclostratigraphy of the Kuruman IF and Dales Gorge Member into account, which seem to partly underlie the problems that we encounter in establishing the correlations (Section reference 15). These differences specifically pertain to the presence of a relatively strong ~23 m cycle in the Kuruman IF compared to ~16 m cycle, and a very strong ~7 m and ~9 m cycle (and moderately strong ~11.5 m) in Dales Gorge Member. As a result there are intervals in the stratigraphy where a ~5 m-scale 'BIF' is reinforced by a maximum in the ~23 m cycle in the Kuruman IF, while in the supposedly time-equivalent interval in the Dales Gorge Member this 'BIF' is suppressed by minima in the ~7 and 9 m (and ~11.5 m) cycles, or vice versa. For instance, we observe that the weak BIF 2e in the Kuruman IF corresponds to a minimum in the ~23 m cycle (Figure 5 and Figure S7), while its counterpart DB4 in the Dales Gorge Member (according to option IIb) corresponds to maxima in the ~7 m and ~9 m cycles (Figures 7, 8 and Figure S7). Conversely, the prominent BIF 3b in the Kuruman corresponds to a maximum in the ~23 m cycle, which counteracts the minimum in the ~16 m cycle in this interval (note also the minimum in the ~16 m filter around 3b in the MS record in Figure 5), while the correlated DS6 in the Dales Gorge Member corresponds to minima in the ~7 m and ~9 m cycles, reinforcing the ~16 m-scale (shale) minimum. Similar explanations may be formulated for the pattern mismatch in the correlation of 4b to DB10 and 5c to DB13 upper, albeit less convincingly (Figure S7). Furthermore, it remains strange why the very weak 5e would correlate to the prominent lower part of DB15, and the moderately strong 6a to the weaker upper part of DB15 (Figure 14).

Further discussion points concerning option IIb are the implied absence of an extra 405 kyr-related cycle in between 5a.2 and 5b, and the implied extra 405 kyr-related cycle in between 4a and 4b. Concerning the 5a.2 to 5b interval, the absence of a relatively thin cycle '5a.3' may not be unrealistic, given also that the ~5 m filtering of the MS record does not pick

up an additional ~5 m cycle maximum. This is also true for the interval between 4a and 4b, where the existence of an additional 'hidden' 405 kyr-related cycle seems not unrealistic given its relatively large thickness. Moreover, the addition of a 405 kyr-related cycle would increase the total number of 405 kyr-related cycles between the well-dated Klein Naute Shale and the shale at 212 m depth to 18 or 19 cycles (interpreting 1a.0 as one to two ~5 m cycles). The assumption of nineteen 405 kyr-related cycles between these two dated horizons would imply a duration of 7.7 Myr, which is identical to the mean U-Pb age difference of 7.7 Myr.

Finally, we note that correlation IIb seems less consistent with the U-Pb geochronology and the number of filtered ~16 m cycles in the uncorrelated upper part of the Kuruman IF and Whaleback Shale-Joffre Members above the Dales Gorge Member. There is only one filtered ~16 m cycle recognised between 6c and the shale in between 7a and 7b, which has a calculated mean age of $2\,468.2 \pm 1.5$ Ma, in contrast to three (filtered) ~16 m cycles in between DB16A and the shale at the Whaleback Shale-Joffre Member boundary, having an older mean age of $2\,469.1 \pm 0.65$ Ma (Figure 14). However, the many in-situ brecciation textures encountered above 7a (see Figures S1 and S4 in Lantink et al., 2019), as well as the large time difference between the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the shales at 111 m and 130 m depth (~4 Myr), point to the likely occurrence of hiatuses or condensed intervals in this upper part of the Kuruman IF; this may be related to the transition towards a more shallow-marine setting as represented by the granular IF facies of the overlying Griquatown IF. As such, it is possible that the number of ~1.2 to 1.3 Myr cycles above 6c was in reality larger. Indeed, the assumption of two additional 1.25 Myr cycles when counting the number of filtered ~16 m cycles (i.e., a total of seven) from shale 212 upwards yields an age of 2 488.2 Ma for the shale in between 7a and 7b, which is identical to its mean $^{207}\text{Pb}/^{206}\text{Pb}$ age.

Discussion

Difficulties in establishing the correlations (Section reference 15)

Our various correlation strategies outlined above (Section reference 11) illustrate that establishing a cyclostratigraphic correlation between the Kuruman IF and Dales Gorge Member is far from straightforward. This is contrary to what one would expect given the likely astronomical origin of the main stratigraphic cycles involved in their characteristic bundling pattern. In fact, we anticipated that finding the correct correlation based on pattern matching would not be a problem, given the relatively straightforward correlations of the cycles in the Kuruman IF and Dales Gorge Member within their individual basins. However, this proved not to be the case, as our initial preferred correlation based on pattern resemblance (option I) turned out to be incompatible with the results of high-precision U-Pb dating and the presence of additional ~5 m-scale alternations (3c-d), forming an extra ~16 m-scale bundle, in between 3b and 4a in the Kuruman IF. Given that the U-Pb zircon ages are in almost perfect agreement with our Milankovitch hypothesis for

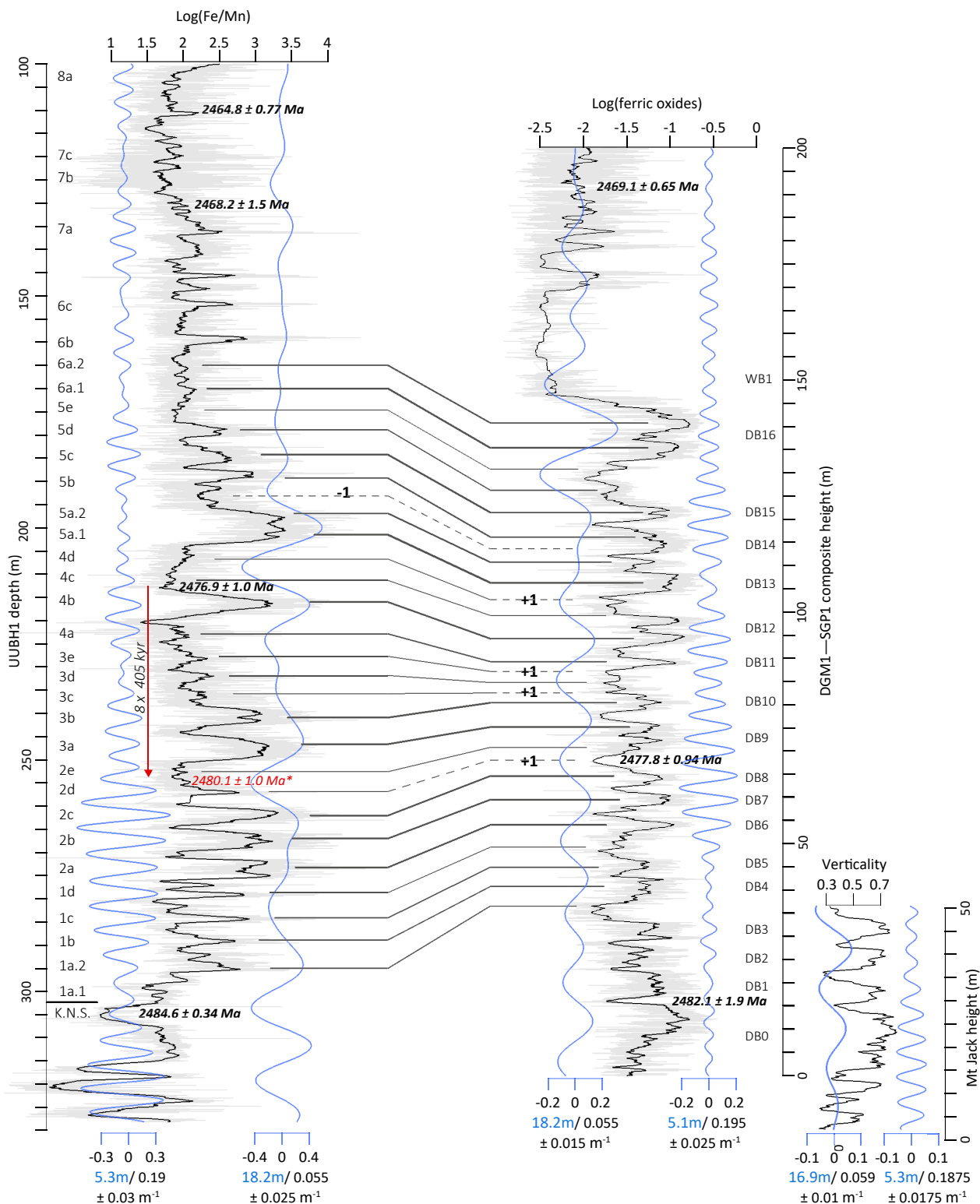


Figure 12. Correlation option 1 for the Kuruman Iron Formation (IF) and Dales Gorge Member. Initial correlation that is based on resemblance in characteristic weathering profile patterns only. Black connecting lines indicate the correlation of ~5 m-scale banded iron formation (BIF) intervals and/or interpreted ~405 kyr cycles (dotted lines where this is uncertain), with thicker lines marking the more prominent banded iron formations (BIFs) that form the basis of the correlation. Note that this correlation implies the presence of three condensed 405 kyr-related cycles in DS11. It is also in disagreement with the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of DS9 and the shale below 4c in the Kuruman IF, whose maximum age difference is less than 3 Myr, while according to the cyclostratigraphic interpretation, there are at least eight 405 kyr-related cycles, i.e. more than 3 Myr in between these two shale levels (see red arrow). *Inferred age of the shale below 2e in the Kuruman IF that is correlated to DS9 in the Dales Gorge Member, based on adding 8 x 405 kyr to the age of the shale below 4c in the Kuruman IF.

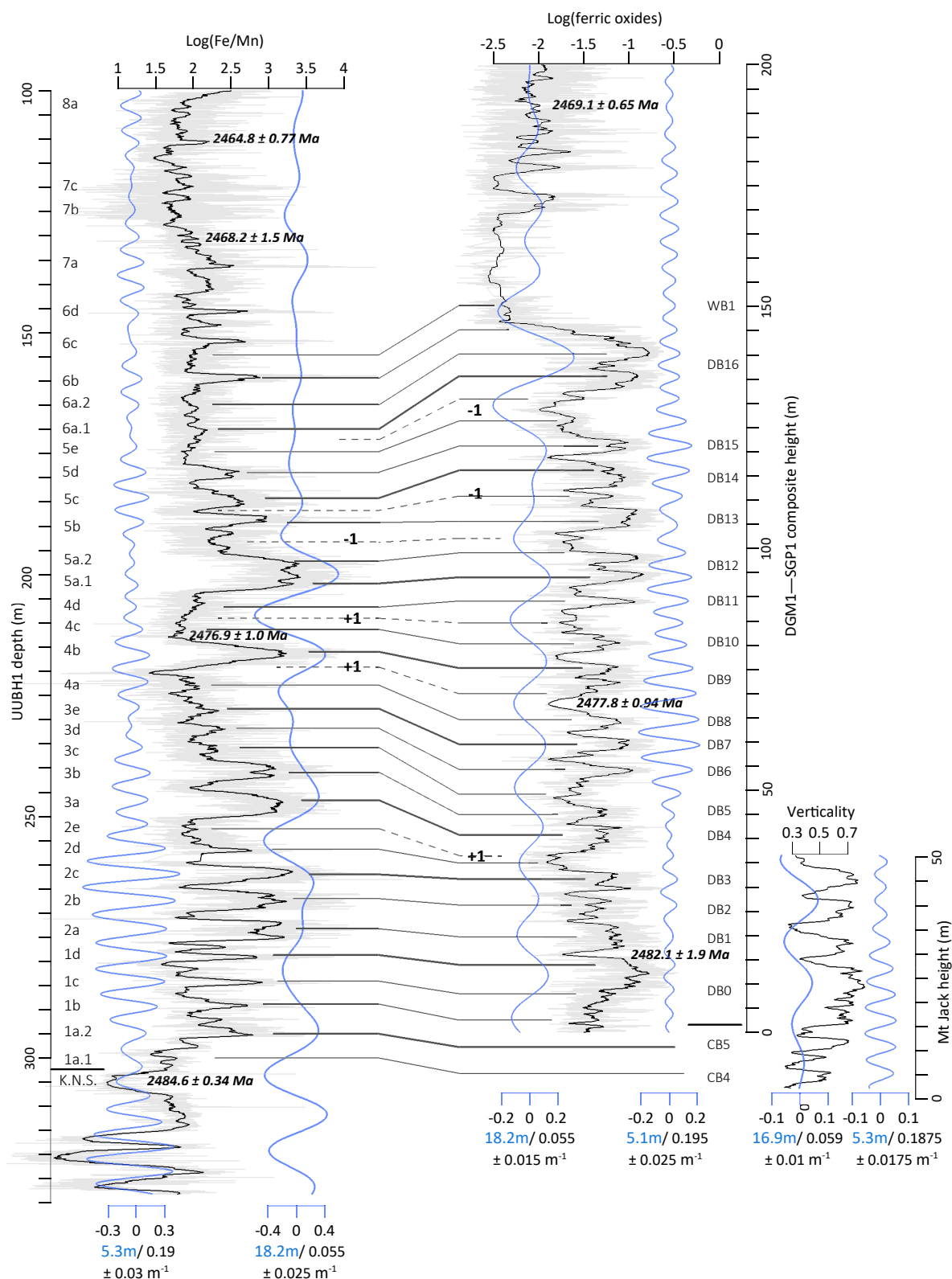


Figure 13. Correlation option 11a for the Kuruman Iron Formation (IF) and Dales Gorge Member. Second correlation based on both similarity in characteristic cycle pattern (as expressed in both outcrop and core proxy data) and consistency with the high-precision U-Pb geochronology. Black connecting lines indicate the correlations of observed ~5 m-scale banded iron formation (BIF) intervals and/or interpreted ~405 kyr cycles (dotted lines where this is uncertain). Thick lines mark the more prominent BIFs of each interpreted ~16 m-scale bundle (broad ~18 m filter outputs shown). Note that this correlation implies the presence of two condensed 405 kyr-related cycles in DS4, one in between 4a and 4b and one in between 4b and 4c. It also implies that DB13 and the top of DB15 / DS16 represent a single ~405 kyr cycle.

these cycles in the Kuruman IF and Dales Gorge Member (Section reference 9), our confidence in these ages and cyclostratigraphic results is high. Moreover, the consistent 1:3 to 1:3.5 cycle hierarchy and lateral continuity of the patterns over hundreds of kilometers in both the Kuruman IF and Dales Gorge Member, combined with their relatively deep marine environment of deposition, argues against the likelihood of major hiatuses in the stratigraphy. Based on these grounds, we consider correlation option I (as a whole) therefore unlikely.

Yet also our second, 'improved' correlation, for which we combined the requirement of pattern resemblance with the U-Pb age constraints (option IIa), resulted in inconsistencies regarding the exact number of identified ~5 m cycles in the Kuruman IF and Dales Gorge Member. We then established a modified correlation option II (option IIb) that largely eliminated these inconsistencies by focusing mainly on the number of (filtered) ~5 m and ~16 m cycles. However, this correlation seemed to make (much) less sense in terms of the expected overall similarity in the cycle pattern. Moreover, several other correlation options are conceivable that differ by one or two 405 kyr-related cycles from this option IIb, given the remaining uncertainty in the exact number of ~5 m cycles. We cannot even rule out the possibility of a combination of options IIa/b and option I for the upper part of the stratigraphy, where the geochronologic and cyclostratigraphic evidence allows for more flexibility and ambiguity.

These uncertainties raise the important question of why it is so much more difficult than expected to establish unequivocally the correlation between the Kuruman IF and Dales Gorge Member, if we accept the hypothesis that the regular large-scale (> metre-thick) alternations in their stratigraphy are Milankovitch-driven. Below we discuss two possible, closely related reasons (Section references 16 and 17).

Difference in depositional environment and associated nonlinear response to the Milankovitch forcing (Section reference 16)

Whereas the Kuruman IF and Dales Gorge Member cycle patterns as expressed in the weathering profile can be traced individually over hundreds of kilometres within their respective sedimentary basins (Section references 3 and 8), we encountered serious problems when trying to correlate the two units based on this characteristic pattern. This observation essentially tells us that the local climate and/or depositional response to the astronomical forcing was apparently very different between the two regions, to the extent that it led to significant differences in stratigraphic expression.

Although the paleogeography of the Hamersley and Griqualand West Basins is believed to have been grossly identical (Figure 2), we note that a distinguishing feature of the eccentricity-scale alternations in the Dales Gorge Member compared with their equivalents in the Kuruman IF, is the more indurated nature of the oxide facies 'BIF' intervals, and the occurrence of thicker stilpnomelane-rich carbonaceous shales within the softer 'S' intervals (Beukes, 1980; Trendall and Blockley, 1970). Based on cyclostratigraphic evidence from the Joffe Member of the Brockman IF, it was recently proposed that the main influence of the precession and eccentricity forcing

on the Hamersley Basin environment occurred via, possibly monsoon-induced, changes in continental runoff and marine productivity, causing associated variations in organic carbon export, iron (oxyhydr)oxide precipitation and settling of fine-grained siliciclastics (Lantink et al., 2023).

By extension of this model, the depositional environment of the Dales Gorge Member could thus have been under a more 'direct' Milankovitch control. This would imply that it was more strongly influenced by the variations in fluvial discharge and biological productivity compared to the Kuruman IF. In contrast, the more mixed iron oxide-carbonate composition of the cycles in the Kuruman IF as indicated by the more gradual changes in relief and gentler hill slopes (Figure 3) suggests a more remote position and/or attenuated response of the inferred eccentricity-scale lithological endmembers (i.e., 'shale' versus 'BIF'). However, we stress that the source location of the postulated runoff must have been relatively distal in any case, given the lack of evidence for a nearby delta system in the Hamersley Basin and very low detrital content of the BIF facies. Instead, a predominance of carbonate breccias and turbidites in several of the S bands in the Dales Gorge Member indicates that deposition occurred downslope of a carbonate platform (Krapež et al., 2003; Martin and Howard, 2023; Pickard et al., 2004) similar to the basinal facies of the Kuruman IF near Prieska (Figure 2), while deposition in the central part of the Griqualand West Basin took place on top of a former ("drowned") platform (Beukes and Gutzmer, 2008; Beukes, 1980, 1987).

The important question remains whether these differences in depositional environment can be related to the observed differences in stratigraphic cycle *pattern* between the Kuruman IF and Dales Gorge Member. As demonstrated by the cyclostratigraphic analysis (Section reference 3), part of the fundamental difference in cycle pattern between the Kuruman IF and Dales Gorge Member weathering profiles can be attributed to the presence or absence of a number of enigmatic, very long-period cycles, namely a relatively strong ~23 m cycle in the Kuruman IF involved in the characteristic large-scale bundling, and a strong ~7 m and ~9 m cycle in the Dales Gorge Member involved in the characteristic merging of ~5 m-scale BIF-S alternations (Section reference 14 and Table 1). The wavelengths and filtering results of the ~7 and 9 m cycles suggest that they may represent combination tones of other (eccentricity) cycles resulting from nonlinear interactions within the climate or depositional system (Section reference 10 and Table 1).

Accordingly, we can speculate that the presumed 'higher-productivity, runoff-influenced' environment of the Dales Gorge Member, although possibly under a more direct Milankovitch control, was simultaneously more susceptible to associated nonlinear responses resulting in the development of (stronger) combination tones and thus fundamental differences in cycle pattern with respect to the Kuruman IF. For example, we can imagine that threshold and stochastic processes were involved with the transport and deposition of suspended river load or shelf sediments derived from continental drainage and associated delta- or shelf-slope instability (Postma et al., 1993; Weltje and de Boer, 1993), although the predominance of carbonate breccias and slumps and silicate hardgrounds at the

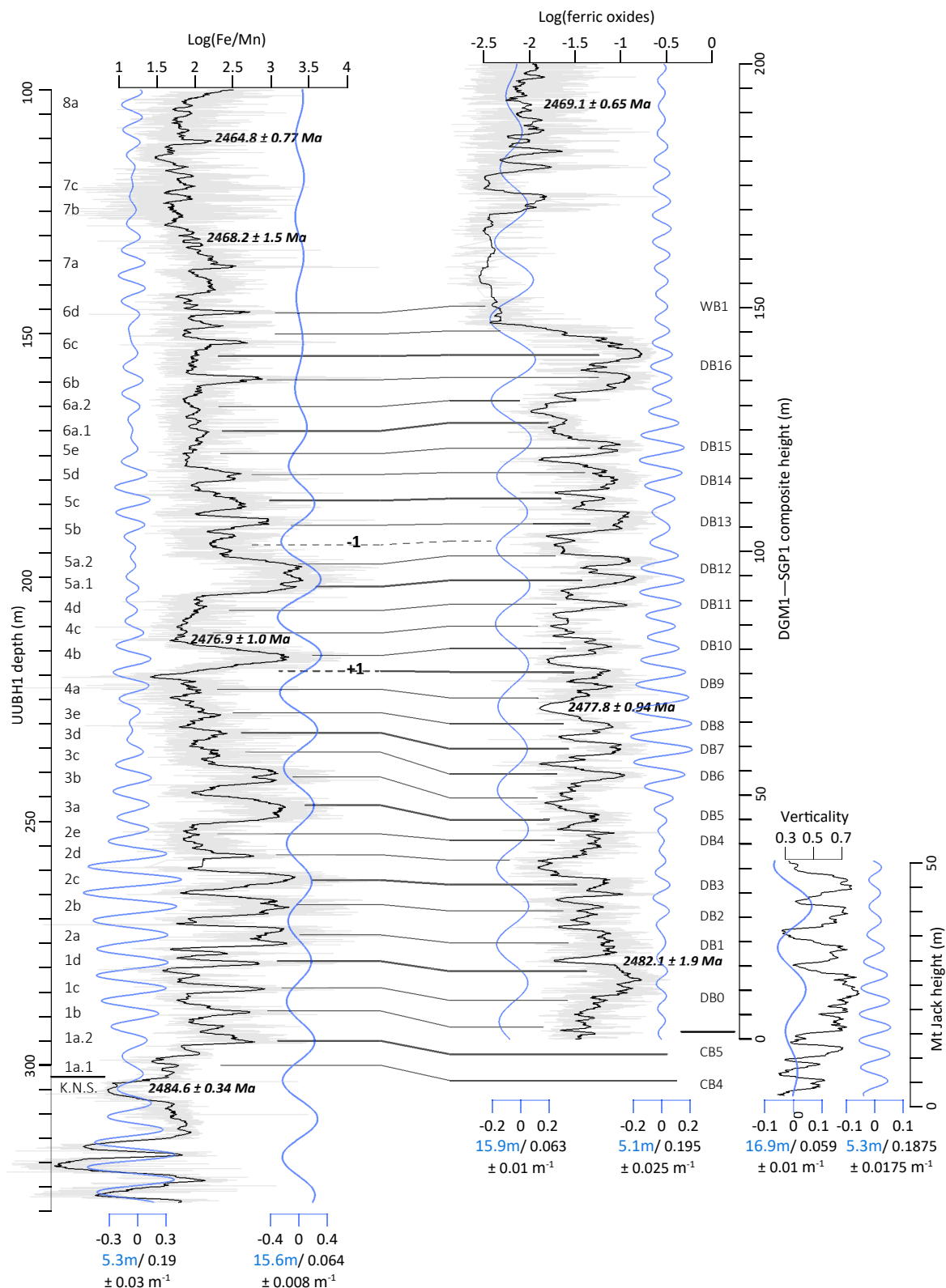


Figure 14. Correlation option IIb for the Kuruman Iron Formation (IF) and Dales Gorge Member. Modified correlation II that is most consistent with the ~5 m and ~16 m filtering. Black connecting lines indicate the correlation of observed ~5 m-scale banded iron formation (BIF) intervals and/or interpreted ~405 kyr cycles (dotted lines where this is uncertain). Thick horizontal lines indicate the correlations of ~5 m-scale BIF intervals that occur near or closest to maxima in the (filtered) ~16 m cycle in the Kuruman IF and/or Dales Gorge Member (narrow ~16 m bandpass filter outputs shown). Compared to option IIa, in this option IIb the Dales Gorge Member is shifted downwards relative to the Kuruman IF by one (filtered) ~5 m cycle in the interval 2e–4c and 5b, and by one (filtered) ~16 m cycle (two ~5 m cycles) in the interval DB13–16.

base of the S bands suggests that this threshold behaviour may have been primarily related to sea level changes (Bekker et al., 2010; Krapež et al., 2003; Rasmussen et al., 2015).

Similarly, we have reason to suspect that the behaviour of the 'ferric iron' or oxide-facies BIF component of the system was particularly nonlinear. Specifically, the abrupt and asymmetric nature, i.e., rectangular or sawtooth shapes, of the BIF-S macroband alternations in the Dales Gorge Member (Figures 3, 7 and 8) and of the Calamina cyclothem (see Figure 9 in de Oliveira Rodriguez et al., 2019), invites speculation about differences in the (response) timescales of water-column iron (Fe^{2+}) oxidation versus replenishment (through upwelling or sea level change), and early diagenetic iron oxide reduction versus retention related to organic carbon export fluxes. In addition, we note interesting similarities in spectral characteristics between the (ferric iron abundance) pattern of the Dales Gorge Member with the MS (i.e., magnetite abundance) record of the Kuruman IF, namely a relatively strong ~9 m (and ~11.5 m) cycle, and a weaker ~23 m cycle than in the Fe/Mn and weathering profile records of the Kuruman IF (Figures 5 and 6). These differences in cycle composition of the MS record seem to explain its anomalous bundling pattern of 2d–3a and 3b–3e (compared to 3ab and 3c–e in the Fe/Mn and weathering profile records; Figure 5), which is consistent with their correlation to DB4–5 and DB6–8 in the Dales Gorge Member, respectively, according to option IIb (Figures 14 and Section reference 14).

Conversely, we can speculate that the relatively strong ~23 m cycle and absence of a strong ~7 and ~9 m cycle in the Kuruman IF weathering profile and Fe/Mn pattern reflects a more sluggish, longer-term response to the Milankovitch forcing – resulting in preferential amplitude transfer to the longer-period (harmonic) cycles – that is more characteristic of the 'carbonate facies' component of the system compared to the 'oxide facies' and 'shale facies' components. Preliminary additional support for this interpretation is provided by the carbonates abundance record of the Dales Gorge Member, which exhibits similar spectral features to the Kuruman IF pattern, i.e., a relatively stronger ~23 m cycle and weaker ~7 m cycle than in the DGM1 ferric oxides record (Figures 8 and 9). However, we are well aware that making such (causal) connections between the different sedimentary components/settings and potential differences in the mode or extent of the nonlinear Milankovitch-induced response is (far too) premature, given the limited number of proxy records analysed so far. But most importantly, we do not yet know enough about the origin of the different cycles in the Kuruman and Brockman IF stratigraphy, or the functioning of the early Paleoproterozoic climate and BIF system in relation to astronomical forcing, to draw any conclusions at this time.

This brings us to our second proposed reason for why establishing a cyclostratigraphic correlation between the Kuruman IF and Dales Gorge Member proved to be so difficult, which is outlined below.

Our relative ignorance of the cycle patterns (Section reference 17)

A more general, overarching explanation for the problems with identifying the correlations has been our relative lack of

knowledge about the cycles in the stratigraphy of the Kuruman IF and Dales Gorge Member. More specifically, there is still much uncertainty about the origin and composition of the cycle patterns from both an astronomical and geological perspective, such as which Milankovitch parameters were involved in the climatic forcing, what their periods and amplitudes were, and how the cycles were eventually recorded in the stratigraphy. As a consequence, this leaves room for doubt about the (correct) cyclostratigraphic interpretation of the patterns and how to correlate them across basins.

A primary aspect of our ignorance regarding the interpretation of the cycle patterns pertains to a limited understanding of the responsible climatic and depositional processes underlying them. This lack of process understanding was already evident from our earlier discussion on proxy-dependent differences in cycle manifestation (Section reference 16). The problem is that the proxy records have been selected based on mainly empirical grounds (i.e., visual inspection of regular stratigraphic changes), rather than on an intrinsic understanding of their relationship with the astronomical forcing. In other words, we are unsure about what precisely the proxy variations reflect, i.e. what is their climatic, environmental or possibly biological significance. As such, it is not clear which of the selected proxy records, or which of their spectral traits, provides a (more) reliable representation of the astronomical signal and is thus most suitable for establishing the correlations. A more general problem with using sedimentary proxies (as opposed to, e.g., isotope ratios) is that they may depend more on local depositional conditions than on regional or global climate signals and are more susceptible to distortion resulting from dilution and diagenetic effects (Herbert, 1994; von Dobeneck and Schmieder, 1999; Weedon, 2003; Westphal et al., 2004).

Then there is the question of how to link the results of the Kuruman IF and Dales Gorge Member to the recent precession-scale observations and associated climate model for the Joffre Member (Lantink et al., 2023). For example, we note that there is an offset or asymmetry between how the long eccentricity-related alternations are defined in the lithology – namely between iron oxide-facies 'BIF' and carbonate/shale-facies 'S' intervals – and regular alternations of chert → iron oxide → mudrock (→ iron oxide) at the precession scale (Lantink et al., 2023). Different lithological extremes (opposites) thus seem to define the cyclicity at the precession level compared to (very) long eccentricity. However, we do not yet understand how these transitions in lithological expression were translated, via nonlinear amplitude response, across Milankovitch timescales, and may have implications for our cyclostratigraphic interpretation of the sedimentary patterns.

This problem closely ties to the uncertainty about the so-called 'phase relation' between the Milankovitch forcing and stratigraphic variations in lithology. In Lantink et al. (2023), the carbonate-mudrock layers of precession-scale Knox cyclothem in the Joffre Member were linked to periods of increased monsoonal intensity during southern-hemisphere precession maxima; in line with this interpretation, the 'S' intervals in the Kuruman IF and Dales Gorge Member would thus be likely candidates for representing (long) eccentricity maxima. Given

the larger precession amplitude and hence larger amplitude of the climate oscillations during intervals of maximum eccentricity, we would expect to find a stronger lithological imprint of the Milankovitch signal, i.e., one that is more characteristic, in these more shaley/carbonaceous intervals. However, during our search for the most plausible correlation based on pattern resemblance (Section references 12 and 13), we have mainly focused on the characteristic pattern exhibited by the 'BIF' intervals. This strategy has partly a historical reason, as a characteristic cycle pattern was initially identified on the basis of the prominence of the BIF intervals as visible in the weathering profile of the Kuruman IF (Lantink et al., 2019). At the same time, we note that intervals of pronounced expression of the (precession-scale) Calamina cyclothem of the Dales Gorge Member, have so far only been identified in the BIF macrobands (Table 6 and 8 in Trendall and Blockley, 1970). This observation seems at odds with the prediction of largest precession amplitude during the S intervals interpreted as (very) long eccentricity maxima, thus posing a challenge to our lithological phase relationship hypothesis.

On a more fundamental level, the fragmentary or weak expression of the precession cycle as well as of short eccentricity in the stratigraphy of the Dales Gorge Member and Kuruman IF, leaves room for doubt about our first-order Milankovitch hypothesis of precession- and eccentricity-controlled (summer) insolation changes affecting monsoonal intensity. In particular, we have so far largely ignored the potential contribution of the obliquity cycle, and hence the possible manifestation of its longer-period amplitude modulators in the stratigraphy as well (Table 1). As mentioned in (Section reference 8), our main reason for invoking a precession-eccentricity dominance on the deposition of the Kuruman IF and Dales Gorge Member, is the combined cyclostratigraphic and U-Pb evidence for a strong ~405 kyr eccentricity imprint, which is the amplitude modulator of precession and not obliquity. However, this does not mean that obliquity may not also have exerted a significant control, knowing that additional obliquity signals are typically observed in Phanerozoic sediment sequences deposited around mid- and low latitudes during icehouse or coldhouse periods (e.g.; de Vleeschouwer et al., 2017; Lourens et al., 1996; van der Laan et al., 2012). Moreover, model studies have shown that obliquity can also directly affect low-latitude climate systems such as the monsoon (Bosmans et al., 2015; Tuenter et al., 2003). A high-latitude climate, obliquity forcing scenario may be more in line with the hypothesis of Krapež et al. (2003) and Pickard et al. (2004), who ascribed the density current structures in the S intervals of the Dales Gorge Member to periods of eustatic sea level fall. However, attributing the S intervals to colder 'glacial' periods seems again more difficult to reconcile with their inferred phase relation to (very long-period) eccentricity maxima, and thus maxima in precession-driven summer insolation.

All uncertainties added together regarding the Milankovitch forcing – from the primary insolation changes to the (nonlinear) climatic and sedimentary feedbacks – thus leave us with a considerable degree of ambiguity about the astronomical or nonlinear origin, or otherwise, of individual large-scale (> metre-thick) cycles, their expression within the stratigraphy of the

Kuruman IF and Dales Gorge Member, and consequently how to correlate their combined patterns of characteristic 'BIF-S' alternations and bundling. In particular, in several parts of the stratigraphy, ambiguity about the precise expression of the ~5 m cycle proved to be an important additional handicap for establishing a cyclostratigraphic framework, which should start from this key cycle that is thought to be related to the relatively stable ~405-kyr eccentricity cycle ($g_2 - g_3$) (Figures 12 to 14). Part of this ambiguity stems from unresolved uncertainties in sedimentation rate stability for these rock successions. Specifically in the thicker S and BIF macroband intervals of the Dales Gorge Member, the number of ~5 m-scale alternations remains ambiguous due to uncertainty in how much (compacted) sedimentation rates may have varied between BIF and S lithologies. As such, a locally weak expression of the ~5 m cycle compared to for example the more enigmatic ~7 m cycle could alternatively be explained by an increase in the depositional rate. Conversely, long intervals of reduced sedimentation rate or even condensation in the more shale-dominated intervals of the Kuruman and/or Brockman IF remain a possibility that could partly explain mismatches in cyclostratigraphic pattern correlation.

However, it is important to realise that the problems encountered with the correlation of the characteristic cycle patterns in the Kuruman IF and Dales Gorge Member did not only arise from the complexities of the geological response to and stratigraphic recording of the astronomical forcing; the correlations were further complicated by fundamental uncertainties in the dynamical properties of the (long-period) Milankovitch parameters themselves, due to chaotic diffusion within the solar system, and hence uncertainty in how the expected orbital interference patterns may have looked like during the early Paleoproterozoic. In particular, the uncertainty in the (stability of the) period of the ~16 m-scale, interpreted $g_4 - g_3$ eccentricity cycle, combined with the ambiguity in the number of ~5 m-scale, interpreted $g_2 - g_3$ eccentricity cycles (i.e. sedimentation rate stability), gave room for different cyclostratigraphic interpretations and corresponding correlation options of the characteristic bundle patterns. For example, bundle DB13 to 15 is interpreted as a single ~16 m-scale cycle when correlated to 5bcd in the Kuruman according to option IIa (Figure 13), which implies a shift in the period of $g_4 - g_3$ from ~1.3 Myr to ~1.6 Myr and back around this interval (1:4 ratio with the ~5 m cycle; Figure 13). In contrast, DB13–15 is interpreted as a double ~16 m-scale cycle according to option IIb (Figure 14), which implies a relatively stable $g_4 - g_3$ period of ~1.2 to 1.3 Myr for this interval and in the rest of the stratigraphy (1:3 ratio with the ~5 m cycle; Figure 14).

Potential solutions

Our expectations for establishing a 405 kyr-cycle based framework and associated high-resolution astrochronology for the lower Paleoproterozoic in the Hamersley and Griqualand West Basins have been somewhat tempered, given the serious difficulties encountered during this study (Section reference 11). However, this does not necessarily mean that this goal cannot be reached, and significant progress may be made in the

foreseeable future regarding our understanding of the various sources of uncertainty discussed above (Section reference 15).

First of all, a logical continuation of our study on regular large-scale alternations in the stratigraphy of the Kuruman IF and Dales Gorge Member, seems to shift the focus of research to the (search for possible) intermediate- to small-scale rhythms. In particular, a systematic or more focused analysis of potential short eccentricity-, precession- and/or obliquity-related variability is expected to further our understanding of the primary Milankovitch-induced climatic and depositional processes, and their lithostratigraphic translation to the longer-period orbital-scale cyclicity. For example, the expression of obliquity may have so far just escaped our attention, as its period becomes progressively closer to that of precession (and thus more difficult to distinguish from precession) as we look further back into the history of the Earth-Moon system (Berger and Loutre, 1994; Farhat et al., 2022; Waltham, 2015). In addition, investigations of precession and short eccentricity signals in the Kuruman IF and Dales Gorge Member could help to better constrain the stratigraphic expression, and possible thickness progression, of the long eccentricity cycle required to establish the correlations. Furthermore, we imagine that differences in lithological expression of the smaller-scale cycles between the different long-period orbital-scale extremes (i.e., in the 'BIF' versus 'S' intervals) and at their transitions, may provide further clues about the lithological phase relationships and differences in (nonlinear) sedimentary proxy expression. However, these approaches critically hinge on the existence of such intervals in the stratigraphy of the Kuruman IF or Dales Gorge Member wherein the full hierarchy of Milankovitch cycles is sufficiently continuous and well recorded. A potentially easier starting point or more promising candidate might therefore be the Joffre Member of the Brockman IF, in which the imprint of precession and both its short and long eccentricity amplitude modulators appear to be well developed in certain intervals (Lantink et al., 2022; 2023), suggesting a more direct or less nonlinear response compared to the Dales Gorge Member and Kuruman IF.

In conjunction with more detailed cyclostratigraphic studies, the development of new, more climate-sensitive proxy records could provide alternative perspectives on the origin and composition of the characteristic cycle patterns in the Kuruman IF and Dales Gorge Member and how the correlation should be addressed. For example, previous chemostratigraphic studies have demonstrated the presence of primary and early diagenetic variations in the stable carbonate-carbon and iron isotope composition of these rocks (Heimann et al., 2010; Li et al., 2015; Tsikos et al., 2023), raising the question whether these proxies also track cyclicity at the Milankovitch-scale and can provide constraints on the various and/or varying processes underlying the observed changes in relative carbonate and (ferric) iron content at the long eccentricity-scale. In parallel with these efforts, the use of simple chemical (mass balance) or physical (toy) model simulations may help to further specify and test hypotheses for the observed cycle patterns in a more quantitative way. Such models may be particularly useful for exploring the effects of nonlinear behaviour arising from feedbacks within the climate system and/or stratigraphic distortion, as was done in

the pioneering work on late Pleistocene glacial-interglacial cycles (e.g. models of Imbrie and Imbrie, 1980; Le Treut and Ghil, 1983; Short et al., 1991) and on Cretaceous carbonate cycles (e.g. models of Herbert, 1994; Ripepe and Fischer, 1991).

Regarding the fundamental uncertainties in orbital dynamics during the Precambrian, we suggest that the cyclostratigraphic interpretations and correlation of the patterns may benefit from comparison with a selection of orbital models showing different scenarios for (manifestations of) chaotic behaviour as formulated in (Section reference 8) and Table 1 (i.e., $g_4 - g_3$, $s_3 - s_4$). In other words, by serving as example 'target' curves, these solutions may inform us about how the characteristic interference patterns *might* have looked like when certain Milankovitch cycles had very different frequencies and/or amplitudes compared to the more recent past. Alternatively, a more systematic (statistical) assessment of specific occurrences of chaotic behaviour, based on large ensembles of astronomical solutions, may be more appropriate (e.g. Hoang et al., 2021). Specific questions that emerge from this study are: how likely is it that the period of $g_4 - g_3$ had a stable period of ~1.2 to 1.3 Myr for the entire interval of correlation i.e., for more than 10 Myrs? Which resonance state or ratio with $s_3 - s_4$ does a ~1.2 to 1.3 Myr or ~1.8 to 1.9 Myr period of the $g_4 - g_3$ cycle correspond to, and what would the corresponding interference patterns look like in case of a mixed precession and obliquity influence?

A final proposed though rather challenging strategy, is to generate additional, and more precise, U-Pb TIMS ages. We note that some of the existing zircon ages have very small uncertainties, in particular, the 2σ uncertainty of the Klein Naute Shale, which is only ± 0.34 Myrs, while others have much larger uncertainties (>1.5 Myrs). If possible, reducing the uncertainty in the $^{207}\text{Pb}/^{206}\text{Pb}$ ages from the analysis of additional zircons would help to more precisely constrain specific correlation options, or a small subset of correlations. Thus far, the small size of the grains and large amount of chemical abrasion needed to remove the radiation-damaged parts unfortunately resulted in only tiny zircon fragments with low Pb concentrations for analysis. Importantly, this strategy could also provide more insight into the origin of the sampled zircons. Current potential hypotheses are that:

- the zircons originate from discrete tuff horizons that are for some reason only preserved within the shale rich horizons (Beukes, 1980; 1983; Beukes and Gutzmer, 2008), or that
- they represent sedimentary re-working of recently deposited ashes into the BIF source region (Krapež et al., 2003; Pickard, 2003; Trendall et al., 2004; Zi et al., 2021).

In the latter case, the ages should be treated as maximum depositional ages that are presumed to be close to the sediment depositional age. If the grains were dominantly detrital, we would expect re-working of zircon from the older tuffs into the younger sediments and also older detrital grains. Our analysis of zircon from the lower part of DS9 and also DS1 contain some Archean zircon suggesting that there is a detrital component in these samples (Dataset S2).

Implications of the early Paleoproterozoic astrochronological framework

Despite the ongoing uncertainties in the correlations, we tentatively argue that our combined cyclostratigraphic and U-Pb dating efforts point more strongly into the direction of correlation options IIa or IIb, than towards correlation I. Both sub-options of correlation II, or other (still unexplored) minor deviations of a single ~405 kyr cycle, would all be consistent with a 'near'-synchronous onset of the Kuruman IF and Dales Gorge Member, confirming a long-standing presumption (e.g. Beukes and Gutzmer, 2008; Button, 1976; Cheney, 1996; Martin et al., 1998; Nelson et al., 1999; Pickard, 2003; Trendall, 1968; Trendall et al., 2004).

At a more detailed level, correlations IIa/b suggest a slightly earlier onset of BIF deposition in the Griqualand West Basin by at least one ~405 kyr cycle compared to the Hamersley Basin, given the fact that BIF 1a of the Kuruman IF is correlated to CB5 of the top of the Colonial Chert Member of the Hamersley Group (Figures 13 and 14); note that cycle 1a.0 of the Kuruman IF forms part of the Kliphuis Member chert (Figure A2). While this one ~5 m cycle offset may not be correct, lithological observations from the southern Prieska area in the Griqualand West Basin reveal that the onset of BIF formation locally started at cycle 1b, and cycle 1a is still composed of ferruginous carbonate (see Figure S4 in Lantink et al., 2019). This indicates that BIF deposition in the Prieska area also started one ~405 kyr cycle later than in the central Ghaap plateau region, but at the same time as the Dales Gorge Member. In addition, prolonged BIF deposition at Prieska, where the Kuruman IF is much thicker, has been demonstrated by the cyclostratigraphic correlations of Lantink et al. (2019) (Figure 2). Likewise, BIF deposition continued for much longer in the Hamersley Basin compared to in the central Ghaap plateau area of the Griqualand West Basin, as represented by the ~350 m thick Joffe Member, the base of which loosely corresponds to 7a according to correlations IIa/b (Figures 13 and 14). Thus correlations IIa/b seem to support the hypothesis that the Kuruman IF facies in the southern part of the Griqualand West Basin were deposited more proximal to the Dales Gorge Member (Cheney, 1996) and/or in a similarly deeper-marine (basinal) setting (Beukes and Gutzmer, 2008).

Intriguingly, correlations IIa/b and the constraints from the U-Pb dating are further consistent with suggestions of a genetic link between the impact spherule bed in the DS4 macroband of the Dales Gorge Member (Glikson and Allen, 2004; Hassler and Simonson, 2001) and a 1-cm-thick spherule layer identified at about 50 m above the base of the Kuruman IF (Glass and Simonson, 2012; Simonson et al., 2009). A stratigraphic distance of ~50 m above the base of the Kuruman IF roughly corresponds to cycles 2d–e, which is indeed correlated to DS4 or DB4 according to options IIa/b, supporting the hypothesis that the DS4 and Kuruman spherule layers are distal ejecta deposits of the same meteorite impact event. This event would have caused significant disruption of sedimentation proximal to the impact site, implying that deposition of especially the Dales Gorge Member may have been, or likely was, also affected to some

extent (Hassler et al., 2019). However, given the lateral continuity of the metre-scale cycle patterns in the Dales Gorge Member and the continuation of a 1:3 to 3.5 bundle hierarchy at the interval of concern, we consider it unlikely that the impact obliterated an entire 405 kyr-related cycle, or multiple cycles, and thus forming an issue for the correlations. We further note that a second spherule-bearing interval in the Dales Gorge Member has been more recently found in DS9 (Martin and Howard, 2023), which, as an alternative equivalent to the Kuruman spherule layer, would be consistent with correlation option I rather than option IIa/b. However, the interpretation of the spherules in DS9 as impact event still needs to be confirmed.

Finally, our preliminary astrochronology for the Kuruman IF and Dales Gorge Member may cast new perspectives on the timing and timescales of incipient oxygenation 'transients' recorded in the underlying strata of the Griqualand West and Hamersley Basins. Specifically, geochemical evidence was found for an atmospheric 'whiff of oxygen' in the S1 unit of the Mount McRae Shale in Western Australia (Anbar et al., 2007) some ~30 m below the Colonial Chert Member. Based on a multi-sample Re/Os age of $2\,501 \pm 8$ Ma (Anbar et al., 2007), this event is simultaneously thought to coincide with the Archean-Proterozoic boundary, currently established at 2.5 Ga. According to correlations IIa/b, the base of the Colonial Chert Member is equivalent to the well-dated Klein Naute Shale as developed in the central Griqualand West Basin, i.e. having an age of $2\,484.6 \pm 0.34$ Ma (Figures 13 and 14). A downward extrapolation from this level using the sedimentation rates established for the Kuruman and Brockman IF – an assumption that is not unreasonable given the continuation of a ~16 m cycle in the Gamohaan Formation (Figures 5, 13 and 14) – would thus suggest that the whiff of oxygen of Anbar et al. (2007) is in fact significantly younger (i.e., ca. 2 486 to 2 489 Ma). This conclusion is of course premature, and further cyclostratigraphic testing combined with high-precision U-Pb dating is needed to also explore possible synchronicity with a putative oceanic 'oxygen oasis' identified in the Naute Shale (Kendall et al., 2010), the South African counterpart of the Mount McRae Shale in the basinal facies of the Griqualand West Basin (Beukes and Gutzmer, 2008). Such future downward extension of the astrochronological framework can thus help us to distinguish between more locally manifested redox phenomena, or larger-scale oxygenation transients in the lead-up to the GOE, including the potential role of multi-million year Milankovitch forcing (Boullila, 2012; Lantink et al., 2023). The latter scenario might also render these intervals as suitable candidates for a chronostratigraphic redefinition of the Archean-Proterozoic boundary (Martin and Howard, 2023).

Conclusions

The primary aim of this study was to establish a 405 kyr cycle-based framework for the early Paleoproterozoic Kuruman IF of South Africa and Dales Gorge Member of the Brockman IF in Western Australia. Achieving this goal seemed realistic at first given the evidence from cyclostratigraphic analysis and high-precision TIMS U-Pb zircon dating for a ~405 kyr eccentricity

origin of a clear ~5 cycle, and a prominent ~1.3 Myr cycle possibly related to $g_4 - g_3$, identified in both stratigraphic units. However, we subsequently encountered significant problems when trying to determine a correlation based on matching their characteristic cycle patterns, and the final correlation remains unsolved to date. In part, the difficulty in correlating appears to stem from a difference in expression and amplitude of certain cycles (i.e., a ~7 m/560 kyr, ~9 m/700 kyr and ~23 m/1.8 to 1.9 Myr cycle) whose origins remain enigmatic, but which may be related to a difference in depositional environment. More generally, these issues illustrate our current lack of understanding of the (nonlinear and likely complex) response of the early Proterozoic climate and BIF system to the astronomical forcing, as well as the fundamental uncertainty about the astronomical forcing itself, i.e. solar system dynamical behaviour at that time.

Nevertheless, our correlation efforts have provided a much more precise estimate of the absolute and relative timing of Kuruman IF and Dales Gorge Member BIF deposition than was previously available. This illustrates the potential strength of the integrated (cyclo)stratigraphic approach in enabling more precise reconstructions of the sedimentary and paleogeographic histories of the Griqualand West and Hamersley Basins. Possible strategies to further constrain the correlations and gain more insight into the origin of the cycle patterns include a systematic analysis of sub-405 kyr-scale variability (i.e. precession-, short eccentricity-, and possible obliquity-related patterns), further improving of the U-Pb geochronology and/or exploring other chronostratigraphic markers to corroborate long-distance correlations, searching and testing for other (more) climate-sensitive proxies, comparison with astronomical example solutions, and the use of climatic and geochemical model simulations.

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Appendix

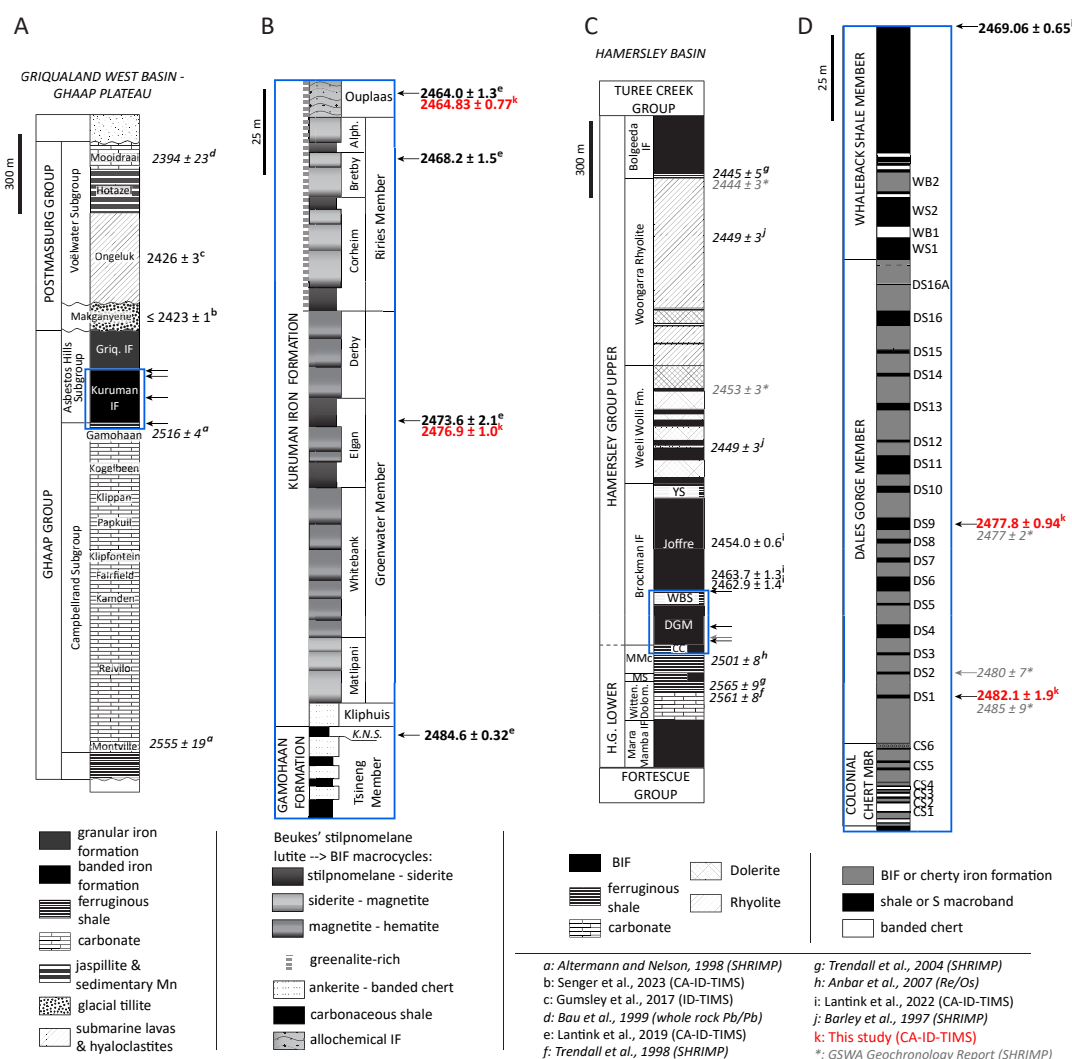


Figure 1A. See over page for caption.

Figure A1. Stratigraphy and geochronology of the Transvaal Supergroup in the Griqualand West Basin and Mount Bruce Supergroup in the Hamersley Basin. **(A)** Schematic column for the Ghaap carbonate platform area adapted from Figure 2 in Beukes (1987) and Figure 2 in Pickard (2003). Arrows indicate the positions of the ages of lutites 1 to 4 shown in (B). **(B)** Zoom-in on the Kuruman Iron Formation (IF) and upper Gamobaan Formation showing the classical stilpnomelane lutite → (BIF) macrocycles and members as identified by Beukes in the old drill core WB98 from Whitebank. Adapted from Figure 5 in Beukes (1980) and Figure 4 in Beukes (1983). **(C)** Schematic column for the Mount Bruce Supergroup after Trendall and Blockley (1970). MS = Mount Sylvia Formation, MMc=Mount McRae Shale. Arrows indicate the positions of the ages shown in (D). **(D)** Zoom-in on the stratigraphy of Colonial Chert, Dales Gorge and Whaleback Shale Members representative for the Wittenoom area based on Trendall and Blockley (1970) p. 37, 73 and 87. Shale macrobands are labelled according to the later established formal nomenclature as presented in Harmsworth et al. (1990). All ages are reported with 2σ uncertainty. References for the Geological Survey of Western Australia (GSWA) reports are Wingate et al., 2018 (Weeli Wolli), Wingate et al., 2020 (Woongarra Rhyolite), Wingate et al., 2021a (DS1), Wingate et al., 2021b (DS9) and Wingate et al., 2021c (DS2).

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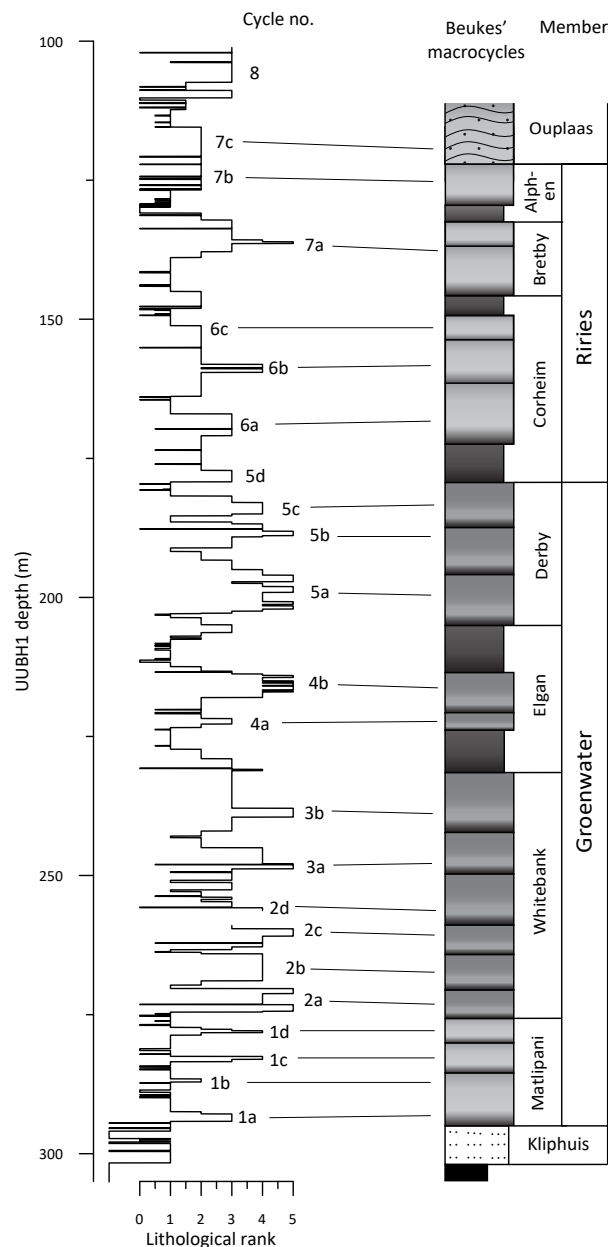


Figure A2. Lithological rank series of the UUBH1 core revealing the characteristic cycles of Lantink et al. (2019) (left) and a comparison to Beukes' macrocycles and the traditional members (right) observed in the old drill core WB98 from Whitebank (modified after Beukes, 1980; 1983). Colours and symbols are the same as in Figure A1.