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Precambrian Cyclic Rhythmites: Solar-Climatic or Tidal Signatures? [and Discussion]

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Precambrian cyclic rhythmites: solar-climatic or tidal signatures?

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[Plates 1 and 2]

For more than 60 years geologists have sought evidence of solar-climatic cyclicity in rhythmically laminated sedimentary rocks, but claims in general have not been persuasive. Three Precambrian rhythmite sequences in Australia that comprise varve-like laminae recently have received attention, however, as their conspicuous cycles of *ca.* 10–14 and/or 20–25 laminae have been ascribed a sunspot-cycle origin. They are the 2500 Ma old Weeli Wolli Formation, the 1750 Ma old Wollogorang Formation, and the 650 Ma old Elatina Formation. New observations for the Weeli Wolli Formation, a siliceous banded iron-formation, suggest a cycle period exceeding the 23 microband couplets proposed by Trendall, casting doubt on the solar interpretation. The Weeli Wolli cyclicity may record Earth-tidal rhythms that modulated the discharge and composition of silica- and iron-bearing fumarolic waters. The structure of the cycles of silty dolomite and mudstone in the Wollogorang Formation does not support a sunspot-cycle origin, and a tidal control on sedimentation should be considered.

The Elatina sequence of cyclic sandstone and siltstone laminae displays several empirical similarities to the sunspot series. The discovery of thicker, more complex lamina-cycles in the correlative Reynella Siltstone has, however, caused reappraisal of the solar interpretation of the Elatina rhythmites. The Reynella cycles consistently contain 14 or 15 laminae, with many laminae comprising pairs of 'semi-laminae'; the overall structure of the cycles is similar to the mixed (semidiurnal and diurnal) fortnightly tidal growth patterns of modern bivalves. Also, recent observations that fine material can be transported in suspension to deeper waters offshore by ebb-tidal currents provides a tidal mechanism that can explain the deposition of thin, laterally extensive, graded laminae whose thickness would be a measure of tidal range and current speed. By this tidal model, the Elatina laminae are regarded as diurnal increments, and the lamina-cycles as commonly abbreviated fortnightly groupings. The Elatina series so interpreted may encode unique information on lunar orbital periods and the Earth's palaeorotation: the data indicate *ca.* 30.5 days per lunar month, 13.1 lunar months and *ca.* 400 days per year, and lunar apsides and lunar nodal cycles of 9.7 and *ca.* 19.5 years respectively some 650 Ma ago.

Evidence for significant modulation of terrestrial climate by the solar activity cycle in the geological past may prove as elusive as have convincing indications of solar signals in modern patterns of weather and climate.

Introduction

A review of evidence for solar variability in the geological past is relevant to the theme of this Discussion Meeting. Confirmation that solar cyclicity similar to that of today has influenced sedimentary processes millions of years ago would (i) demonstrate the durability of the solar activity cycle, (ii) imply that such cyclicity is capable of influencing the Earth's climate, and

(iii) encourage modelling of future solar activity and its possible influence on future terrestrial climate.

Since the early works of Brooks (1926), Udden (1928), De Geer (1929) and Bradley (1930), numerous geologists have sought solar signals, particularly the *ca.* 11-year sunspot period, in regularly laminated sedimentary rocks ('rhythmites') whose laminae were presumed to be annual ('varves') (see Anderson 1961; Richter-Bernburg 1964; Duff *et al.* 1967; Schove 1983). Such studies have used the principle that for a particular deposit varve thickness is a function of climate and that any influence of solar variability on climate should therefore be recorded by changes in varve thickness. Rhythmites of Phanerozoic age (less than *ca.* 570 Ma) have been most studied, and although solar signals commonly have been claimed the patterns in the rocks are not conspicuous and rigorous statistical analysis (see, for example, Anderson & Koopmans 1963) has failed to reveal significant periodicites.

In recent years, however, three cyclic rhythmites of Precambrian age (greater than *ca.* 570 Ma) have received attention in solar physics (see, for example, Bracewell 1986; Sonett & Trebisky 1986) because their cyclicity is conspicuous and in some ways shows empirical similarity to sunspot cyclicity. These rhythmites occur in the following.

1. The Weeli Wolli Formation, a 2500 Ma old banded iron-formation in the Hamersley Basin, Western Australia (Trendall 1973).

2. The Wollogorang Formation, a 1750 Ma old dolomite–mudstone sequence in the McArthur Basin, northern Australia (Jackson 1985).

3. The Elatina Formation, a 650 Ma old sandstone–siltstone sequence deposited in the Adelaide Geosyncline, South Australia, during the Marinoan Glaciation (Williams 1981, 1985; Williams & Sonett 1985).

The origin of these Precambrian cyclic rhythmites is critically reviewed here in the light of new observations. It is concluded that the rhythmites are all better interpreted as recording tidal rather than solar rhythms. Consequently, strong doubts remain as to whether solar cyclicity has significantly affected terrestrial climate in the geological past.

Weeli Wolli Formation

The early Proterozoic banded iron-formations (BIFS) typically display a thin microbanding of chert and iron oxide couplets that usually are regarded as varves (see, for example, Trendall & Blockley 1970; Garrels 1987), although Walter (1972) suggested that some microbanding may be diurnal and possibly related to the modulation of hot-spring activity by earth tides. The microbanding of the Weeli Wolli Formation differs from that of other BIFS in the Hamersley Basin (Trendall & Blockley 1970) in commonly being much thinner and typically displaying a conspicuous cyclicity (figure 1, plate 1). The cyclicity arises from regular variations in both the absolute and relative thickness of chert and iron oxide portions of the microband couplets, giving the Weeli Wolli BIF a characteristic 'striped' appearance (Trendall 1973). The microbands usually are very thin (0.05 mm thick, or less) and only the cyclic stripes are readily discernible (figure 1*b*, *c*). Local pods of chert have better resisted diagenetic compaction, however, allowing the microbands to be more easily seen and counted (figure 1*a*). Trendall & Blockley (1970) noted that the Weeli Wolli cycles contain about 30–38 microband couplets, an estimate later changed to 25 microband couplets (Trendall 1972). Trendall (1973) subsequently determined an average of 23.3 (range 21–28) microband couplets for 23 such

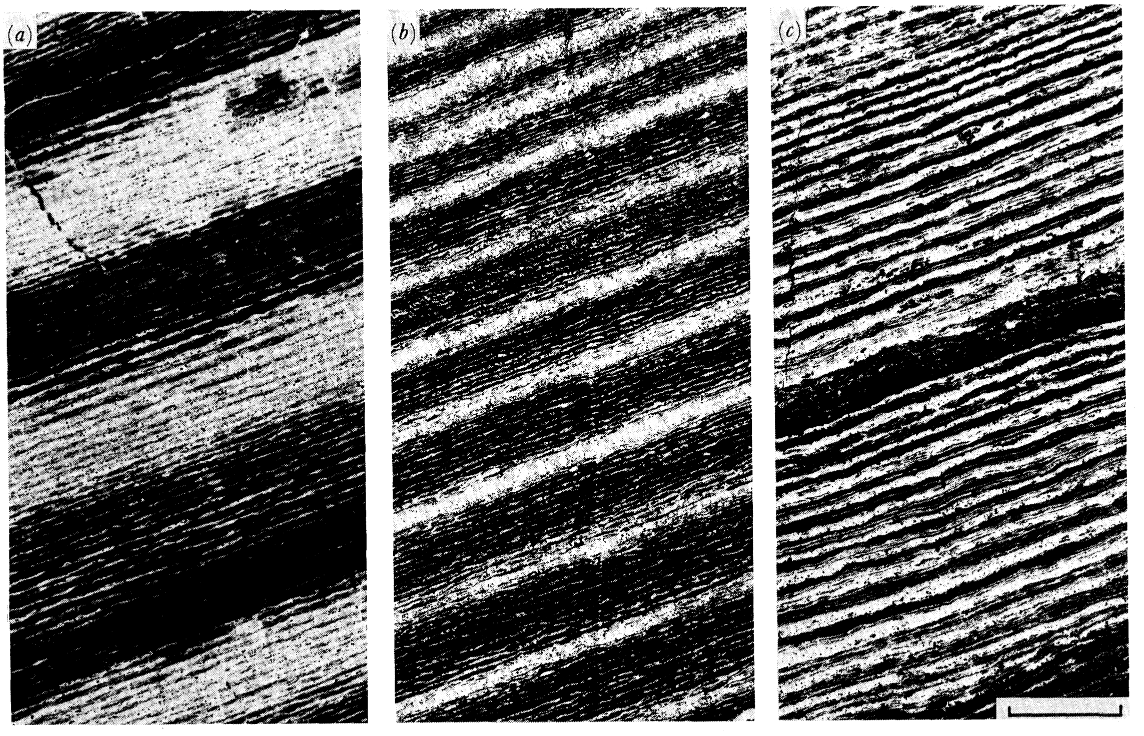

FIGURE 1. Early Proterozoic cyclic banded iron-formation from the Weeli Wolli Formation, Western Australia. Scale bar 5 mm. (*a*) Chert pod containing discernible microband couplets of chert (white) and iron oxide (black); up to about 30 microband couplets occur between the centres of the cyclic 'stripes'. (*b*) Moderately compacted iron-formation with thinner microbands and cycles. (*c*) Strongly compacted iron-formation in which only the cyclic stripes are readily discernible.

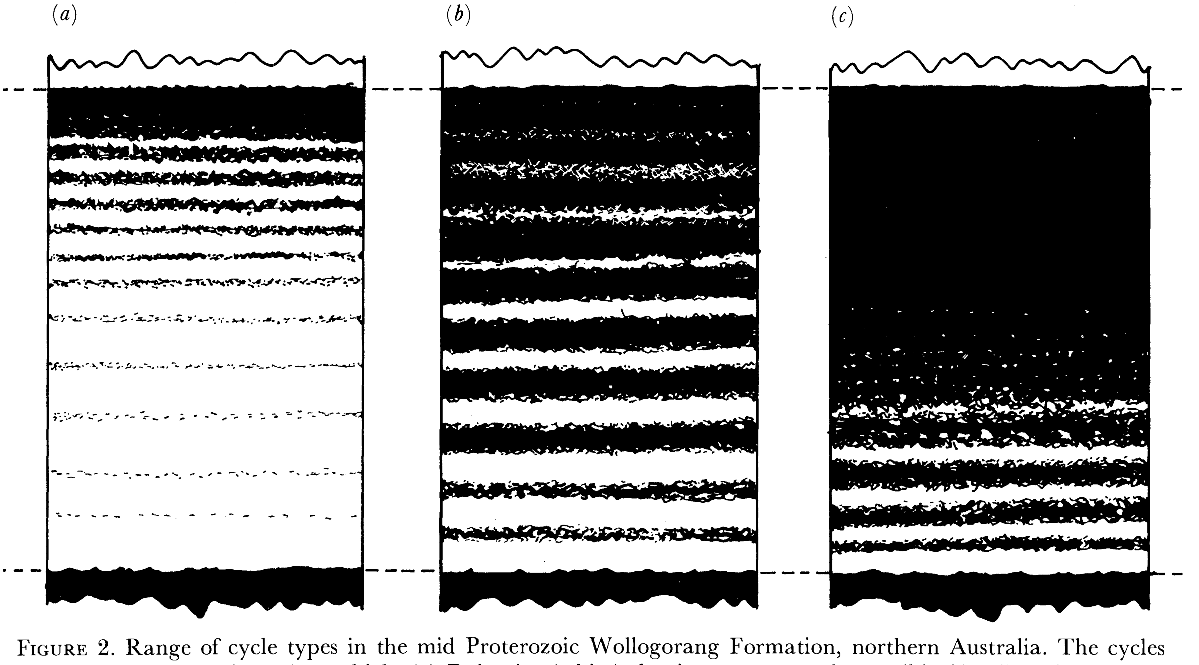

FIGURE 2. Range of cycle types in the mid Proterozoic Wollogorang Formation, northern Australia. The cycles commonly are about 1 cm thick. (*a*) Dolomite (white) dominant over mudstone (black). (*b*) Dolomite and mudstone in about equal proportion. (*c*) Mudstone dominant. (After Jackson 1985.)

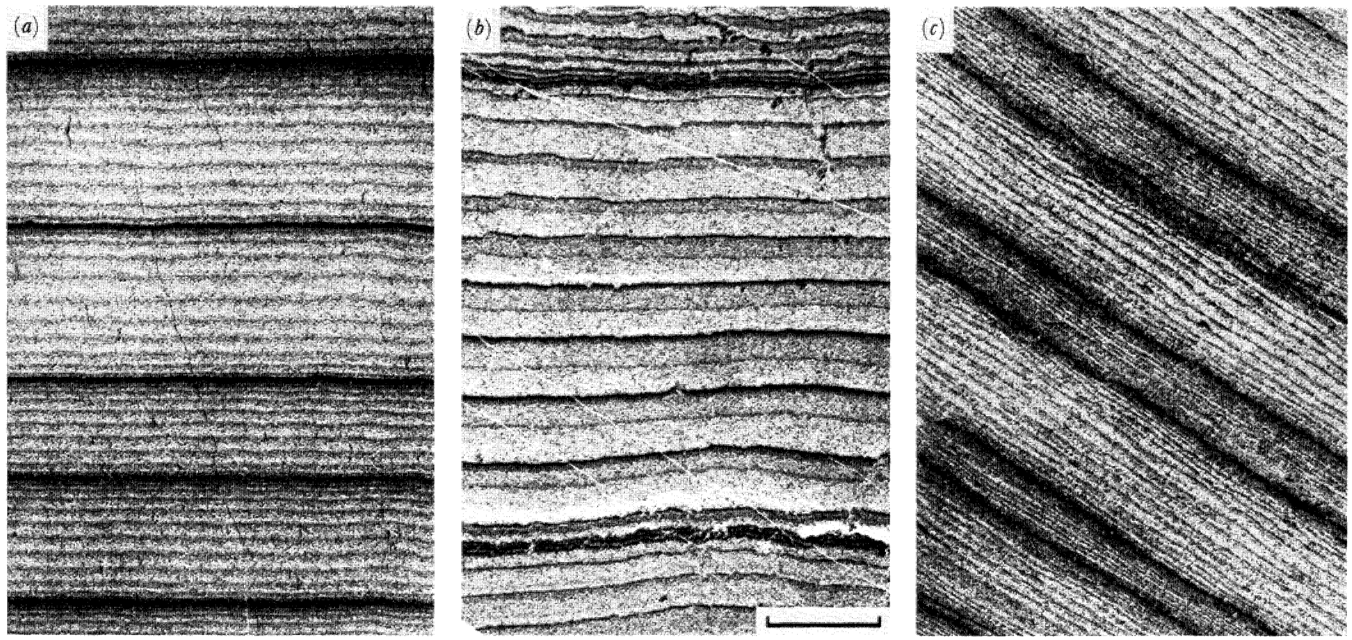

FIGURE 3. Late Proterozoic cyclic rhythmites, South Australia. Clayey material appears darker than sandy to silty layers. Scale bar 1 cm. (*a*) Elatina Formation. Four complete lamina-cycles of about 11–14 graded laminae are bounded by dark, clayey bands. (*b*) Reynella Siltstone, showing one complete, thick lamina-cycle containing 14 laminae of fine sandstone with clayey tops; most laminae show 'semi-laminae'. (*c*) Siltstone associated with the Chambers Bluff Tillite, showing seven complete, alternately thick and thin lamina-cycles each totalling from 15 to 25 graded laminae; laminae are eroded in places at tops of cycles.

cycles; he interpreted the couplets as varves and suggested the cyclicity may reflect the influence on the basinal environment of the double sunspot cycle, which today has a mean period near 22 years.

Counts I have carried out on thin-sections of newly collected chert pods indicate as many as 28–30 microband couplets per cycle. Cycles containing fewer microband couplets usually show evidence that some adjacent microbands have amalgamated; counts for such cycles probably underestimate the true cycle period. These observations might suggest a cycle period near 30 microband couplets, casting doubt on the solar interpretation.

A submarine fumarolic or volcanic-exhalative origin has been proposed for numerous BIFS (see, for example, Simonson 1985; Fralick 1987); such an origin for the Weeli Wolli BIF is supported by the local presence of beds of volcanic ash (Trendall & Blockley 1970) and aspects of the BIF geochemistry. Today, some geyser activity (Rinehart 1972*a*, *b*) and the composition of gas bubbles in mineral-spring water (Sugisaki 1981) are modulated by earth tides. The question is raised, therefore, whether the Weeli Wolli cyclicity records earth-tidal rhythms that modulated the discharge and composition of silica- and iron-bearing fumarolic waters. As the primary components of the solid earth tide are semidiurnal and fortnightly, the microband couplets could perhaps be semidiurnal increments arranged in fortnightly groups or fortnightly tidal increments grouped in annual cycles through seasonal influences on sedimentation, among other possibilities. The second suggestion may be preferred because geothermal areas usually are so sluggish mechanically that the semidiurnal and diurnal components are filtered out, whereas the activity of geysers may be influenced by the fortnightly tidal component (Rinehart 1974). Furthermore, a yearly time value for the Weeli Wolli cyclic stripes gives sedimentation rates for the compacted facies (figure 1*c*) that are comparable to presumed rates for other BIFS in the Hamersley Basin whose microbanding is regarded as annual (see Trendall & Blockley 1970).

Wollogorang Formation

The middle Proterozoic Wollogorang Formation (Jackson 1985) contains a dolomitic black shale facies that displays laminae of carbonaceous mudstone and silty dolomite arranged in conspicuous cycles. The cycles (figure 2, plate 1) are 1–20 mm thick, and typically comprise a lower portion of mainly dolomite and subordinate mudstone laminae and an upper portion of mainly mudstone with thin dolomite laminae. Jackson (1985) interpreted the dolomite–mudstone lamina couplets as distal lacustrine varves deposited below effective wave base. He suggested that the cycles may reflect an influence of sunspot cyclicity on climate.

The solar interpretation of the Wollogorang cycles must be viewed with reservation, however, for the following reasons.

1. The markedly asymmetric structure of the cycles (figure 2) bears little resemblance to that of the typical sunspot cycle which, although positively skewed, shows a gradual rise to a maximum over some 4–5 years.

2. Jackson (1985) determined a mean period of 7 (± 2 standard deviation) lamina couplets per cycle for a sequence of 100 cycles, and a mean of 11 (± 2 s.d.) couplets for 12 thicker cycles within that sequence. The greater number of laminae in the thicker cycles suggests that many of the cycles are abbreviated and that the counts underestimate the true cycle period.

Asymmetrical sedimentary cycles might form in a tidal setting by algae and mud coating coarser sediment during neaps and raising the threshold current speed for movement of sediment in the neap to spring part of the tidal cycle (see de Boer 1981; Allen 1982). Thus the lamina couplets of the Wollogorang Formation could be diurnal increments arranged in skewed fortnightly groups whose lower, neap-to-spring (mudstone to silty dolomite) portion commonly is missing or abbreviated. The carbonaceous character of the mudstone is consistent with this interpretation. The periods of 14.8 and 28.8 couplets determined by spectral analysis of a short sequence (Sonett & Trebisky 1986) also are consistent with the fortnightly and monthly grouping of diurnal increments.

Further study of the Wollogorang cycles is required, although available evidence favours a tidal origin and by implication a marine setting. Confirmation of periodicities near 15 and 30 lamina couplets would lend support to the tidal interpretation.

Elatina Formation

Several late Proterozoic formations in the Adelaide Geosyncline in South Australia locally display conspicuous cyclic rhythmites of siltstone and fine sandstone. Such rhythmites are best exposed in a 10 m thick member of the Elatina Formation (*ca.* 650 Ma old) at Pichi Richi Pass in the Flinders Ranges. Similar rhythmites have been recognized more recently in the correlative Reynella Siltstone at Hallett Cove near Adelaide, and in siltstones overlying the Chambers Bluff Tillite (between 800 and 650 Ma old) in the Officer Basin in northern South Australia.

Periodicities in the Elatina series

The cyclicity and method of study of the Elatina series are described in detail elsewhere (see Williams 1985, 1988, 1989*a*, *b*). Essentially, graded laminae 0.2–3.0 mm thick are grouped in conspicuous 'lamina-cycles' (figure 3*a*, plate 2) containing on average about 12 laminae (range 8–16). Lamina-cycles are bounded by darker, clayey bands where thinner laminae crowd together. The plot of lamina thickness (figure 4*a*) shows a characteristic alternation of high- and low-amplitude lamina-cycles. On average, high-amplitude cycles tend to have sharper crests, and contain fewer laminae, than low-amplitude cycles. Also, cycles have a tendency to positive skewness.

Longer periods are evident as variations in lamina-cycle thickness. The most conspicuous long-term rhythm, the 'Elatina Cycle' (figures 5*a*, *b* and 6*a*, *b*) occurs 59 times in a measured sequence of 1580 lamina-cycle thicknesses obtained from drill core. The Elatina Cycle is marked by first-order peaks in thickness that occur on average every 26.2 (±0.2 s.d. derived from fast Fourier transform (FFT) spectrum; see Williams 1989*a*, *b*) lamina-cycles; most Elatina Cycles also display a second-order peak.

A sawtooth pattern reflecting an alternation of thick and thin lamina-cycles is superimposed on the Elatina Cycle (figures 5*a* and 6*a*). This pattern displays a succession of envelopes with 180° phase reversals (a reversal of the thick–thin alternation) at or near the necks between the envelopes (figures 5*c* and 6*c*). The interval between phase reversals averages 14.6 (±0.1 s.d. from FFT spectrum; see Williams 1989*b*) lamina-cycles, and between 360° changes of phase averages 29.2 (±0.2 s.d.) lamina-cycles. These and other long-term periods, including several harmonics of the Elatina Cycle, are confirmed by spectral analysis (Williams 1985, 1989*a*, *b*). As well, the amplitude of the second-order peak of the Elatina Cycle varies with a period of 19.5 (±0.5) Elatina Cycles (Williams 1989*a*, *b*).

The Elatina rhythmites have no known modern counterpart. Their interpretation therefore

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

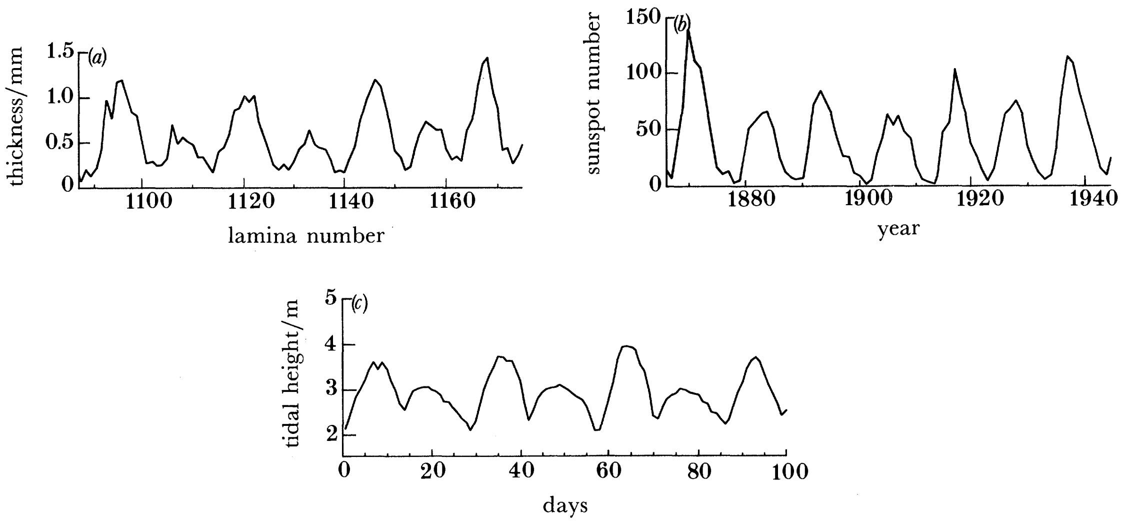

FIGURE 4. (*a*) Thickness of laminae from the Elatina series, showing lamina-cycles of alternate high and low amplitude. Lamina number increases up-sequence. (*b*) Mean annual sunspot numbers for sunspot cycles 11–17. (*c*) Maximum daily tidal heights from 1 January to 10 April 1966, for Townsville, Queensland, showing fortnightly tidal cycles of alternate high and low amplitude.

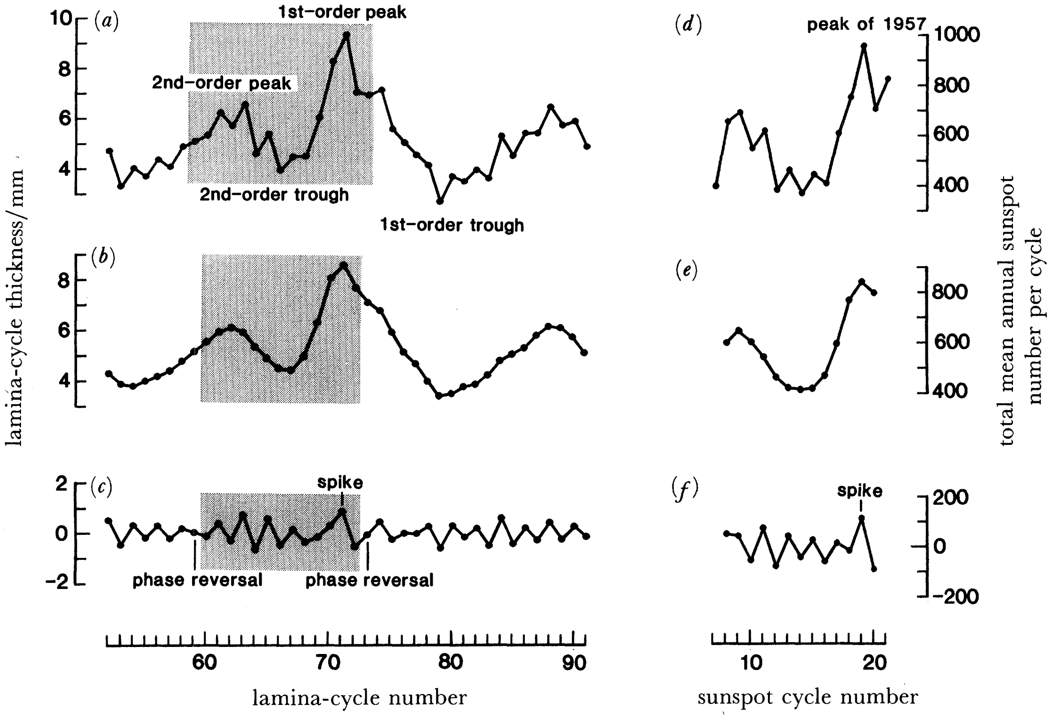

FIGURE 5. Curves comparing the thickness of lamina-cycles in the Elatina series with the magnitude of sunspot cycles for the continuous sunspot record since 1830. (*a*) Unsmoothed curve extracted from the Elatina series, showing the two peaks and troughts of an 'Elatina Cycle'. (*b*) The curve shown in (*a*), smoothed by a 3-point filter (weighted 1, 2, 1). (*c*) The residual sawtooth curve (curve (*a*) minus curve (*b*)). (*d*) Unsmoothed curve showing the total mean annual sunspot number per cycle for sunspot cycles 7–21. (*e*) The curve shown in (*d*), smoothed by a 3-point weighted filter. (*f*) The residual sawtooth curve (curve (*d*) minus curve (*e*)). Correlation coefficients between Elatina (shaded) and sunspot curves are 0.93 (unsmoothed), 0.98 (smoothed) and 0.94 (residual).

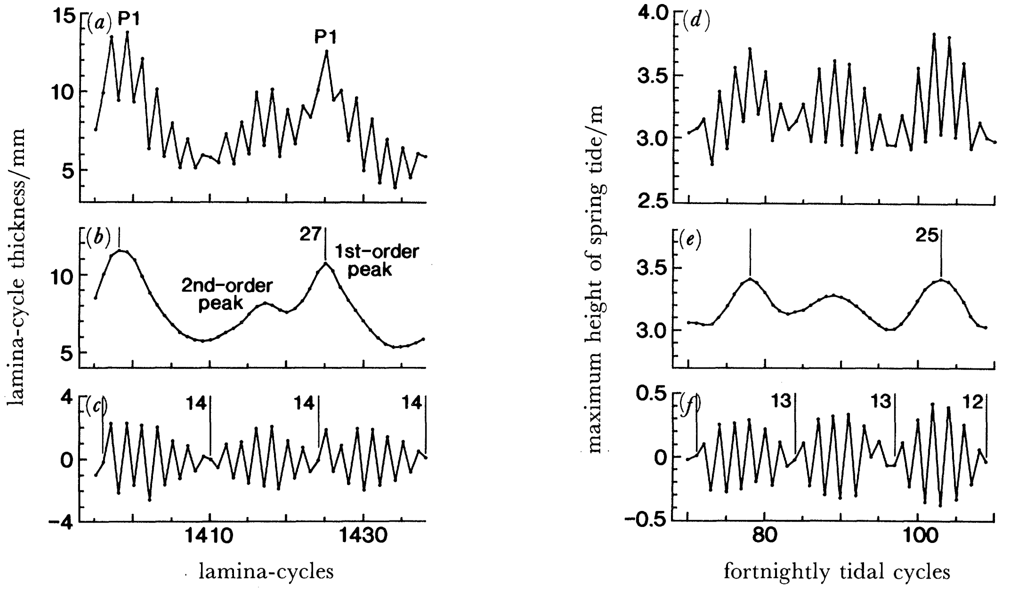

FIGURE 6. (*a*)–(*c*) Thickness of lamina-cycles from the Elatina series; lamina-cycle number increases up-sequence. (*a*) Unsmoothed curve showing first-order peaks (P1) that define the 'Elatina Cycle'. (*b*) Smoothed curve (5-point filter weighted 1, 4, 6, 4, 1); the number gives lamina-cycles between maxima. (*c*) Residual sawtooth curve (curve (*a*) minus curve (*b*)); the vertical lines mark positions of 180° phase-reversals in the sawtooth pattern, and the numbers give lamina-cycles between phase-reversals. (*d*)–(*f*) Tidal patterns for Townsville, Queensland, that are comparable with curves of lamina-cycle thickness. (*d*) Maximum height of the fortnightly tidal cycle from 19 October 1968 to 3 June 1970. (*e*) Smoothed curve (5-point filter weighted 1, 4, 6, 4, 1); the number gives fortnightly tidal cycles between yearly maxima that in part reflect seasonal effects (see Pariwono *et al.* 1986). (*f*) Residual sawtooth curve (curve (*d*) minus curve (*e*)); the vertical lines mark positions of 180° phase-reversals in the sawtooth pattern, and the numbers give fortnightly tidal cycles between phase reversals. (Tidal data for figures 4*c* and 6*d*, *e*, *f* supplied by the Tidal Laboratory of the Flinders Institute for Atmospheric and Marine Sciences, Flinders University of South Australia, copyright reserved.)

depends critically on the time-values ascribed the various sedimentary structures and cycles. A strongly seasonal, arid climate during deposition of the Elatina Formation is indicated by periglacial structures in a penecontemporaneous fossil permafrost horizon bordering the Adelaide Geosyncline (Williams 1986; Williams & Tonkin 1985); a yearly signature therefore should be sought in the rhythmites as a temporal milestone.

The solar-climatic hypothesis

An early interpretation, quite plausible given the periglacial setting, was that the laminae are varves that record spring or summer discharge of turbid meltwater into a deep, periglacial lake (Williams 1981, 1985). The laminae indeed bear resemblance to the 'intermediate distal facies' in the varve classification of Smith (1978). Lamina thickness in the Elatina Formation thus might provide a relative measure of annual meltwater discharge and hence of summer or mean annual temperature, and the Elatina record might be read as an interweaving of climatic cycles.

The varve interpretation underlies the hypothesis that the Elatina periodicities ultimately reflect solar variability (Williams 1981, 1985; Williams & Sonett 1985). The Elatina periods of 12 ± 4, 22–25 and *ca.* 103 'varve-years' may be equated with cycles in the sunspot record, which comprise a basic cycle of *ca.* 11 ± 3 years, the Hale magnetic cycle of *ca.* 22 years, and a longer period between 90 and 110 years. In both the Elatina and sunspot series the basic cycles (figure 4*a*, *b*) are of variable length, alternate cycles of relatively high and low amplitude are common, high-amplitude cycles tend to have sharper crests and to be of relatively short duration, and the cycles on average show positive skewness.

Furthermore, the plot of lamina-cycle thickness may be compared with that of the sum of yearly sunspot number per sunspot cycle (figure 5). Running cross-correlations show that the all-too-brief continuous sunspot record since about 1830 is comparable with that portion of the Elatina Cycle that includes the first- and second-order peaks and the intervening second-order trough; the first-order peak in the Elatina Cycle may be equated with the sunspot peak of 1957. Cross-correlations between respective Elatina (shaded) and sunspot curves shown in figure 5 yield correlation coefficients of 0.93–0.98. The strong correlations between elements of the Elatina and sunspot series permit an excellent simulation of the sunspot cycle (Bracewell 1986).

The empirical similarities between elements of the Elatina and sunspot records might arise through a direct connection, by way of climatic temperature variability, between late Proterozoic 'varve' thickness and solar activity. A solar signal, albeit a very weak one, has possibly been recorded in this way by recent varves deposited in Skilak Lake, Alaska (Sonett & Williams 1985). None the less, a mechanism whereby solar cyclicity might strongly influence the late Proterozoic climate has yet to be demonstrated (see Gérard & François 1987).

New data from the late Proterozoic of South Australia

New observations from other late Proterozoic rhythmites in South Australia throw new light on the origin of the Elatina series (Williams 1988, 1989*a*, *b*).

The Reynella Siltstone at Hallett Cove displays lamina-cycles like those of the Elatina Formation, but also contains some lamina-cycles up to six times thicker (figure 3*b*) that allow the detailed structure of individual cycles to be determined accurately. The thick cycles consistently give counts of 14 or 15 laminae per cycle, which exceed the mean count of 12 laminae per cycle in the Elatina series. A further distinctive feature of the Reynella Siltstone is the presence of *two* graded layers or coarse–fine couplets in many laminae (figure 3*b*). Where such 'semi-laminae' are of about equal thickness, the cycles appear to contain up to 26 or more 'laminae'. Semi-laminae are common even in the thin lamina-cycles in the Reynella Siltstone, but are rare in the Elatina Formation.

The facies at Hallett Cove (Dyson & von der Borch 1986) suggest fluctuations in water depth and distance from the sediment source in a marginal marine or estuarine setting, causing the interbedding of continental and shallow-water marine facies with proximal and distal lamina-cycles of offshore, deeper water origin. An overall greater and more stable depth of water appears to have been maintained at Pichi Richi Pass, where only distal lamina-cycles were deposited.

The lamina-cycles associated with the Chambers Bluff Tillite (figure 3*c*) also show an overall regular change in thickness of laminae and a pattern of alternate thick and thin cycles with phase reversals. Synsedimentary scouring, however, occurs at the tops of cycles and the thinner laminae in such places commonly are truncated. In a measured sequence of nine cycles the number of laminae per cycle ranges from 15 to 25, averaging 20.0. Because of the scouring, this mean must be viewed as a minimum estimate of cycle period.

The presence of up to 25 laminae per cycle suggests affinity with those cycles in the Reynella Siltstone that contain 26 or more semi-laminae; the fewer laminae in some cycles of the

Chambers Bluff Tillite is explained by contemporaneous scouring. A lamina of the Elatina Formation thus equates with a pair of semi-laminae in the Reynella Siltstone and with two laminae in the Chambers Bluff Tillite. The question is raised, therefore, whether the lamina-cycles at Pichi Richi Pass commonly are abbreviated through non-deposition of clastic laminae at the clayey ('dark band') boundaries between cycles. A reappraisal of the Elatina data and the solar-climatic hypothesis, viewed in the light of these new findings, is warranted.

A tidal model for late Proterozoic rhythmite deposition

The three late Proterozoic rhythmites described here comprise a new sedimentary facies with, as noted above, no matching cyclicity yet recognized in recent laminated sediments. Any new 'facies model' proposed for deposition of the rhythmites must take account of the following observations.

1. Laminae in the Elatina Formation including the very thinnest (*ca.* 0.2 mm) can be correlated in drill cores from holes 200 m apart. Laminae usually are graded within the range of fine sand to clayey fine silt. Deposition likely occurred mainly from suspension in quiet waters below wave base.

2. Palaeoslope directions for the Elatina rhythmites indicated by slumps in drill core are to the east, i.e. directly away from the nearby western margin of the Adelaide Geosyncline. Isolated ripples indicate eastward movement of sediment down this palaeoslope by unidirectional currents. Regional palaeocurrent directions for the Elatina Formation also are to the east (Preiss 1987).

3. A tidal influence is suggested by the clayey drapes within isolated climbing ripples that pass laterally into the Elatina laminar rhythmites, and by bimodal palaeocurrent directions in the Reynella Siltstone (Alexander 1984) and locally in the Elatina Formation. The isolated ripples in the Elatina rhythmites have similarity to the much thicker sand-wave deposits with mud drapes of subtidal origin (see Allen 1982).

These observations and the complex cyclicity displayed by all the rhythmites are explicable by deposition from turbid ebb-tidal currents in an offshore marine setting (Williams 1987, 1988, 1989*a*, *b*). In this tidal facies-model, fine sediment is entrained by ebb-tidal currents in tidal inlets and is transported mainly in suspension by turbulent ebb-tidal jets to deeper water offshore (see Özsoy 1986). There, settling suspended sediment would form graded laminae and local small-scale ripples (see Rees 1966) in a distal ebb-tidal delta, estuarine or marine shelf setting below wave base. Sediment deposited offshore in this way is relatively undisturbed by flood-tidal currents, which usually are weak and converge radially toward the tidal inlet (Özsoy 1986).

Effectiveness of the tide as an agent of such entrainment and deposition would be determined by the speed of the ebb-tide and the tidal range (see, for example, FitzGerald & Nummedal 1983; Boothroyd 1985); the potential sediment load of ebb-tidal currents may increase linearly with tidal range and current speed. Hence, relatively thick laminae on the distal delta or shelf would normally be associated with fast ebb-tidal currents and large tidal ranges, such as occur during the spring phase of the tidal cycle. Thin clayey caps could form on sandy laminae during slack water between tides. As movement of sediment by tides may cease below a threshold tidal range and current speed (see Allen 1982; FitzGerald & Nummedal 1983), pauses in deposition of sandy laminae in the distal setting might occur for small, neap-tidal ranges; the quieter waters at such times would allow the settling of further fine material and

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the deposition of distinct clayey bands between fortnightly groups of laminae. Similarly, deposition of cross-bedded, cyclic 'bundle' sequences of shallow-water, subtidal deposits is explained by unidirectional or strongly asymmetrical tidal currents effecting deposition, a direct relation between clastic cross-bed thickness and tidal range and current speed, and the association of mud layers and drapes with slack water and neaps (see, for example, Visser 1980; Allen 1981, 1982).

The tidal rhythms so recorded by the Elatina Formation might be superimposed on an annual signature of sea-level variation or summer influx of turbid periglacial meltwaters. Annual high sea levels (see, for example, Pariwono *et al.* 1986) might combine with seasonal abundances of sandy and silty material in suspension to produce annual intervals of thicker laminae in the ebb-tidal deposits.

Applying this tidal model to the Elatina series, again the question arises regarding the time values to be ascribed the various sedimentary structures and cycles. In view of the prevailing strongly seasonal climate, a regular pulse should be sought in the sediments, other than the individual lamina, that might record annual (summer) peaks of rapid deposition. By these criteria, the first-order peak of the Elatina Cycle (figures 5*b* and 6*b*) stands clear; it is the most regular of all the oscillations, Fourier transform yielding a strong, narrow spectral peak (Williams 1985, 1989*a*, *b*), and invariably is associated with the thickest laminae and therefore the most rapid deposition. The smoothed curve of the Elatina Cycle (figures 5*b* and 6*b*) is indeed similar to the annual curves of sea level for numerous localities (see figure 6*e* and Pariwono *et al.* (1986)).

Late Proterozoic palaeotidal and palaeorotational periods

If the first-order peak of the Elatina Cycle is regarded as a yearly signal, periodicities displayed by the Elatina series can be equated readily with tidal parameters (see Williams 1987, 1988, 1989*a*, *b*).

1. The late Proterozoic year would be represented by 26.2 (± 0.2) lamina-cycles. The lamina-cycle would thus represent the late Proterozoic fortnightly tidal cycle.

2. The graded laminae of the Elatina Formation and Reynella Siltstone would represent diurnal increments recording the lunar day; the semi-laminae of the Reynella Siltstone and the laminae of the Chambers Bluff Tillite would be semidiurnal increments of the lunar day. The characteristic tidal patterns for these formations would thus be diurnal, mixed and semidiurnal respectively (figure 7); the mainly diurnal signature for the Elatina series may reflect a mixed pattern with the semidiurnal signal filtered out by sedimentary processes. Features of lamina-cycles for the Elatina series (figure 4*a*) – alternate cycles of high and low amplitude, the shorter duration and sharper crests of high-amplitude cycles, and the tendency for some cycles to be positively skewed – are all displayed in the daily pattern of fortnightly tidal cycles for Townsville, Queensland (figure 4*c*) (although, as discussed above, a positive skewness of lamina-cycles may also reflect a higher threshold current speed for sediment movement in the neap to spring part of the tidal cycle). The alternation of high and low spring tides and the shorter duration of high springs result from the eccentric lunar orbit and the Moon's more rapid orbital motion at perigee. (Maximum tidal heights are plotted in figures 4*c* and 6*d*, *e*, *f* as they are a relative measure of tidal range.) Furthermore, the lamina-cycles of the Reynella Siltstone that display semi-laminae (figure 3*b*) have a structure similar to the mixed fortnightly tidal growth patterns of modern bivalves (see Evans 1972).

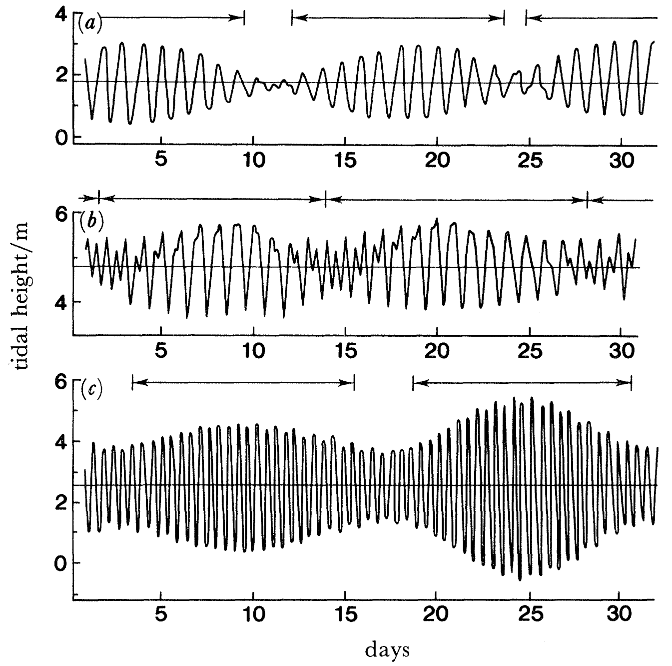

FIGURE 7. Modern tidal patterns (from Godin 1972; Lisitzin 1974). (*a*) Diurnal (as displayed by the Elatina Formation, see figure 3*a*). (*b*) Mixed (as displayed by the Reynella Siltstone, see figure 3*b*). (*c*) Semidiurnal (as displayed by the Chambers Bluff Tillite, see figure 3*c*). The arrows show schematically the tidal ranges for which semidiurnal and/or diurnal tidal cycles effected the deposition of clastic laminae for respective late Proterozoic rhythmites.

A maximum value of about 16 diurnal tides per late Proterozoic fortnightly tidal cycle implies that up to half the laminae are missing from certain lamina-cycles through their non-deposition at neaps when tidal ranges and maximum current speeds fell below threshold values for sand–silt transport to the area studied. The 'dark bands' of clayey material bounding many lamina-cycles would mark horizons of arrested clastic deposition. Such abbrevation explains the general uniformity of clastic lamina thickness at minima between lamina-cycles (see figure 4*a*). Strongly abbreviated cycles are not necessarily bounded by thicker clayey bands, however, suggesting that the deposition of clayey material also ceased temporarily in the distal setting during protracted neaps of small tidal ranges. Figure 7 shows in a general way the tidal ranges that effected deposition of clastic laminae in the rhythmites.

3. Pairs of lamina-cycles of high and low amplitude (figure 4*a*) would represent the lunar monthly tidal cycle. There would be 13.1 (± 0.1 s.d. from FFT spectrum; see Williams (1989*a*, *b*)) lunar months per late Proterozoic year, compared with 12.37 today. The number of lunar days per late Proterozoic lunar month cannot as yet be directly measured accurately because of the common abbreviation of lamina-cycles. The greatest number of laminae for two successive lamina-cycles in the Elatina series is 29, and the thick lamina-cycles of the Reynella Siltstone contain up to 15 diurnal laminae; these figures suggest 29–30 lunar days per lunar month and in turn imply around 30–31 solar days per lunar month.

4. The second harmonic of the Elatina Cycle, with a period of 13.1 lamina-cycles, would represent the half-yearly tidal signal. The half-yearly tide, by its modulation of tidal range, influenced the number of laminae deposited per lamina-cycle in the Elatina Formation (Williams 1989*a*).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

5. The alternation of high and low spring tides at Townsville shows a pattern of 'sawtooth envelopes' and phase reversals (figure 6*f*) like that in the Elatina series (figures 5*c* and 6*c*). This pattern also results from the eccentricity of the lunar orbit. Modern tides, as exemplified by 20 years of data for Townsville, average 27.9 spring tides for a 360° change of phase; the mean value some 650 Ma ago was 29.2 spring tides. These periods, which may be termed the 'tidal year', are slightly longer than respective solar years because of prograde rotation of the Moon's perigee. The late Proterozoic data indicate that the period of the lunar apsides cycle (rotation of the Moon's perigee) was then $29.2\pm0.2/(29.2\pm0.2-26.2\pm0.2) = 9.7\pm0.1$ years (see also Williams 1989*a*, *b*).

6. The amplitude modulation of the second-order peak of the Elatina Cycle indicates a long-term period of 19.5 (±0.5) Elatina Cycles or years, which is interpreted as that of the palaeolunar nodal cycle (Williams 1989*a*, *b*).

Palaeotidal and palaeorotational data for late Proterozoic time *ca.* 650 Ma ago as determined from the rhythmites of the Elatina Formation and Reynella Siltstone, and those calculated for that time by Lambeck (1978, 1988) based on palaeontological data, are compared with their modern equivalents in table 1. The data imply an average equivalent phase lag (the angle between the Earth–Moon axis and the Earth's tidal bulge, derived from the response of the solid earth and ocean tides; see Lambeck 1980) near 3° since late Proterozoic time rather than the present value of 6°.

TABLE 1. LATE PROTEROZOIC (*CA.* 650 Ma) AND MODERN TIDAL AND ROTATIONAL PERIODS

	late Proterozoic			
	Lambeck (1978, 1988)[a]			
parameter	(*a*)	(*b*)	this study[b]	modern
solar days in lunar month	*ca.* 30.7	*ca.* 30.2	30.5 (±0.5)	29.53
lunar months in year	*ca.* 14.4	*ca.* 13.2	13.1 (±0.1)	12.37
lunar apsides cycle/years	—	—	9.7 (±0.1)	8.85
lunar nodal cycle/years	—	—	19.5 (±0.5)	18.61
days in year	*ca.* 440	*ca.* 400	400 (±7)	365
length of day/h	*ca.* 20.1	*ca.* 21.9	21.9 (±0.4)	24.0

[a] The values from Lambeck (1978, 1988) are derived from Phanerozoic palaeontological data. They are based on an average equivalent phase lag angle of (*a*) 6° (the present value), and (*b*) 3°, and assume that tidal friction is the only phenomenon responsible for secular changes in the Earth's rotation and the Moon's revolution.

[b] Periods indicated by the rhythmites of the Elatina Formation and Reynella Siltstone (see Williams 1987, 1988, 1989*a*, *b*), with revised error estimates based on FFT spectra where applicable, as discussed in the text.

Overall, the similarities between the structure and relative periods of cycles in the Elatina series and modern tidal cycles are evident in figures 4 and 6, figures 3 and 7, and table 1. Such agreement argues strongly that the late Proterozoic rhythmites in South Australia indeed record a full spectrum of palaeotidal cycles that provide a unique set of palaeorotational and palaeotidal periods for *ca.* 650 Ma ago.

CONCLUSIONS

The Precambrian cyclic rhythmites whose conspicuous cyclicity has been compared with sunspot cyclicity – the Weeli Wolli Formation, the Wollogorang Formation, and the Elatina Formation – are, in the light of new geological data and critical re-examination, better

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

interpreted as encoding tidal rhythms. Despite the varve-like features of the Elatina Formation and the strong correlations between elements of the Elatina and sunspot series, an ebb-tidal model of deposition is much preferred because it can explain the complex patterns of the Elatina series over the *full* range of frequencies as well as new observations from other late Proterozoic rhythmites in South Australia. Furthermore, the ebb-tidal model alone appeals to rhythmic processes operating strongly at the Earth's surface today, and requires stability of the depositional system for only about 60–70 years rather than the 20000 years necessitated by the varve-solar interpretation. The tidal interpretation of the Elatina series implies that graded strata carrying tidal signals should be preserved in modern, laminated subtidal deposits built by ebb-tidal currents, although bioturbation by benthic fauna may hinder preservation.

In view of these reinterpretations, it would seem that the pre-recent geological record has yet to provide unequivocal evidence for significant modulation of terrestrial climate by the solar activity cycle. Such evidence may prove as elusive as have convincing indications of solar signals in modern patterns of weather and climate. Hence, we cannot conclude, on present geological evidence, that the Sun displayed an activity cycle like that of today during the early eras of Earth history.

On the credit side, the Elatina series evidently provides the first firm benchmark for Precambrian palaeotidal periods and palaeorotation. The study of such rhythmites promises to greatly illuminate the Precambrian history of the Earth's rotation and the Moon's revolution.

I thank Professor K. Lambeck, Professor G. W. Lennon, Dr C. J. Durrant and Dr W. V. Preiss for assistance and helpful discussions.

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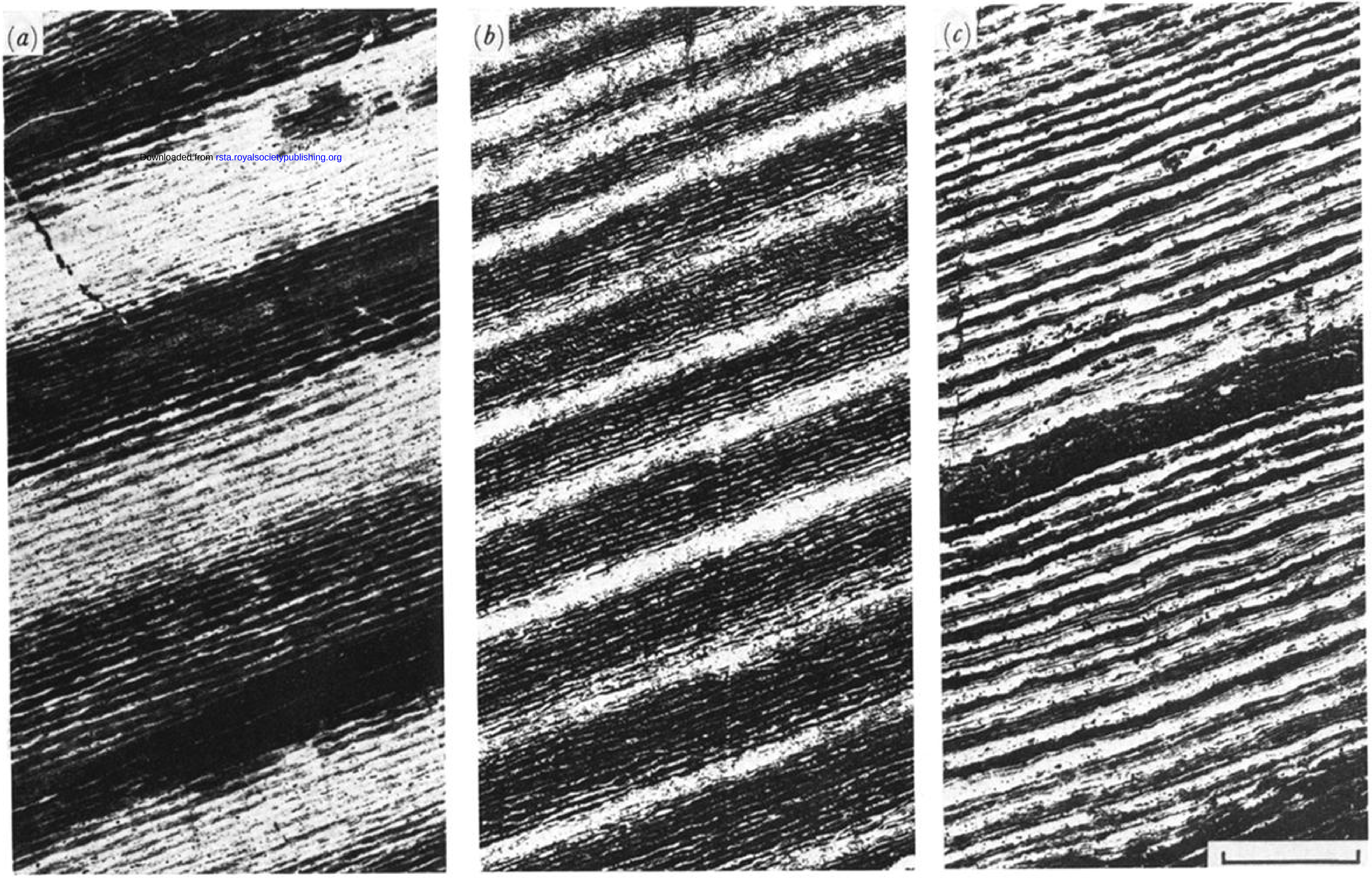
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Discussion

J.-C. Gérard (*Institut d'Astrophysique, Université de Liège, Belgium*). Are the deposition rates derived from the thickness of the Elatina Formation laminae compatible with the tidal interpretation of the periodicities?

G. E. Williams. Yes, they are. By the tidal interpretation, the 10 m thick rhythmite member of the Elatina Formation at Pichi Richi Pass was deposited in about 60 years, giving a mean rate of deposition of around 17 cm a^{-1}. This rate is compatible with deposition rates of up to 1 m or more per year determined for estuarine and shallow-water clastic tidal deposits; the comparatively low rate of deposition for the Elatina rhythmite member accords with its envisaged distal, offshore setting. Of course, such rates of deposition are not maintained continuously in the same area over very long intervals of time. Many sedimentary sequences, including tidal deposits, comprise beds or sedimentary packages deposited relatively rapidly and bounded by bedding planes representing long intervals of erosion, reworking or non-deposition.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



IGURE 1. Early Proterozoic cyclic banded iror-formation from the Weeli Wolli Formation, Western Australia. Scale bar 5 mm. (*a*) Chert pod containing discernible microband couplets of chert (white) and iron oxide (black); up to about 30 microband couplets occur between the centres of the cyclic 'stripes'. (*b*) Moderately compacted iron-formation with thinner microbands and cycles. (*c*) Strongly compacted iron-formation in which only the cyclic stripes are readily discernible.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

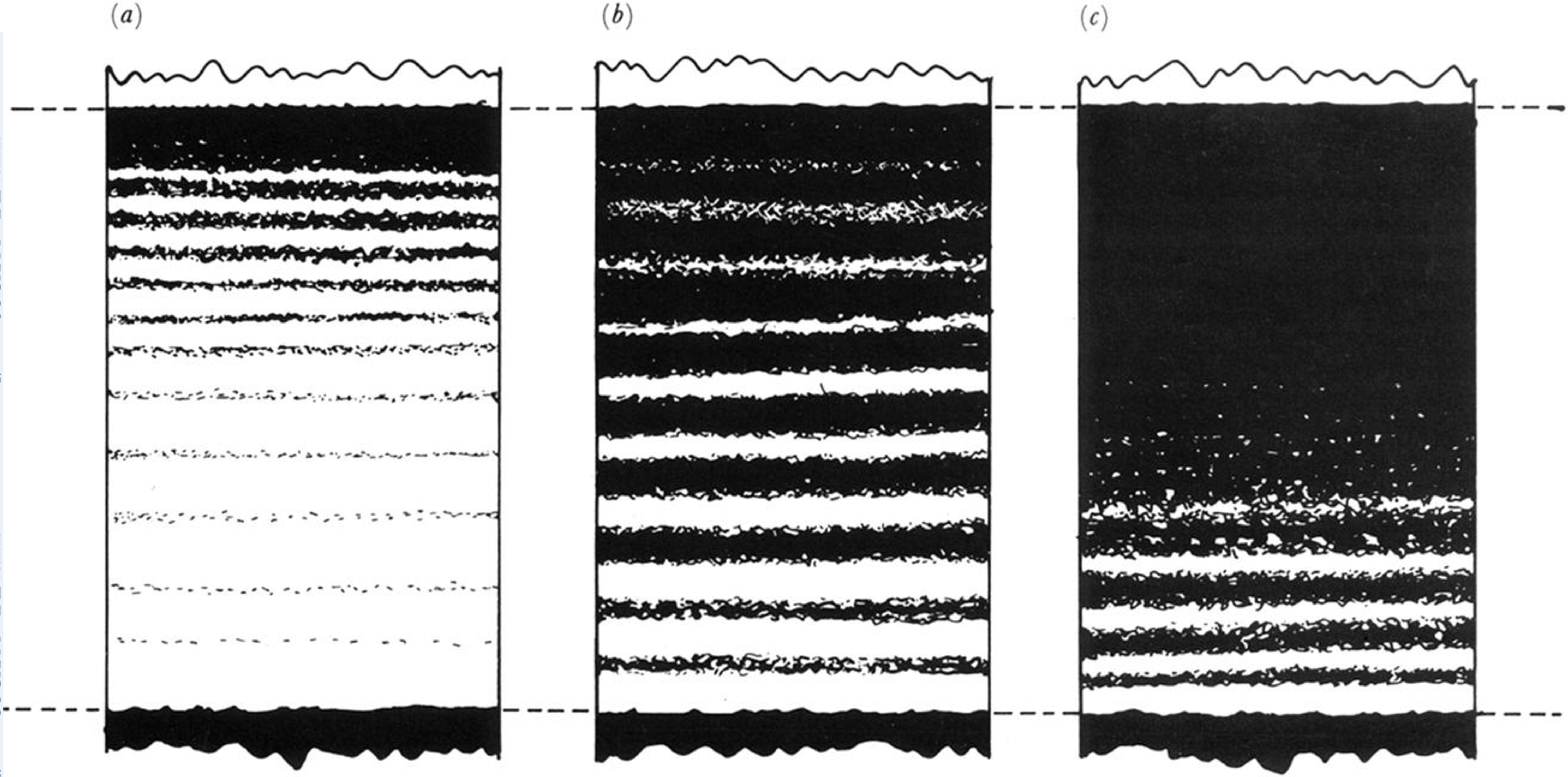


FIGURE 2. Range of cycle types in the mid Proterozoic Wollogorang Formation, northern Australia. The cycles commonly are about 1 cm thick. (*a*) Dolomite (white) dominant over mudstone (black). (*b*) Dolomite and mudstone in about equal proportion. (*c*) Mudstone dominant. (After Jackson 1985.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

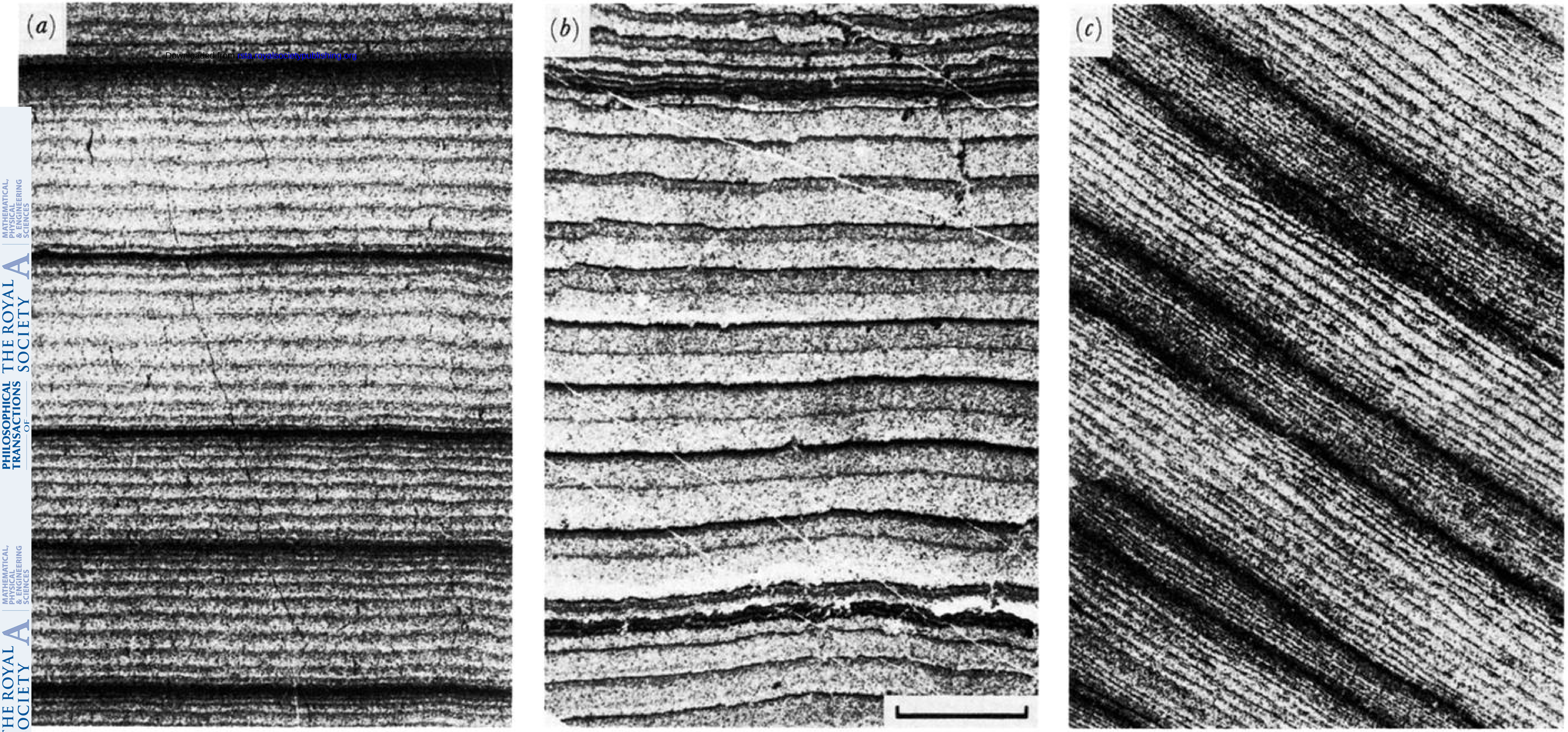


FIGURE 3. Late Proterozoic cyclic rhythmites, South Australia. Clayey material appears darker than sandy to silty layers. Scale bar 1 cm. (*a*) Elatina Formation. Four complete lamina-cycles of about 11–14 graded laminae are bounded by dark, clayey bands. (*b*) Reynella Siltstone, showing one complete, thick lamina-cycle containing 14 laminae of fine sandstone with clayey tops; most laminae show 'semi-laminae'. (*c*) Siltstone associated with the Chambers Bluff Tillite, showing seven complete, alternately thick and thin lamina-cycles each totalling from 15 to 25 graded laminae; laminae are eroded in places at tops of cycles.