Aust. J. Phys., 1985, 38, 1027–43

Solar Affinity of Sedimentary Cycles in the Late Precambrian Elatina Formation*

G. E. Williams

Department of Planetary Sciences, Lunar and Planetary Laboratory,
University of Arizona, Tucson, AZ 85721, U.S.A.
Permanent address: Exploration Department,
The Broken Hill Proprietary Co. Ltd, P.O. Box 860, Norwood, S.A. 5067.

Abstract

Climatic cyclicity is recorded by regular variations in the thickness of siltstone–fine sandstone laminae interpreted as annual deposits (varves) within the Elatina Formation, a late Precambrian ($\sim$680 million years old) periglacial lake deposit in the Flinders Ranges, South Australia. Earlier conclusions, based on the study of limited rock outcrop, that the climatic cycles reflect solar variability are strongly supported by a complexity of periods revealed through study of drill cores of the $\sim$10 m thick varved sequence. The wealth of new data generated by the drilling program, which was CSIRO-sponsored largely because of the support of R. G. Giovanelli, has application to solar physics and solar–planetary science.

1. Introduction

This paper is presented as a personal tribute to Dr R. G. Giovanelli in acknowledgment of his enthusiastic and practical support of my work on the solar affinity of cyclic layering in ancient sedimentary rocks in South Australia. These rocks could be viewed as a fossil solar observatory that may provide valuable data for solar physics and planetary science.

It should be recounted how Giovanelli contributed to this project. In June 1981 I described apparent solar periods (principally $\sim$11 and $\sim$22 years) in the thickness variations of varved (annually layered) periglacial lake deposits of the late Precambrian Elatina Formation in the Flinders Ranges (Williams 1981). Giovanelli expressed considerable interest in this work. In late 1981 I mentioned to him that, because the rocks are not well exposed, the project would best be advanced by a diamond-drilling program to obtain a complete cored sequence of the $\sim$10 m thick varved interval. On Giovanelli's advice I sought CSIRO funds for such drilling (Williams 1982) and, largely through his strong support, the Trustees of the CSIRO Science and Industry Endowment Fund agreed to sponsor the program. Giovanelli told me later that only after I had sent him a polished specimen of the Elatina Formation in mid-1982 and he had shown it to colleagues did he feel confident that financial support would be forthcoming. A photograph of this rock specimen appears in his recent book (Giovanelli 1984, Fig. 101) and, appropriately, in the present volume (Bracewell 1985; Fig. 3, p. 1013).

* Paper presented at the R. G. Giovanelli Commemorative Colloquium, Part II, Tucson, Arizona, 17–18 January 1985.

0004-9506/85/061027$02.00

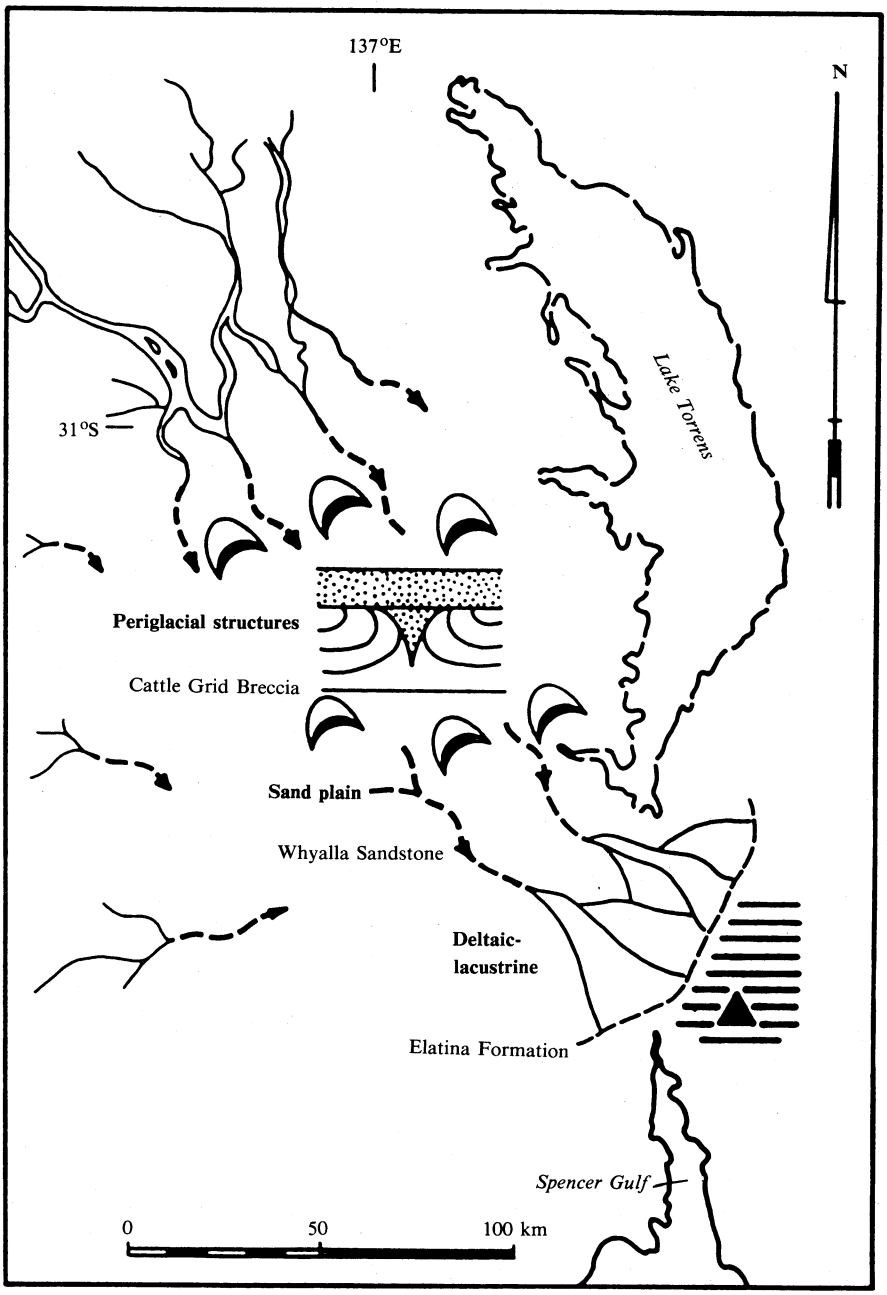


Fig. 1. Palaeogeographic scenario for north-central South Australia during the Marinoan Glaciation ~680 million years ago, showing the sand plain with schematic barchan dune forms (Whyalla Sandstone) indicating palaeowinds directed south-eastward; the location of the Marinoan fossil permafrost horizon (Cattle Grid Breccia) buried by the Whyalla Sandstone; and the periglacial lake within which the varved interval of the Elatina Formation accumulated (the triangle marks the site of the varve cycles in Pichi Richi Pass). The source of the annual meltwaters lay to the west and north-west.

The drilling was carried out in December 1982 (Williams 1983*a*). As some drill core was lost through rock fracturing, a group of three vertical holes was drilled to allow matching of cores and construction of the longest possible continuous varved sequence. During 1983 the drill cores were logged and the three sequences correlated.* The end result was a stratigraphically continuous log, 9·39 m long and spanning an estimated ~19 000 'years' (where years in quotes refers to varve-time), that could be measured precisely.

In June 1983 I gave a colloquium on the results of the drilling at the CSIRO Division of Applied Physics in Sydney. I was struck by Giovanelli's mental energy, maintained despite debilitating illness, and his enthusiastic interest in the Elatina project. Subsequent to Giovanelli's death, I conducted a detailed study of the core material at the University of Arizona between February and June 1984. The new data strongly support the original conclusion that solar-related periods are exhibited by the rocks and promise to contribute significantly to our understanding of solar processes.

This paper reviews some of the findings from the drill cores and the evidence for a solar connection; the more detailed accounts of the Elatina time-series and the implications for solar physics and planetary science will appear elsewhere. None of this work could have proceeded without the early support of Dr Giovanelli.

2. Geological Setting

The Elatina Formation at Pichi Richi Pass in the Flinders Ranges, South Australia, comprises deltaic-lacustrine sandstones and siltstones of western provenance deposited in a periglacial lake during the Marinoan Glaciation about 680 million years ago (Fig. 1). Correlative continental sandstones (Whyalla Sandstone) which occur up to 150 km north–west of Pichi Richi Pass contain aeolian dune cross-stratification that indicates palaeowinds directed south-eastward. Sand-wedge structures in a penecontemporaneous fossil permafrost horizon within the catchment area of the lake (Williams and Tonkin 1985) are similar to sand wedges forming through repeated seasonal contraction and expansion of the upper part of permafrost in modern arid periglacial regions; the structures provide good evidence for a markedly seasonal, arid Marinoan periglacial climate and imply strong seasonal control on meltwater discharge into the periglacial lake.

The Elatina Formation records climatic cyclicity as regular variations in the thickness and grain size of graded (fining-upward) laminae (Fig. 2) that were deposited by density underflows in the lake (Williams 1981, 1983*b*). The laminae, which range from about 0·2 to 3 mm in thickness, typically comprise a lower, paler sandy layer and an upper, silty to clayey layer. Scattered rock fragments up to several mm in diameter apparently were derived from melting river ice. Conspicuous groups or cycles of about 10–14 laminae that usually are bounded by thinner, darker, more clayey laminae characterize the sequence. The thickness of graded laminae varies regularly, attaining maxima near cycle centres. A cycle 'doublet' of alternate thick and

* This involved first placing strips of clear tape on the cores and then marking on the tape the true thicknesses of conspicuous varve-cycles measured between darker bands in the rock. The strips of tape were then transferred to transparent sheets to build up a sequence of cycle thicknesses. Overlaying the completed logs from the three drill holes allowed correlation between holes and the bridging of gaps caused by core breakage.

thin cycles is common (Fig. 2*b*) and longer rhythms are revealed through fluctuations in cycle thickness. Similar cyclicity is displayed by other lake deposits of Marinoan age up to 400 km from Pichi Richi Pass.

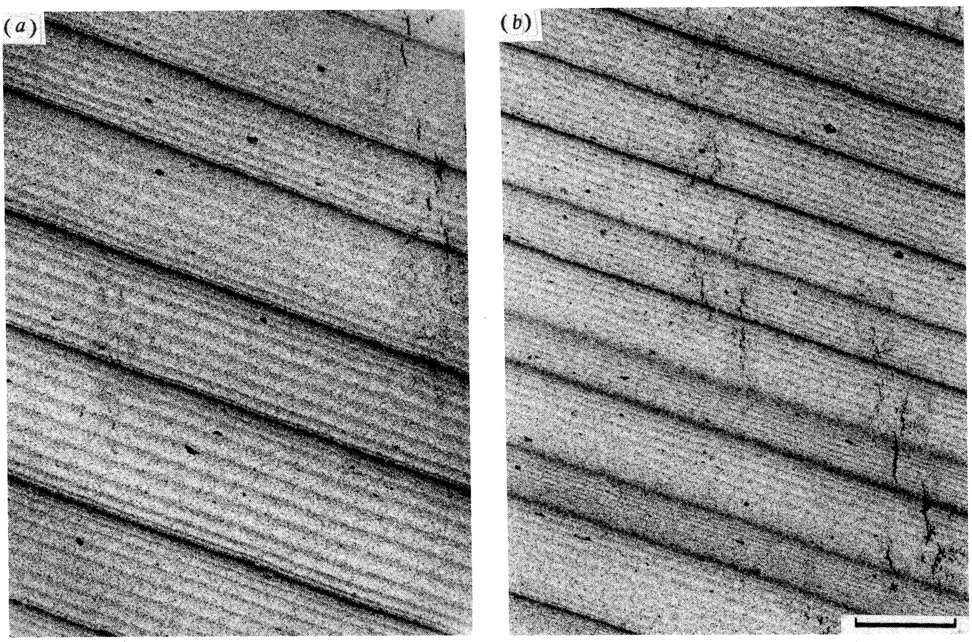


Fig. 2. Cyclic lamination in drill core from the Elatina Formation, Pichi Richi Pass. The graded (fining-upward) laminae comprise a lower, paler layer of very fine sandstone and an upper, silty layer. Conspicuous cycles of about 10–14 laminae are bounded by thinner, darker, more clayey laminae. Scattered 'drop grains' occur within the cycles. The lower half of (*b*) displays cycle 'doublets' resulting from alternate thick and thin successive cycles. The scale-bar is 1 cm.

The non-random variation in thickness of the graded laminae, together with the envisaged environment of deposition and strongly seasonal arid palaeoclimate, argue strongly that the laminae record non-random spring or summer meltwater discharge into the lake and that each lamina is thus an annual increment or varve. The laminae are similar to the 'intermediate distal facies' in the varve classification of Smith (1978), which comprises delicate but distinct varves with summer layers usually too thin to display sublaminae. The relative thinness of the Elatina varves therefore is explicable by their deposition in a distal portion of an extensive (30+ km) lake situated as much as 150 km from the source of the meltwaters, coupled with limited meltwater discharges in an arid periglacial setting. Through comparison with modern glaciolacustrine sedimentation (Perkins and Sims 1983), varve thickness is interpreted as a measure of relative mean annual temperature. Plots of varve and varve-cycle thicknesses against time thus may be viewed also as plots of time-variation in relative mean annual temperature. As the thinnest varves reflect the coldest climatic conditions, their more clayey composition may be explained by deposition of suspended fines through more widespread freezing or overturn of cold surface waters (Williams 1981).

3. Time-series Analysis

From thickness measurements of drill core material, distinct periods have been identified in two related sequences:

(i) a detailed sequence of 1337 varves obtained from enlarged photographs of thin sections;

(ii) a long sequence of 1580 cycles, each cycle consisting of 8–16 varves, obtained from the composite log of the drill cores.

Thicknesses were determined with a precision of 0·01 mm at the Laboratory of Tree-ring Research, University of Arizona, and recorded on a floppy disc; the data were then transferred to the Lunar and Planetary Laboratory INTERDATA 8/32 computer for time-series analysis, which was carried out in association with C. P. Sonett (see Williams and Sonett 1985*a*, 1985*b*).

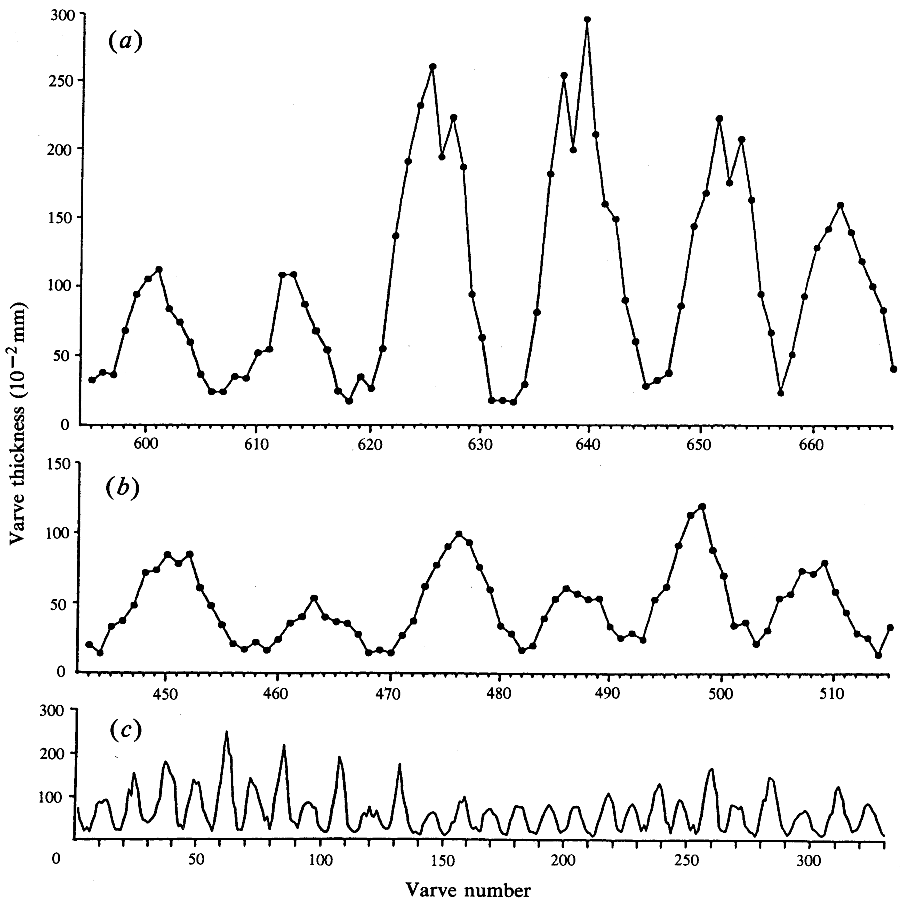


Fig. 3. True thicknesses of varves extracted from the detailed sequence (varve number increases up-sequence), showing (*a*) thick varves producing high-amplitude varve cycles with multiple peaks, with a minor 'spike' occurring within a thickness minimum at varve number 620; (*b*) thin varves producing low-amplitude varve cycles that display alternate high and low maxima; (*c*) small-scale plot showing long-term modulation of varve-cycle amplitudes.

(a) Detailed Sequence

A piece of core 93 cm long that contained well preserved varves was selected for detailed study. Overlapping thin sections were cut and a 4·4× photographic enlargement made of each. The varve boundaries were then carefully ruled on the photographs with a very fine (0·13 mm) pen; such marking proved necessary because the granularity of the rocks made the boundaries appear diffuse when viewed through the eyepiece of the measurer. Boundaries appeared sharper and easier to mark by sighting along the varves on the photographs. Some very thin varves, possible random (intra-annual) layers, and rare soft-sediment deformation made counting uncertain in places, and the count of 1337 measurements has an estimated accuracy of ±5%.

The 1337 varves span 110 full cycles (cycle numbers 1405–1514) near the top of the core sequence of 1580 cycles. Characteristic features of the plot of varve thickness against time, portions of which are shown in Fig. 3, are listed as follows:

(i) Conspicuous fluctuations in varve thickness define a 12 'year' cycle:

Cycles measured	Mean period ('years')	s.d. ('years')	Range ('years')
Between minima	12·0	1·6	8–16
Between maxima	12·0	1·8	8–16

(ii) The cycles show an overall tendency to positive skewness, i.e. the rise to maximum tends to be steeper than the fall to minimum. The mean ascent period is 5·57 'years' and the mean descent period 6·45 'years'.

(iii) The varve thicknesses fall to approximately the same minimum level every ~12 'years' (mean = 0·19 mm and s.d. = 0·07 mm), whereas the intervening maxima have a large range in thickness (mean = 1·20 mm and s.d. = 0·47 mm).

(iv) Detailed features include the occurrence of multiple peaks for certain maxima (Fig. 3*a*), the very minor 'spikes' within some ~12 'year' minima (Figs 3*a* and 3*b*), and the common occurrence of alternating cycles of high and low maxima (Figs 3*b* and 3*c*).

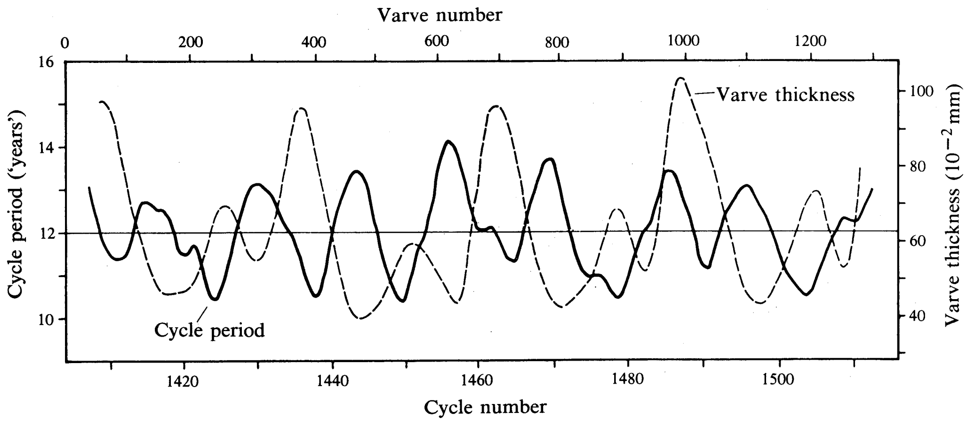


Fig. 4. Variation with time in the period of the ~12 'year' cycle measured between thickness minima (smoothed by a 5-point filter weighted 1, 4, 6, 4, 1), compared with varve thickness for the detailed sequence (smoothed by a 111-point filter); the cycle number increases up-sequence.

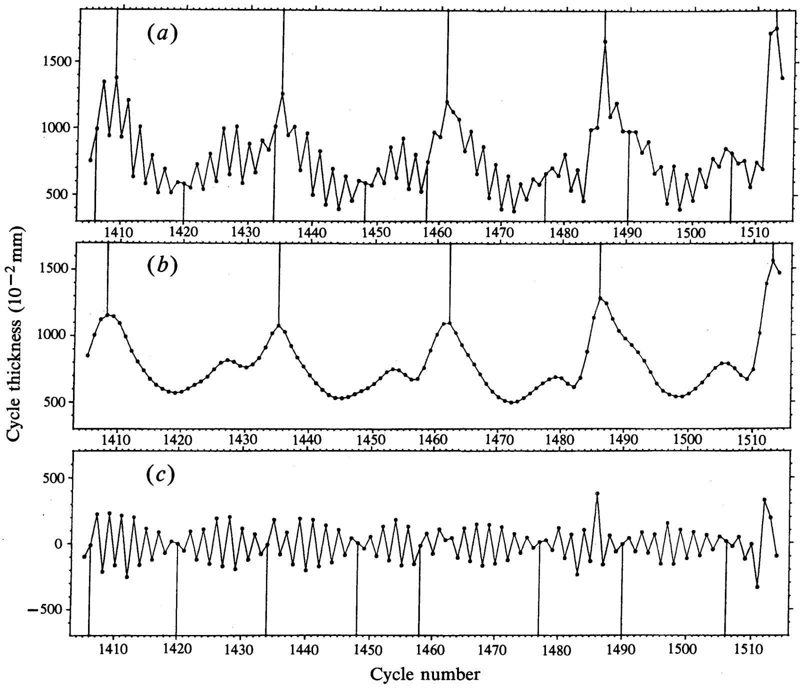


Fig. 5. Thicknesses of ~12 'year' cycles for the stratigraphic interval covered by Fig. 4, extracted from the long sequence (cycle number increases up-sequence), showing (*a*) cycle thicknesses with distinct maxima every 25–27 cycles and a sawtooth pattern reflecting the characteristic alternation of relatively thick and thin cycles; (*b*) curve (*a*) smoothed by 5-point filter weighted 1, 4, 6, 4, 1; (*c*) high frequency curve obtained by subtracting curve (*b*) from curve (*a*). The vertical lines above curves (*a*) and (*b*) mark boundaries of Elatina Cycles and those below curves (*a*) and (*c*) mark positions of 180° phase-reversals.

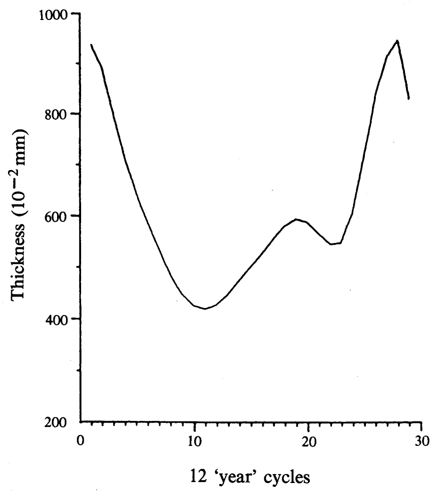


Fig. 6. Mean of the 59 Elatina Cycles contained in the smoothed curve of the long sequence (cf. Fig. 5*b*).

(v) Regular fluctuations in the amplitude of the ~ 12 'year' cycles and in varve thickness define longer periods of up to ~ 26 cycles (Fig. 3*c* and Fig. 4).

The smoothed plot of cycle duration against time shown in Fig. 4 indicates that cycle periods are modulated by a longer rhythm with a mean period near 13 cycles. Also, the thickest varves tend to coincide with relatively short cycle periods. Such negative correlation means that stronger, higher cycles tend to be of shorter duration than average. This explains the earlier estimate of ~ 11 'years' for the mean cycle period (Williams 1981, 1983*b*), as outcrop specimens displaying thicker, more easily counted varves and cycles were selected for examination first.

(b) Long Sequence

A high level of confidence can be placed in the composite log of 1580 ~ 12 'year' cycles because of the excellent correlation among the three drill holes. Fig. 5 shows the plot of cycle thicknesses against time for the same 110 cycles covered by the varve-thickness measurements. This short interval is representative of the full sequence of 1580 cycles, which has the following features:

(i) Maxima in ~ 12 'year' cycle thicknesses occur about every 26 cycles. This long periodicity, termed here the 'Elatina Cycle', repeats 59 times in the measured sequence. Data for the Elatina Cycle are:

Between maxima for:	Mean	s.d. (~ 12 'year' cycles)	Range
Unsmoothed curve (Fig. 5*a*)	26·2	1·5	20–29
Smoothed curve (Fig. 5*b*)	26·2	0·9	23–28

Despite its wide range in duration (240–348 'years' for the unsmoothed curve and 276–336 'years' for the smoothed curve), the Elatina Cycle is nonetheless quite well centred around a mean value of 314 'years'. The mean Elatina Cycle is shown in Fig. 6.

(ii) Second-order peaks that occur consistently in the same position relative to the maxima of the Elatina Cycle (Fig. 5*b* and Fig. 6) confirm the presence of a second harmonic (see Williams 1981, 1983*b*) with a mean period therefore near 13·1 ~ 12 'year' cycles (~ 157 'years'). The harmonic components of the Elatina Cycle are discussed in Section 3*c*.

(iii) Superimposed on the Elatina Cycle is a 'zig–zag' or sawtooth pattern resulting from the characteristic alternation of relatively thick and thin ~ 12 'year' cycles (Fig. 2). The high frequency curve (Fig. 5*c*) reveals that the sawtooth pattern comprises a succession of envelopes characterized by 180° phase-reversals at or near the necks between the envelopes. This phase reversal was described and illustrated by Williams (1983*b*) and is employed by Bracewell (1985) in his analysis of modern solar data. A total of 106 such phase-reversals occurs in the measured sequence; the interval between reversals averages 14·6 ~ 12 'year' cycles (s.d. $= 2{\cdot}2$ and range $=$ 9–23 cycles). The overall sawtooth pattern with phase-reversals is described mathematically as a beat between two oscillations with periods near two cycles (C. J. Durrant, personal communication 1985). As the mean period for a 360° change of phase (29·2 ~ 12 'year' cycles or 350 'years') is longer than the mean period of the

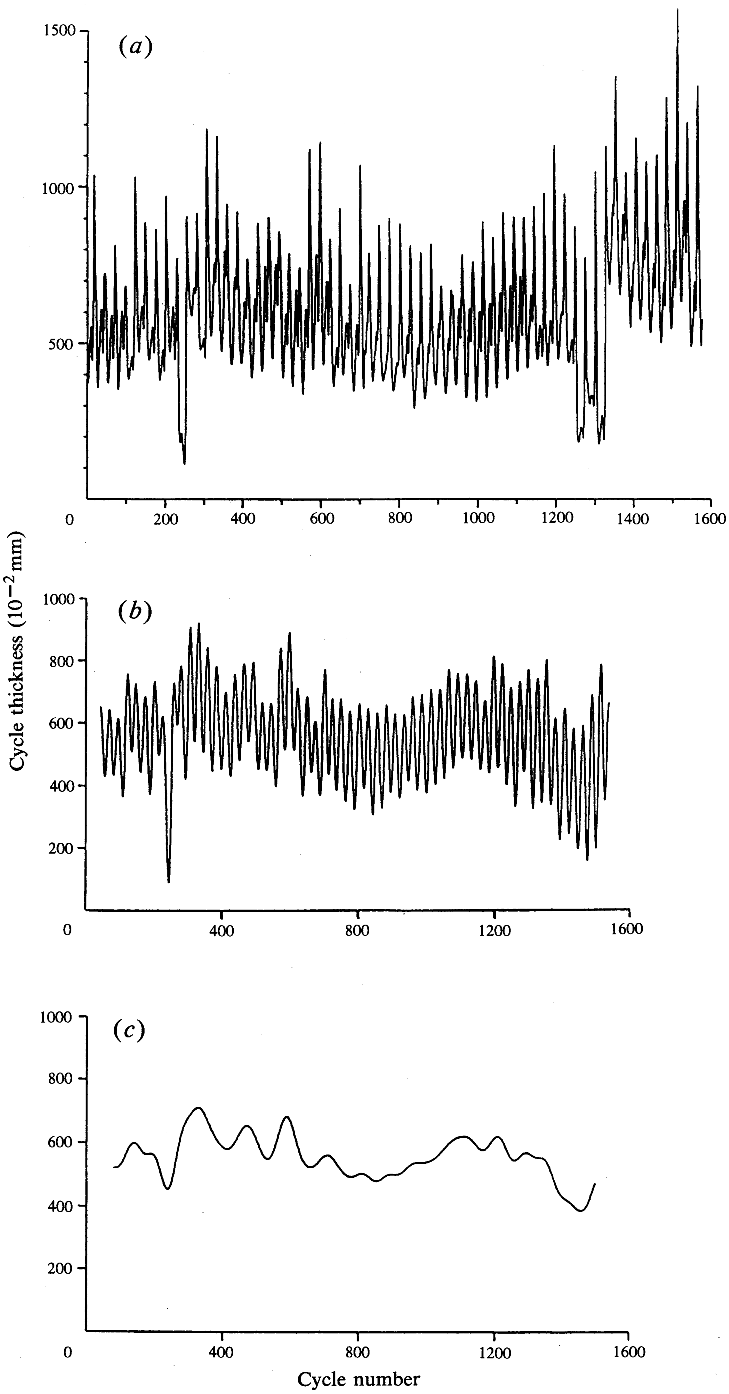


Fig. 7. Thicknesses of ~12 'year' cycles for the entire long sequence (cycle number increases up-sequence) showing (*a*) unsmoothed curve with low-amplitude wave interrupted by two step-like features between cycle numbers 1200 and 1400; (*b*) as (*a*), with 'corrections' to remove the two step-like features (see Section 3*b* for details) and smoothed by a 81-point filter; (*c*) as (*a*), with 'corrections' and smoothed by a 161-point filter.

Elatina Cycle (26·2 cycles), the positions of phase-reversals gradually advance up-sequence relative to amplitude maxima. The detailed structure of amplitude maxima therefore varies according to their position relative to that of envelopes and necks of the sawtooth curve (Fig. 5*a*).

The Elatina Formation also records very long periods. A low-amplitude wave with a period of roughly 700–800 $\sim$12 'year' cycles is discernible in the full plot of $\sim$12 'year' cycle thicknesses (Fig. 7*a*), despite two abrupt changes in cycle thickness near the top of the sequence. As such abrupt changes in thickness are best explained by geological (tectonic and/or geomorphological) influences on sedimentation rates in the ancient lake, two 'corrections' were made ($+190\times10^{-2}$ mm to cycles 1250–1330 inclusive, and -352×10^{-2} mm to cycles 1331–1578 inclusive) to eliminate the 'step function'. Several very long periods are evident in the smoothed plot of the 'corrected' sequence (Figs 7*b* and 7*c*).

Table 1. Main periods identified in the Elatina time-series

Visual mean	DFT[A]	MEM[A]	Visual mean	DFT[A]	MEM[A]
Detailed sequence ('years')			Long sequence ($\sim$12 'year' cycles)		
		Order = 300			Order = 400
		7·6 (0·01)		2·1 (0·51)	2·1 (0·42)
	8·0 (0·03)	8·0 (0·01)		3·8 (0·01)[B]	
	9·7 (0·06)	9·7 (0·02)		4·4 (0·02)[B]	4·4 (0·01)
	10·3 (0·29)	10·3 (0·07)		5·3 (0·04)	5·3 (0·04)
	11·0 (0·46)	11·1 (0·27)		6·6 (0·07)	6·6 (0·06)
	11·2 (0·60)			8·8 (0·16)	8·8 (0·08)
	11·6 (0·23)	11·5 (0·06)	13·1	13·1 (0·55)	13·1 (0·47)
12·0	11·9 (0·66)	11·9 (0·50)	26·2	26·1 (1·00)	26·2 (1·00)
	12·3 (0·54)				
	12·5 (0·64)	12·4 (1·00)	Long sequence, 'corrected' ($\sim$12 'year' cycles)		
	13·0 (0·30)	13·0 (0·13)			Order = 400
	13·5 (0·24)	13·5 (0·06)			103 (0·03)
	14·4 (0·16)	14·3 (0·04)		134 (0·21)	144 (0·14)
	22·4 (0·18)	22·3 (0·11)		195 (0·19)	226 (0·06)
	25·8 (0·21)	25·9 (0·05)	700–800	778 (1·00)	723 (1·00)
	103·2 (0·15)	104·7 (0·10)			
$\sim$156	158·6 (0·45)	157·6 (0·66)			
$\sim$312	333·2 (1·00)	341·2 (0·28)			

[A] Power spectral densities in parentheses, normalized to unity for the strongest periods.
[B] Power spectral densities from DFT of 'high-frequency' curve (see Fig. 5*c*).

(c) Spectral Analysis

The time-series discussed above were analysed by discrete Fourier transform (DFT) and the maximum entropy method (MEM) using the Burg algorithm. In general, both methods gave similar results with regard to periods identified. The MEM, because of its sensitivity and generally acceptable spectral stability, was preferred for relatively short data sets. The periods identified by spectral analysis (Table 1) confirm those previously identified visually, and are divisible into three groups: periods <30 'years', the Elatina Cycle and its harmonics, and very long periods.

The DFT spectrum of the 1337 varve-thickness measurements (Fig. 8*a*) reveals several distinct periods in the range of 10–14 and 22–25 'years', as well as longer

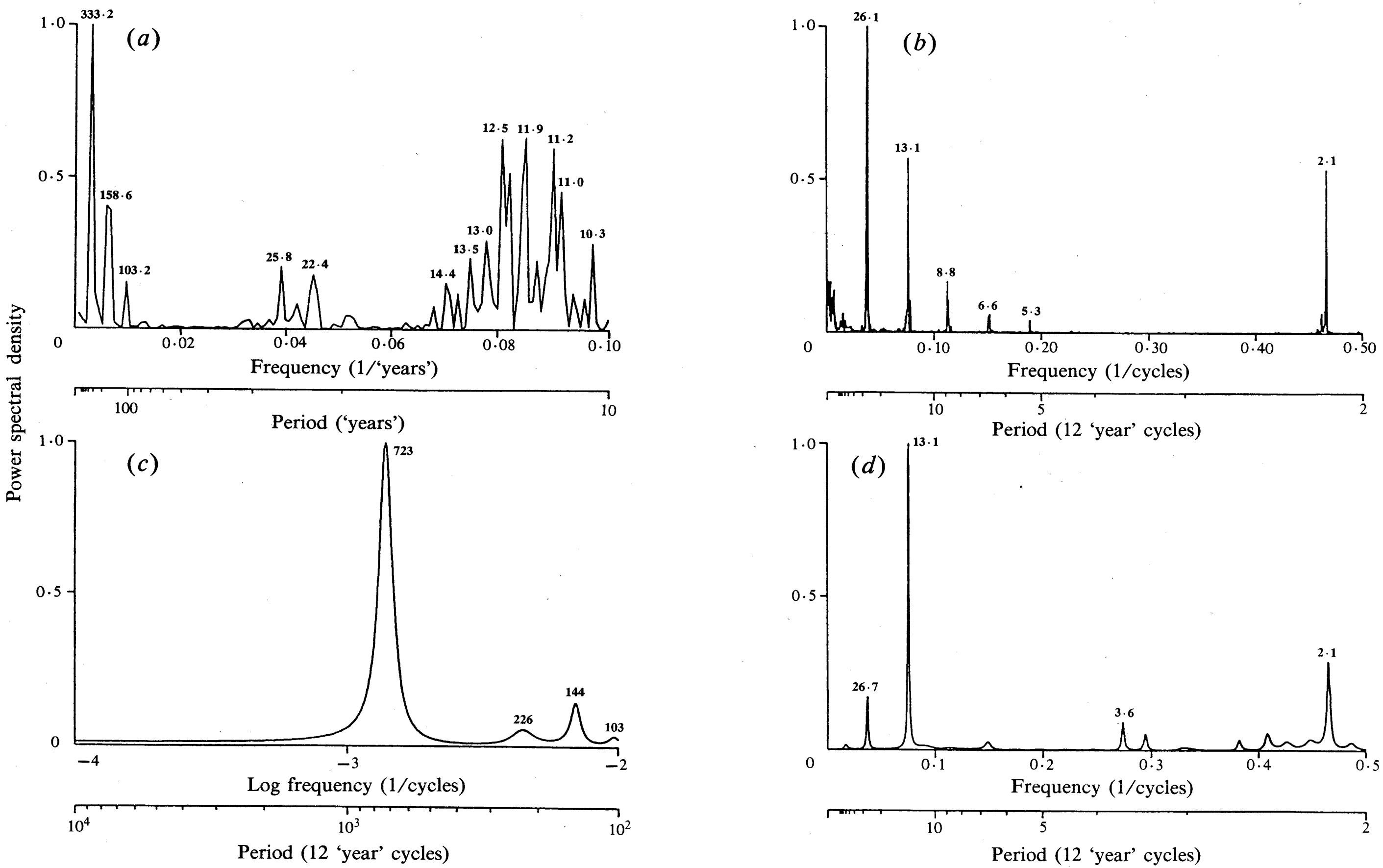


Fig. 8. The DFT and MEM spectra, normalized to unity for the strongest lines, showing (*a*) DFT unsmoothed spectrum of the 1337 varve-thickness measurements with linear frequency scale; (*b*) DFT unsmoothed spectrum of thickness measurements of 1580 ~12 'year' cycles with linear frequency scale—peaks for the first through fifth harmonic of the (26× ~12 'year') Elatina Cycle are discernible; (*c*) MEM spectrum for the 'corrected' and smoothed long sequence shown in Fig. 7*b*, using the Burg algorithm at an auto-regressive order of 400, with log frequency scale; (*d*) MEM spectrum for the unsmoothed curve of ~12 'year' cycle period against time, using the Burg algorithm at an auto-regressive order of 50, with linear frequency scale.

periods of about 103, 158 and 333 'years'. Additional, weaker peaks not shown in Fig. 8*a* occur at 8·0 and 9·7 'years'. A beat between the periods identified at 22·4 and 25·8 'years' may account for the pattern shown in Fig. 5*c*.

The DFT spectrum of the 1580 ~12 'year' cycles (Fig. 8*b*) reveals a distinctive 'harmonic series' consisting of a fundamental period of 26·1 cycles and progressively higher harmonics of 13·1, 8·8, 6·6 and 5·3 cycles. The DFT and MEM plots at more detailed scales than Fig. 8*b* reveal two further harmonics at 4·4 and 3·8 cycles. The strong period near 2 cycles represents the ubiquitous cycle doublet. Good agreement exists between mutual periods identified in the detailed and long sequences, although the period of 26·1 cycles (Fig. 8*b*) is better resolved than the equivalent period of 333 'years' (Fig. 8*a*), which is beyond the limit of accurate resolution for the detailed sequence.

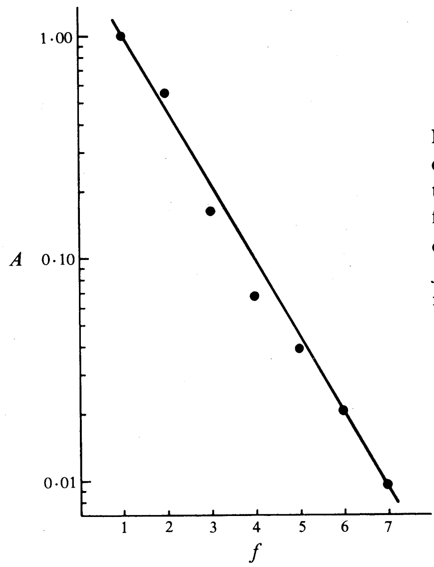


Fig. 9. DFT power spectral density amplitudes A of the Fourier series coefficients for the seven harmonics of the Elatina Cycle; f is the harmonic number.

The harmonic series is of particular interest. The complex periodic function termed the Elatina Cycle comprises, in accord with Fourier series expansion, a fundamental frequency and a number of higher harmonics (in the present case, six) of that fundamental. The DFT power spectral density amplitudes A of the Fourier series coefficients define an exponential function (Fig. 9), which is approximated by the equation

$$A \approx 220\,\mathrm{e}^{-0\cdot 8f},$$

where f is the harmonic number (C. J. Durrant, personal communication 1985). The harmonic series is represented also in the spectra of the detailed sequence (Fig. 8*a*) and of all four quarters of the long sequence.

The MEM spectrum of the low-frequency portion of the long sequence (Fig. 8*c*) suggests very long periods around 144 and 723 ~12 'year' cycles (about 1730 and 8680 'years' respectively). The longer period is consistent with the low amplitude wave discernible in the data (Fig. 7) but statistically is of uncertain significance in view of the relatively short record analysed.

As noted above, the period of the ~12 'year' cycle is modulated by a longer period near 13 cycles (Fig. 4). The MEM spectrum of cycle period against time (Fig. 8*d*) indicates that the duration of the ~12 'year' cycle is indeed modulated principally by a period of 13·1 cycles and to a lesser degree by periods of 2·1, 26·7 and 3·6 cycles. The periods of 26·7 and 13·1 ~12 'year' cycles equate with the fundamental and second harmonic of the 'harmonic series' in the amplitude spectrum (Fig. 8*b*); the fundamental harmonic predominates in modulating the ~12 'year' cycle amplitude whereas the second harmonic predominates in modulating cycle frequency. The period near 2 cycles reflects a tendency for cycles of short duration to alternate with cycles of long duration, although such alternation in period shows no systematic relation to the amplitude alternation of the ~12 'year' cycle (Fig. 5*c*).

4. Discussion

(a) The Solar Connection

The new data provided by study of the drill cores strongly support earlier conclusions, based on the examination of limited rock outcrop (Williams 1981, 1983*b*), that the climatic periods recorded by the Elatina Formation reflect solar variability. Features of the Elatina time-series that point to a solar connection are discussed below.

The Elatina periods of 10–14, 22–25 and ~105 'years' accord with cycles in the sunspot record, which similarly displays several discrete periods between 8 and 13 years, the Hale cycle of ~22 years, and a longer period between 90 and 110 years (Cohen and Lintz 1974; Herman and Goldberg 1978; Sonett 1982). The longer Elatina periods of ~157 and ~314 'years' are comparable with certain solar and climatic periods for Holocene time as indicated by tree-ring studies (Williams 1983*b*; Sonett 1984*b*). The very long periods of up to ~9000 'years' may have counterparts in the recent climatic record (see Mörner 1984; Treut and Ghil 1983), although a solar connection for such periods is not established.

The plot of varve thickness against time (Fig. 3) is similar to the familiar plot of mean annual sunspot number, particularly the reliable record since about A.D. 1830, in the following ways:

(i) Cycles display a wide range of periods [8–16 'years' for the Elatina Formation; 9·0–13·6 years between minima and 7·3–17·1 years between maxima for sunspot cycles (Waldmeier 1961)].

(ii) Minima fall to approximately the same level whereas maxima display a wide range of values.

(iii) Cycle amplitudes display long-term variations.

(iv) Alternating cycles of high and low maxima are common.

(v) Some maxima display multiple peaks, and minor 'spikes' occur within some minima. Such features are displayed by the plot of mean annual sunspot (umbral) areas since A.D. 1920 (see Howard *et al.* 1984, Fig. 2). (The measurement of sunspot areas may be regarded as a more meaningful representation of solar variability than the rather arbitrarily derived sunspot numbers, which do not show 'spikes' at solar minimum.)

(vi) The ~12 'year' varve-cycles display a tendency to positive skewness, a feature also of sunspot cycles (Howard *et al.* 1984; Wilson 1984).

The similarity of varve- and solar-cycle structure argues for a *direct* connection between varve thickness and solar activity, a conclusion reached previously on the evidence of overall skewness of a limited sample of cycles and the close similarity of portions of the cycle-thickness curve to the plot of annual mean sunspot number at maxima of the sunspot cycle (Williams 1981, 1983*b*). (The latter comparison is further discussed below.) As shown by Bracewell (1985), the varve-cycle pattern can be generated artificially from a sequence of mean annual sunspot numbers by assigning a direct connection between varve thickness and sunspot number, whereas the varve pattern cannot be mimicked for the inverse relation.

The frequency modulation of the ~12 'year' cycle (Fig. 4) militates against the graded laminae representing tidal increments. Quite apart from the strong dissimilarity between the envisaged Elatina palaeoenvironment and a tidal setting (Williams 1981; Williams and Tonkin 1985; see Fig. 1), such modulation of frequencies is incompatible with regular tidal periods. Interestingly, the duration of the sunspot cycle over the reliable portion of the record since A.D. 1830 appears modulated by a longer period, most minimum-to-minimum cycle lengths last century grouping around 11·5 years and this century near 10·0–10·5 years (Wilson 1984). A further similarity between the Elatina and solar records is the tendency for cycle duration to vary inversely with cycle amplitude. In the Elatina record, stronger cycles tend to be of shorter than average duration (Fig. 4), and Bracewell (1985) shows that sunspots cycles of large amplitude tend to be of short duration, and vice versa. In view of the modulation of cycle duration, the difference in mean period between the Elatina 12 'year' and sunspot 11 year cycles appears of little significance; the reliable solar record may be too brief to yield a truly representative mean period.

As previously observed (Williams 1983*b*), portions of the plot of ~12 'year' cycle thicknesses may be compared with the graph of mean annual sunspot number at cycle maxima since A.D. 1830. Similarities include: (i) the structure of certain Elatina Cycle amplitude maxima and that of the solar maximum culminating in A.D. 1957; and (ii) the sawtooth pattern of cycle amplitudes (which maintains phase across the A.D. 1957 solar maximum). Such similarities between the Elatina and solar series are evident in Fig. 10. Cross-correlation between the overlapping portions of the curves shown in Fig. 10 yields the highly significant correlation coefficients (Pearson) of 0·95 [curves (*a*) and (*b*)] and 0·93 [curves (*a*) and (*c*)]. Importantly, only the reliable portion of the sunspot record may be compared in this way to parts of the Elatina curve, which increases confidence that the Elatina Formation indeed records solar variability.

Although the Elatina record exhibits deep minima in 12 'year' cycle amplitudes every ~270–340 'years', it shows no evidence for a cessation of cyclicity similar to that of the alleged Maunder Minimum between about A.D. 1645 and 1715 (see Eddy 1976). It is noteworthy that Chinese naked-eye observations suggest sunspot cyclicity continued during the 17th and early 18th centuries and may imply that the Maunder Minimum is an artefact of insufficient data (Cullen 1980; Ding Youji *et al.* 1983).

(b) Implications and Applications

Overall, the evidence from both the Elatina detailed and long sequences supports a direct connection between solar variability, climatic temperature change, and varve-thickness cyclicity during the Marinoan Glaciation in South Australia ~680 million years ago. This raises the question as to why the solar cycle apparently influenced the terrestrial climate so markedly in late Precambrian time. One suggested explanation, that the dipole component of the Earth's magnetic field and therefore the Earth's magnetospheric 'shield' may have been much weaker at that time (Williams 1981), has been examined through the palaeomagnetic study of the Elatina varves. The rocks contain a strong primary remanent magnetization (Embleton and Williams 1985), which argues against the idea of a weak geomagnetic field during deposition.

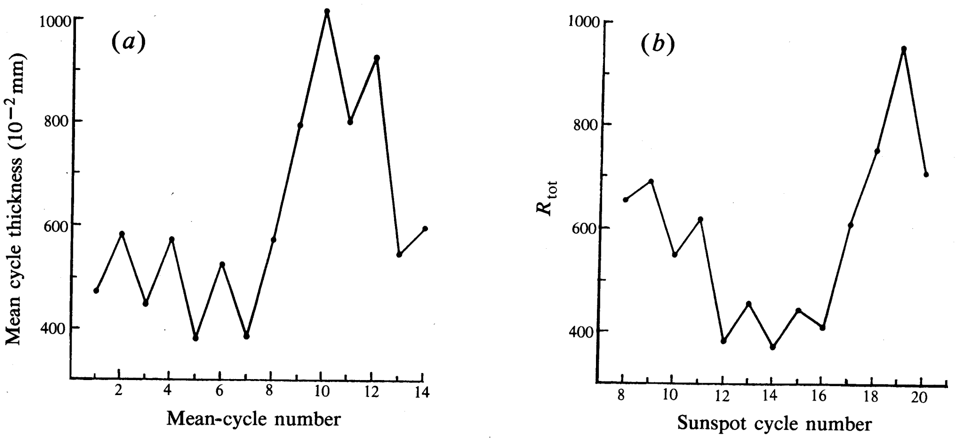
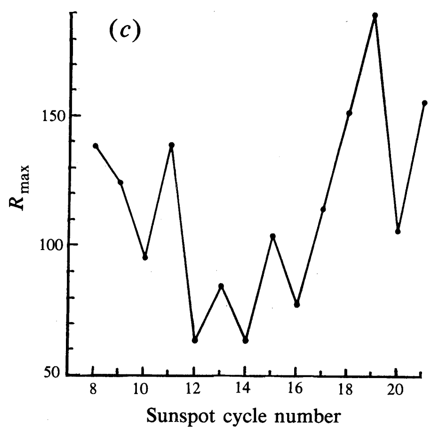


Fig. 10. Comparison of amplitude curves for ~12 'year' cycles and sunspot cycles showing (*a*) mean of five amplitude peaks from the Elatina long sequence (centred around cycle numbers 89, 176, 855, 1196 and 1250) across which the phase of the sawtooth pattern is maintained (a 'mean peak' was determined to reduce random noise in the geological data); (*b*) total annual mean sunspot number R_{tot} for sunspot cycles since A.D. 1830; (*c*) annual mean sunspot number R_{max} at maxima of sunspot cycles since A.D. 1830.



An alternative idea that warrants computer simulation is that greatly enhanced solar influence on the Precambrian climate resulted from a much smaller oxygen content of the Precambrian atmosphere compared with now. Cloud (1983) calculated a value between 1% and 7% of the present atmospheric level of O_2 ~2000–670 million years ago. Such a small oxygen content would have resulted in a greatly reduced height of the atmospheric ozone layer compared with that of today, as solar UV radiation would then have penetrated more deeply into the atmosphere before being absorbed. Changes of local O_3, possibly due to variations in solar UV flux, might then have directly influenced ground-level temperatures. By this means the solar activity cycle may have exerted a much greater influence on ground-level temperatures during the Precambrian era than now occurs. Actually, a weak solar influence on glacial climate and glaciolacustrine sedimentation may still occur today, as analysis of a 236-year varve sequence from Skilak Lake, Alaska, has revealed solar periods and other features in accord with the Elatina time-series (Sonett and Williams 1985*a*).

The Elatina record, in view of its clarity and great length, may provide invaluable data upon which to model the physics of the solar activity cycle. For example, the suggestion (Williams 1983*b*) that the cycle doublet of alternate high and low amplitude maxima may be an inherent feature of solar activity is supported by the new Elatina data presented here. An explanation of the solar sawtooth pattern is the alternately additive and subtractive effect of a relict magnetic field within the Sun on the alternating solar magnetic cycle (Levy and Boyer 1982; Boyer and Levy 1984; Sonett 1984*a*). This idea appears inconsistent, however, with the episodic 180° phase-reversals in the Elatina sawtooth curve, as it is difficult to perceive a relict magnetic field regularly reversing polarity. As discussed above, the pattern is explicable as a beat between two oscillations with periods near 2 cycles. The Elatina 'harmonic series' and the frequency modulation of the ~12 'year' cycle may hold clues to additional solar processes (Sonett and Williams 1985*b*). The application of the Elatina record to solar physics is further discussed by Bracewell (1985).

The Elatina data also may allow prediction of the relative amplitude and duration of future solar activity cycles. If the solar maximum of A.D. 1957 is equated with the ~26-cycle maxima in the Elatina Cycle (Fig. 10), the observed amplitude and frequency modulations of the ~12 'year' cycle suggest that future solar activity cycles will display the following features:

(i) An overall sawtooth decline in relative amplitude into a deep trough over the next 9 or 10 cycles (see Williams 1983*b*).

(ii) A 180° phase-reversal in the sawtooth pattern probably within the next few cycles. This feature is predicted because the last 13 solar cycles have maintained the phase of the alternating high–low amplitude pattern, and the mean duration between phase-reversals in the Elatina record is 14·6 (~12 'year') cycles.

(iii) An overall increase in the duration of the solar activity cycle to a value exceeding the mean for the past hundred years, to accompany the decline in relative amplitude.

Ancient annually layered rocks, particularly those of Precambrian age, thus should be viewed as potential solar observatories that may provide valuable data to solar physics and planetary science. That the rich Elatina record is now available for such application is due in no small measure to the perception and enthusiasm of R. G. Giovanelli.

Acknowledgments

I thank the Trustees of the CSIRO Science and Industry Endowment Fund for sponsoring the diamond drilling of the Elatina Formation; Mr L. Kinnear and Mr G. Stokes for permission to carry out the drilling on their property; Dr C. P. Sonett and Mr T. Trebisky, Lunar and Planetary Laboratory, The University of Arizona, for valuable assistance with the time-series analysis; Dr W. Robinson, Head, Laboratory of Tree-ring Research, The University of Arizona, for a temporary appointment and use of facilities; and the National Solar Observatory, Tucson, Arizona, for a Visiting Scientist appointment. I am grateful also to Drs L. Cram, R. Loughhead, C. Durrant,

W. Livingston, J. Goad, R. Jokipii, L. Hood, F. Herbert, D. Hunten, A. Skumanich, R. Bracewell, P. Foukal and C. Farrelly for helpful discussions on various aspects of the work. My four months' research at The University of Arizona in 1984 was supported by a grant from the U.S. National Science Foundation.

References

Boyer, D. W., and Levy, E. H. (1984). *Astrophys. J.* **277**, 848–61.

Bracewell, R. N. (1985). *Aust. J. Phys.* **38**, 1009–25.

Cloud, P. (1983). *Geol. Soc. Am. Mem.* **161**, 245–51.

Cohen, T. J., and Lintz, P. R. (1974). *Nature* **250**, 398–400.

Cullen, C. (1980). *Nature* **283**, 427–8.

Ding Youji, Luo Boarong, and Feng Yongming (1983). *In* 'Weather and Climate Responses to Solar Variations' (Ed. B. M. McCormac), pp. 545–57 (Colorado Associated University Press: Boulder).

Eddy, J. A. (1976). *Science* **192**, 1189–202.

Embleton, B. J. J., and Williams, G. E. (1985). Low palaeolatitude of deposition for late Precambrian periglacial varvites in South Australia: implications for palaeoclimatology. *Earth Planet. Sci. Lett.* (in press).

Giovanelli, R. G. (1984). 'Secrets of the Sun' (Cambridge Univ. Press).

Herman, J. R., and Goldberg, R. A. (1978). 'Sun, Weather, and Climate' (NASA: Washington, D.C.).

Howard, R., Gilman, P. A., and Gilman, P. I. (1984). *Astrophys. J.* **283**, 373–84.

Levy, E. H., and Boyer, D. (1982). *Astrophys. J.* **254**, L19–22.

Mörner, N.-A. (1984). *In* 'Climatic Changes on a Yearly to Millennial Basis' (Eds N.-A. Mörner and W. Karlen), pp. 1–13 (Reidel: Dordrecht).

Perkins, J. A., and Sims, J. D. (1983). *Quat. Res. (New York)* **20**, 308–21.

Smith, N. D. (1978). *Can. J. Earth Sci.* **15**, 741–56.

Sonett, C. P. (1982). *Geophys. Res. Lett.* **9**, 1313–16.

Sonett, C. P. (1984*a*). *Nature* **306**, 670–3.

Sonett, C. P. (1984*b*). *Rev. Geophys. Space Phys.* **22**, 239–54.

Sonett, C. P., and Williams, G. E. (1985*a*). Solar periodicities expressed in varves from glacial Skilak Lake, southern Alaska. *J. Geophys. Res.* (in press).

Sonett, C. P., and Williams, G. E. (1985*b*). Frequency modulation and stochastic variability of the Elatina varve sequence and the solar activity cycle (in preparation).

Treut, H. Le, and Ghil, M. (1983). *J. Geophys. Res.* **88**, 5167–90.

Waldmeier, M. (1961). 'The Sunspot-Activity in the Years 1610–1960' (Schulthess: Zürich).

Williams, G. E. (1981). *Nature* **291**, 624–8.

Williams, G. E. (1982). Solar-climatic cycles in the geological past: proposal for diamond-drilling the Elatina Formation (ca. 680 million years old), South Australia. Report to Trustees of the CSIRO Science and Industry Endowment Fund, Canberra, January 1982 (unpublished).

Williams, G. E. (1983*a*). Solar-climatic cycles in the geological past: report on diamond-drilling the Elatina Formation, Pichi Richi Pass, South Australia. Report to Trustees of the CSIRO Science and Industry Endowment Fund, Canberra, January 1983 (unpublished).

Williams, G. E. (1983*b*). *In* 'Weather and Climate Responses to Solar Variations' (Ed. B. M. McCormac), pp. 517–33 (Colorado Associated University Press: Boulder).

Williams, G. E., and Sonett, C. P. (1985*a*). Periglacial varve-cycles in the late Precambrian Elatina Formation, South Australia. *In* 'Ice Cores, Varves and Tree-Rings' (Eds D. J. Schove and R. W. Fairbridge) (Balkema: Rotterdam) (in press).

Williams, G. E., and Sonett, C. P. (1985*b*). Solar signature in sedimentary cycles from the late Precambrian Elatina Formation, Australia. *Nature* (in press).

Williams, G. E., and Tonkin, D. G. (1985). Periglacial structures and palaeoclimatic significance of a late Precambrian block field in the Cattle Grid copper mine, Mount Gunson, South Australia. *Aust. J. Earth Sci.* **32** (in press).

Wilson, R. M. (1984). A comparative look at sunspot cycles. NASA Tech. Paper No. 2325.

Manuscript received 9 April, accepted 13 September 1985