PERIODICITIES IN STROMATOLITE LAMINATION FROM THE EARLY PROTEROZOIC HEARNE FORMATION, GREAT SLAVE LAKE, CANADA

by CHRISTOPHER B. JONES

ABSTRACT. Stromatolites from the Hearne Formation exhibit several orders of finely preserved laminae. This lamination has previously been interpreted in terms of daily, fortnightly, monthly, and annual periodicities, the ratios of which have been used to estimate a past rate of the Earth's rotation. Parallels between Hearne Formation stromatolites and certain Recent algal mats suggest, however, that the finest Hearne Formation laminae may reflect episodes of storm sedimentation, while the second order of lamination represents seasonal maxima in algal productivity. Visual measurements of periodicity are generally unreliable, but as adjacent laminae are mineralogically differentiated, the sequence of accretion can be recorded quantitatively by electron microprobe analysis. The chemical measurements demonstrate the antithetic relationship of Mg to Ca, Si and Al. Mg is interpreted as representing originally organic (blue-green algal) rich laminae, whereas the other three elements represent laminae originally dominated by detrital matter. Fourier spectral analysis reveals a strong second-order periodicity in Mg and Al, though with opposite phase, indicating that Al is broadly representative of the inorganic fraction of lamination. Selective filtering of the Mg time series allows first- and second-order variations to be highlighted separately, and the average ratio of the two orders, counted as peaks in the filtered time series, is found to be about seven.

THE inherently cyclic nature of the lamination in many ancient stromatolites has led to several attempts to interpret particular cyclic sequences in terms of their contemporary geophysical periodicities, such as the day, month, and year, and hence to infer values for the past rates of the Earth's rotation (McGugan 1967, Pannella *et al.* 1968, Pannella 1972*a*, 1972*b*, Mohr 1975). In the case of carbonate stromatolites the justification for these interpretations has been based on a combination of the fact that daily, tidal (semi-daily), and seasonal lamination has been described in certain Recent stromatolite forming environments (Monty 1967, Gebelein 1969, Gebelein and Hoffman 1968, Davies 1970) and the assertion that, in the fossil stromatolites, laminae are grouped together in numbers which are indicative of fortnightly and monthly periodicities (Pannella 1975). However, none of the studies of the Recent algal mats and domes actually describes daily or tidal laminae grouped in numbers equivalent to the present number of days or tides in a fortnight, a month, or a year. In the instances of Recent lamination where there is some form of clustering of one scale or order of lamination to give rise to another, the second order has been described as annual or seasonal (Davies 1970, Park 1973). Park, in his carbon 14 study of lamination in buried algal peat of the Trucial Coast, was able to demonstrate that daily lamination was not preserved at all, and that the laminae which were preserved reflected events of storm sedimentation occurring with a frequency of three to five per year. In a study of millimetre-scale lamination in algal domes in north-west Andros Island, Hardie and Ginsburg (1977) came to a similar conclusion, finding that the very resilient, laterally continuous laminar couplets were the product of storm sedimentation with an average frequency of three per year, whereas daily tidal covering produced no detectable lamination. In the light of these results from Recent stromatolites, considerable caution should be exercised in attempting to identify daily, fortnightly, and monthly cycles in fossil stromatolites.

[Palaeontology, Vol. 24, Part 2, 1981, pp. 231–250.]

There is a problem in measuring the identified cycles in a repeatable way. The results published by Pannella (1972*a*, 1975) were obtained by visual identification of laminar features, though it has been found by Hipkin (1972) and Jones (1976) that the results of visual counting procedures can be grossly divergent if repeated by more than one observer. If, as Pannella states (1975, p. 257), temporal interpretations in stromatolites are usually based on 'numerological relationships', there is a danger that the expectation of finding a particular numerical relationship will bias the procedure of measurement. In an effort to define the cyclic properties present in examples of rhythmic stromatolite lamination, material was collected for study from the early Proterozoic Hearne Formation (Pethei Group, Great Slave Supergroup) in the east arm of Great Slave Lake. Because of the uncertainties in the visual feature counting method of analysing periodicity, and the difficulty of relating the results to current knowledge of the growth and preservation of stromatolite laminae, an alternative approach has been adopted, in which conventional petrographical observations are supplemented by measurements of the chemical composition of the laminae. By making electron microprobe traverses recording the concentrations of several elements along the sequence of lamination, it is possible to describe variations in mineral composition which, because of the often very fine grain sizes, are not apparent through normal petrographical techniques. These measurements also provide a means of representing the sequence of accretion in a form which can be subjected to quantitative tests for periodicity.

GEOLOGICAL SETTING OF THE HEARNE FORMATION

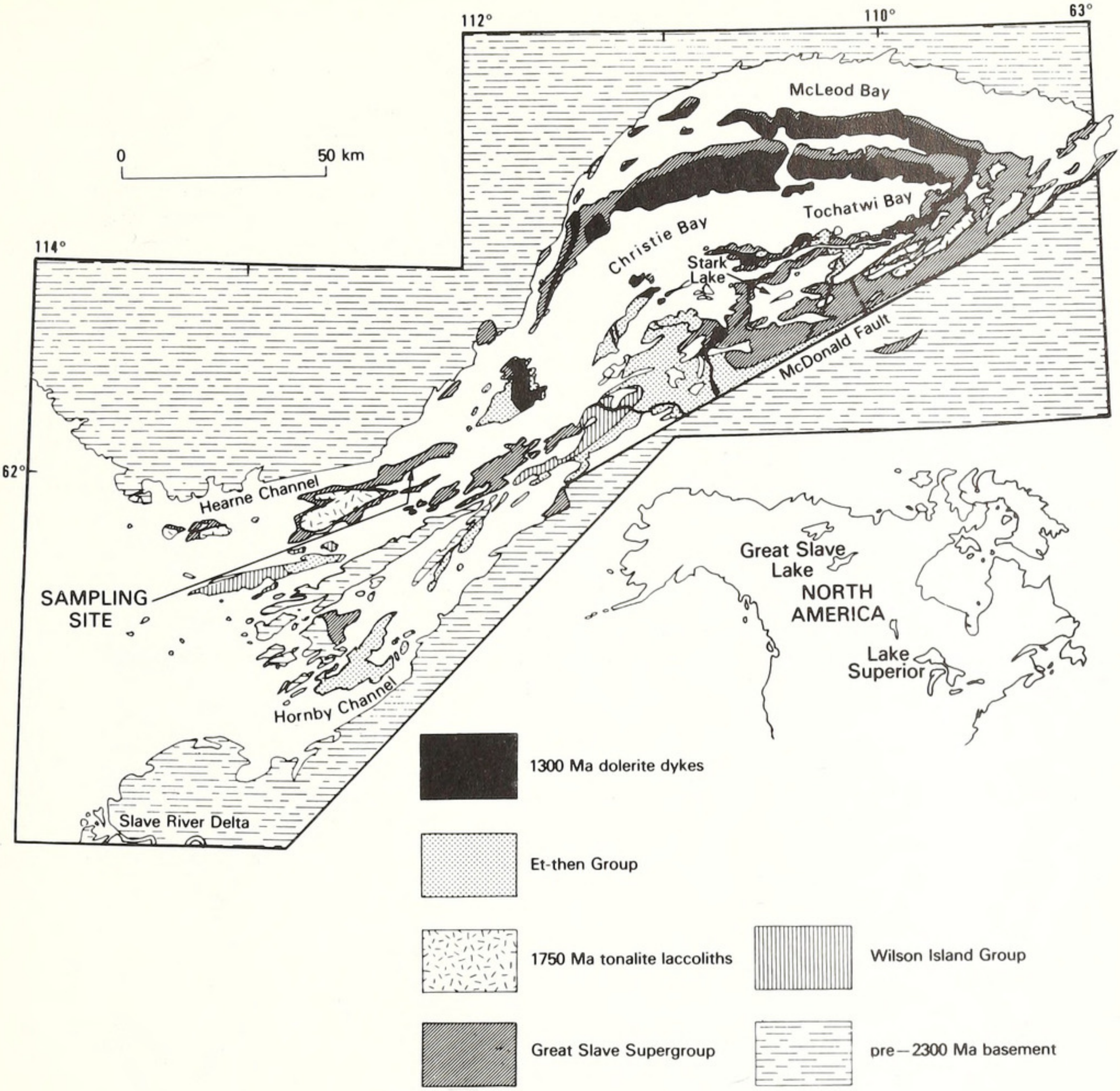
The Hearne Formation is exposed on Blanchet Island in the east arm of Great Slave Lake (text-fig. 1), which is eroded into the younger, post-2300 ma Precambrian basement. It consists of about 100 m of limestone and dolomite at the top of the Pethei Group, which is dated between 1795 and 1872 ma and formed part of the deeply subsided, fault-bounded Great Slave basin which is connected to the Coronation Geosyncline (Hoffman, 1973, 1974). The group is interpreted as an alternation of platform-shoaled and platform-submerged facies in a 400 m thick cratonic sequence, which extends laterally into a 600 m trough sequence of stromatolites, basin-floor and greywacke-turbidite facies. The material studied was collected from a 3 m bed at the top of the Hearne Formation, exposed on the south-east facing shore of the northern part of Blanchet Island. Hoffman (1968) interprets the Hearne Formation in general as having been deposited in a permanently submerged (back-reef lagoon) site, but his facies diagrams (1973, 1974) indicate that the sampled stromatolite bed may be interpreted as having been at least intermittently exposed.

MORPHOLOGY, PETROGRAPHY AND STRUCTURE OF THE LAMINATION

The sampled bed consists of laterally-linked laminated domes which are approximately equilaterally triangular in horizontal cross-section (text-fig. 2) and are chiefly composed of limestone, dolomite, and quartz. The laminae are usually more steeply dipping and limestone-rich on one of the three sides. The diameter and synoptic relief (of individual laminae) of the domes vary between about 2 and 10 cm. In thin section the lamination is defined texturally by an alternation of dark, fine-grained, equigranular micrite and microspar layers and pale, coarse, equigranular, spar and microspar layers (text-fig. 3). The dark, fine-grained laminae are generally rich in dolomite, while the pale coarser laminae are composed of a mixture of calcite, quartz, and dolomite, with minor muscovite (?illite). Where individual grains can be resolved in the dark laminae, they are subhedral to euhedral carbonate rhombs, up to about 5 to 30 μm in diameter and dull brown-green at low magnification, but mottled grey at high magnification. The pale laminae are colourless to pale brown in colour at low magnification.

Carbonate grains range in size from about 40 to 200 μm diameter and are usually subhedral or euhedral. Dolomite rhombs 80 to 100 μm in diameter are common and coarser-grained dolomite occurs in veins which are often parallel to the lamination. Fine-grained carbonate, of similar grain size to that composing the adjacent dark laminae, is patchily present in the pale laminae often extending from the dark laminae.

Quartz is frequently interstitial to the carbonate and with grain sizes between 15 and 30 μm diameter. It is anhedral to subhedral and equigranular, and the grains often exhibit wavy extinction under crossed nicols. In the calcite rich sequences of lamination the quartz makes up less than 20% of the pale laminae, whereas in the calcite poor sequences it may compose up to 40%. Locally, in particular near the axes of the domes,



TEXT-FIG. 1. Geological map of east arm of Great Slave Lake, showing sampling locality.

almost the total composition of the pale laminae may be quartz, which may also be coarser grained at such sites than elsewhere. In the finer-grained zones of lamination the quartz is not easy to distinguish as such, since its first-order grey interference colours can be mistaken for the pale high-order colours of the carbonates. Its full volumetric significance in these stromatolites was only appreciated in the light of the microprobe analysis (see below).

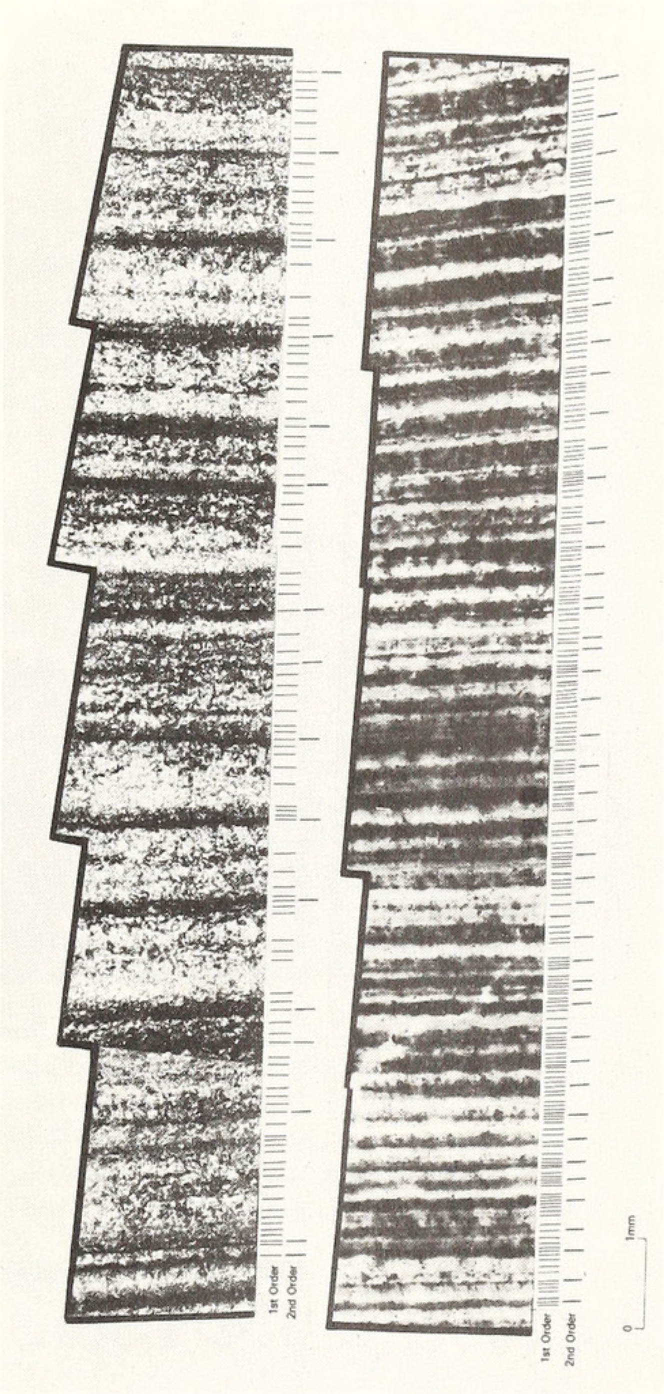
Haematite occurs as a pervasive micrite grade dust, and in granules, often up to 50 μm in diameter. It tends to be concentrated in the finest grained laminae (though this is not invariably the case), and hence the predominantly fine-grained sequences of lamination are also deeply pigmented.

The finest order of lamination consists of couplets of light, coarse-grained and dark, fine-grained laminae, each of which is between 30 and 300 μm thick. It is normally the case that where laminae of this scale are visible they occur in sequences in which either light or dark laminae predominate such as to give rise to an

TEXT-FIG. 2. Horizontal erosion surface across Hearne Formation stromatolites on Blanchet Island at 62 05 20 N., 112 08 00 W., ×0·2. Reproduced by courtesy of the Geological Survey of Canada.

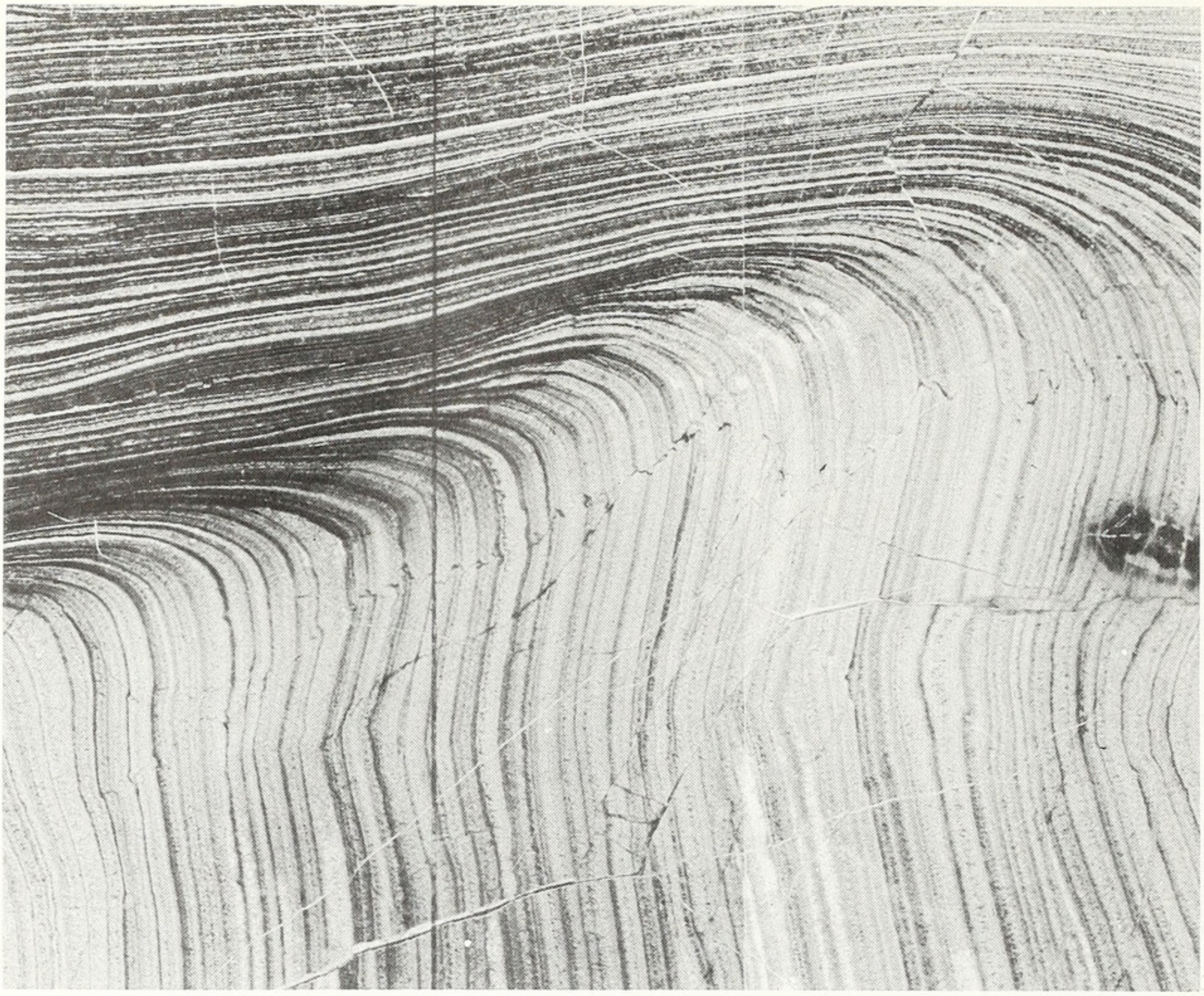
alternation of predominantly light and predominantly dark second-order laminae. Each of these second-order laminar couplets can usually be subdivided into between three and twelve first-order laminae (text-fig. 3). The thickness of these second-order laminae varies between about 0·2 and 1·0 mm and it is this scale of lamination which weathers out most clearly and is most easily identified in hand specimen. Variations in thickness of second-order laminae occur laterally and vertically and are particularly marked at the angles of the dome structures where the second-order laminae in the condensed and expanded parts of the dome may vary in thickness by up to a factor of four (text-figs. 4, 5). The thinner second-order laminae usually coincide with the finer-grained parts of the rock. For example, second-order laminae up to 1 mm thick with spar and microspar texture (text-fig. 3A) may be contrasted with a finely micritic sequence with second-order laminar couplets averaging about 0·3 mm in thickness (text-fig. 3B).

In the direction of accretion, variations are found in the ratio of the thickness of the pale- and the dark-coloured portions of the second-order couplets, in addition to the variations in their combined thickness. Grain size differences between the light and dark parts of a couplet may be quite considerable in the more expanded sequences (text-fig. 3A) or very slight (text-fig. 3B) in which colour differences (due especially to haematite) are nevertheless distinct. The relationship between adjacent light and dark laminae is also variable in that there may be a gradation or an abrupt boundary. Where there is a gradation, which is normally in terms of grain size and colour, the direction of fining is not consistently the same in the sequence. In many of the thin sections studied these variables combine to form sequences of lamination in which the same structure (in terms of thickness and texture) of second-order lamination rarely recurs consecutively more than five or six times (text-figs. 5, 6). Differing from this complexity are specimens (text-fig. 7) in which second-order laminae are clearly and simply defined, and their structure fairly uniform over a long sequence of lamination. The light and dark portions of these second-order couplets are usually approximately equal in thickness. The density of micrite (accompanied by haematite) in these sequences may, however, vary more or less regularly with sharp boundaries, at a scale of between 5 and 20 mm. These latter variations (visible in text-fig. 7) may be classified as a third-order of lamination. It is noticeable that the very regular lamination occurs in a relatively condensed and micrite-rich sequence. The complexities of some of the other lamination, however, are due to major differences in quantity and distribution of the coarse-grained fractions, from one laminae couplet to the next, rather than the micrite fractions which maintain a fairly uniform pattern.



A B

TEXT-FIG. 3. Photomicrographs of Hearne Formation stromatolite lamination showing 'expanded' (A, GSM 77318) and 'condensed' (B, GSM 77324) sequences. Ticks indicate possible visual identifications of the first- and second-order lamination.

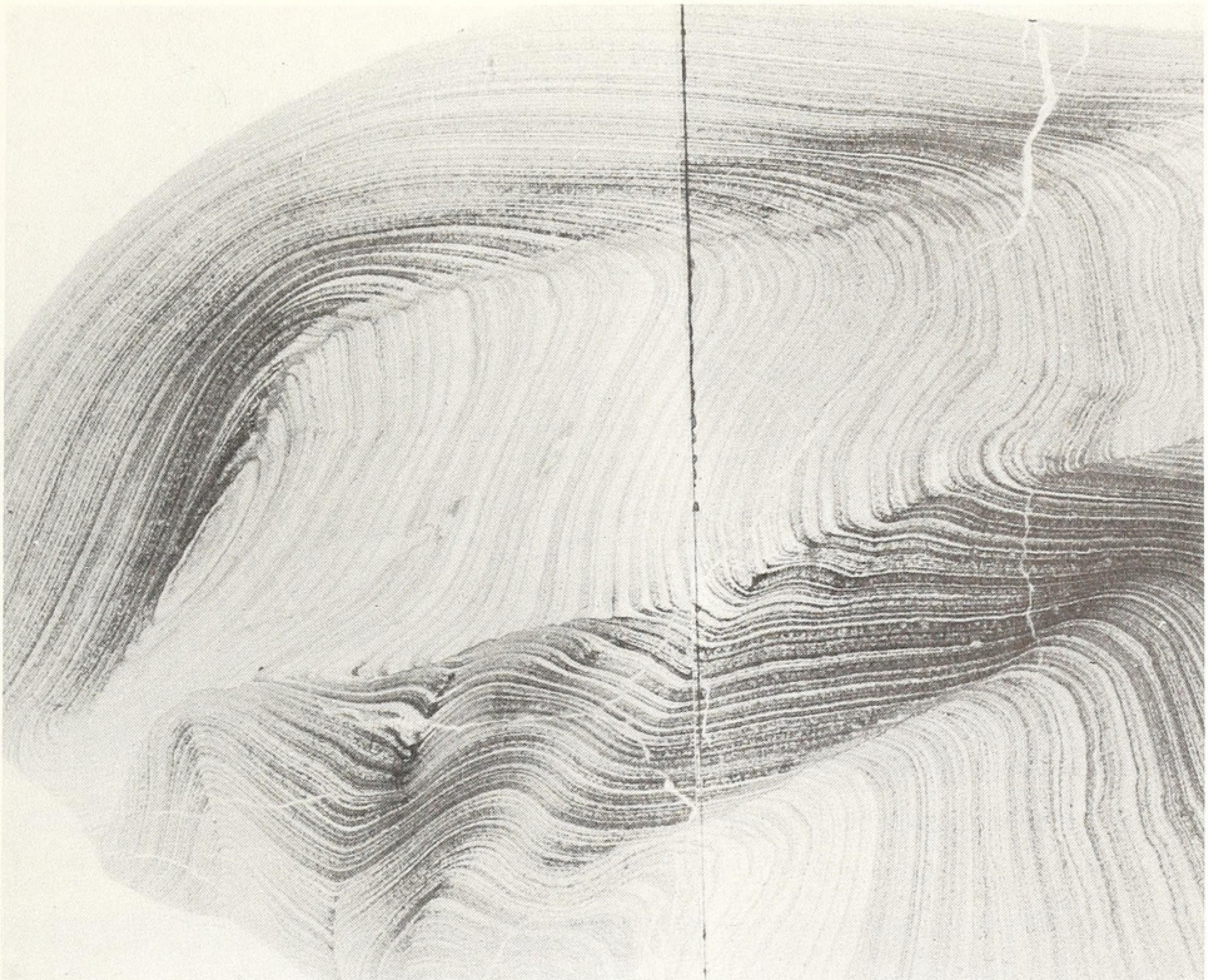


TEXT-FIG. 4. Thin section of Hearne Formation stromatolite (GSM 77326) illustrating a relatively irregular sequence of lamination. The thick, coarse laminae are interpreted as the product of efficient sediment trapping on one side of a dome. The intervening dark laminae may represent quiescent episodes of algal growth. $\times 1{\cdot}6$.

MICROPROBE ANALYSIS

Microprobe traverses recording the variations in the concentrations of some or all of the elements Mg, Ca, Si, Al, and Fe, were made perpendicular to the lamination of six specimens from the Hearne Formation. These elements correspond principally to the presence of dolomite (Mg), calcite and dolomite (Ca), quartz and muscovite (Si), muscovite (Al), and haematite and dolomite (Fe).

Methods. Specimens for analysis were cut either into 2 mm thick slabs or into approximately 30 μm thick glass-mounted thin sections. These were polished with progressively finer grades of diamond paste before being coated with an electrically conducting carbon film. The microprobe used was a Cambridge Geoscan with two spectrometers from which measurements could be recorded manually, by reading the counts over a pre-set period of time on the digital display, or automatically on the chart recorder. In order to measure chemical variations along a traverse on the specimen, either of the methods of spot counting or continuous recording were used. The former method required that counts per selected period of time be recorded at equally spaced intervals on the specimen, which was moved manually, referring to the co-ordinates on the specimen control carriage. In the continuous-recording, or scanning, method the specimen was moved on the specimen stage by motors. Because of the considerable tedium of spot counting (a 1 cm traverse sampled at

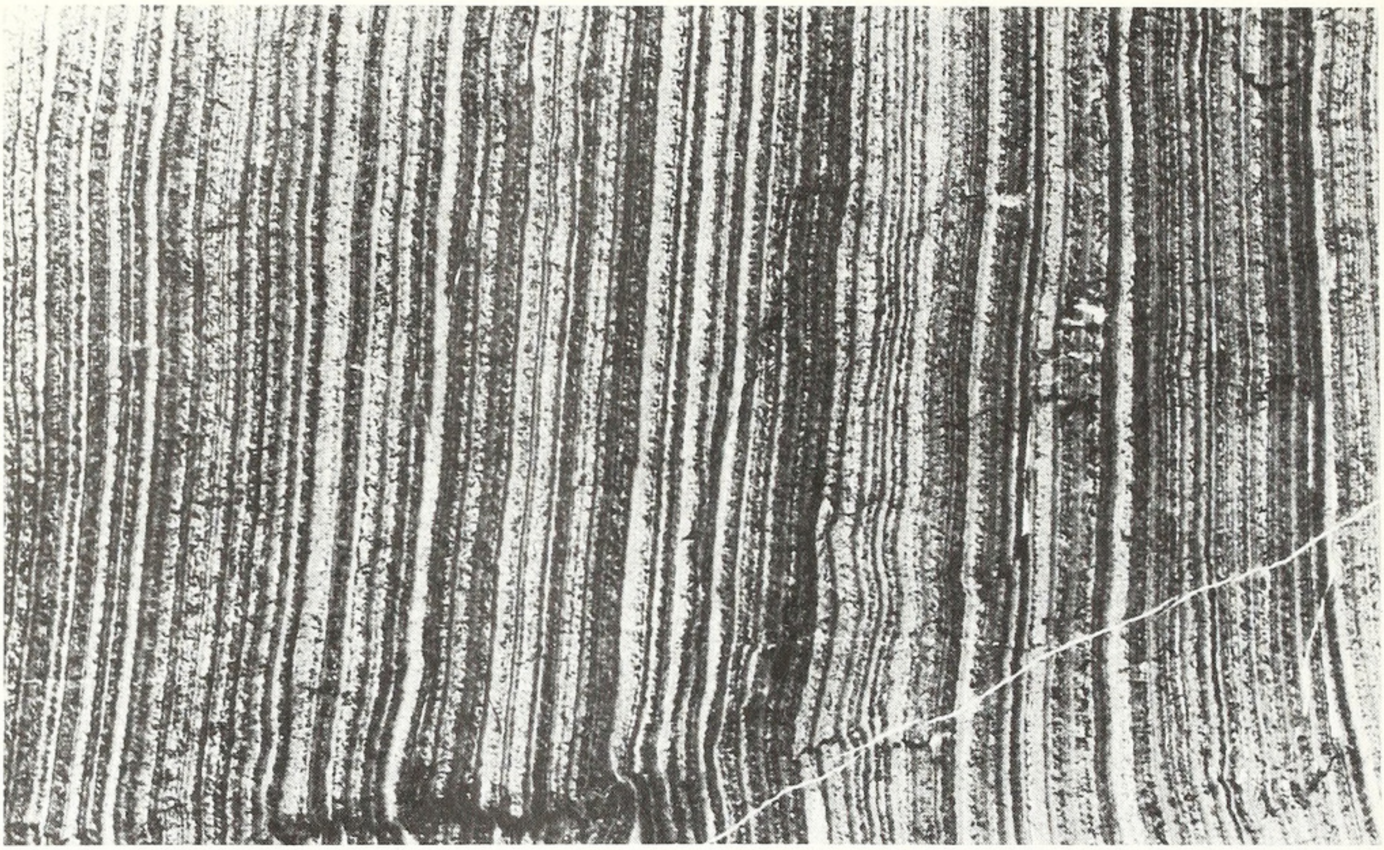


TEXT-FIG. 5. Thin section of Hearne Formation stromatolite (GSM 77317) illustrating the relationship between 'condensed' and 'expanded' sequences of lamination, $\times 1{\cdot}3$.

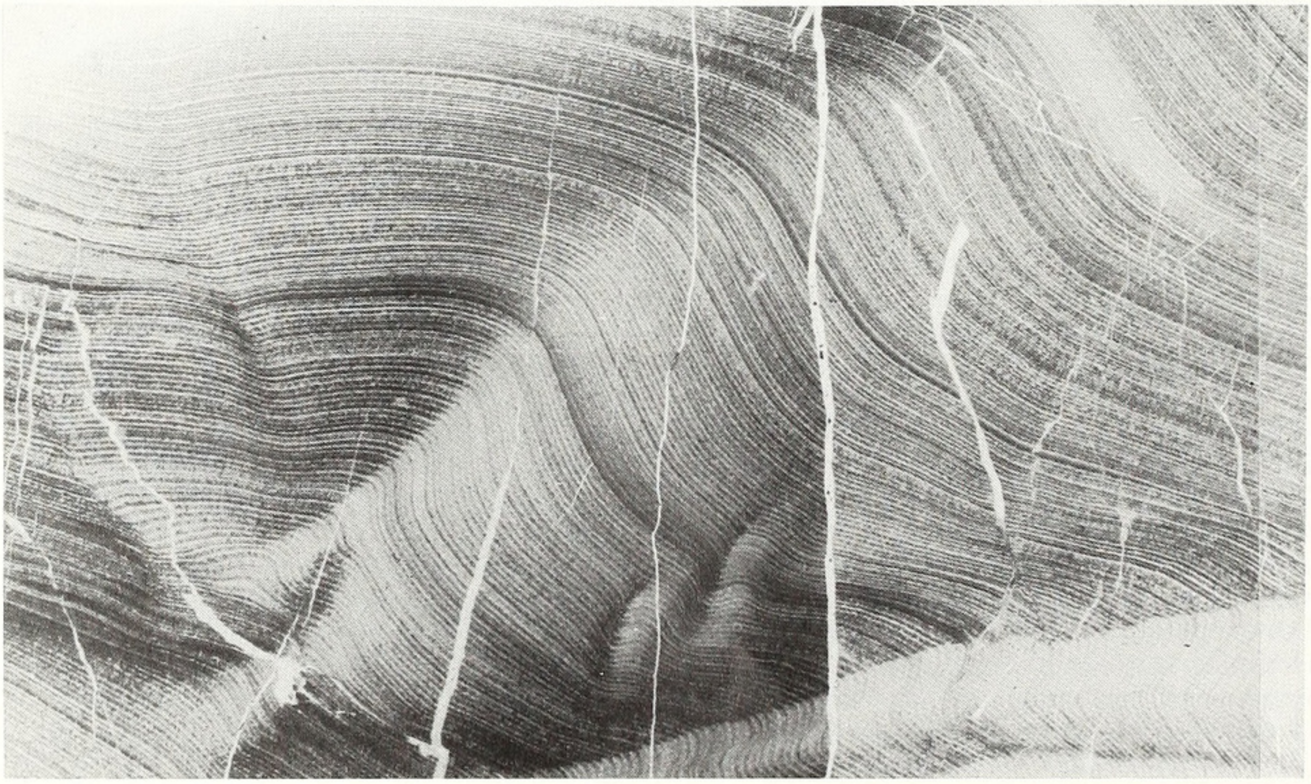
10 μm intervals would require 1,000 pairs of readings), most measurement was done automatically by means of the chart recorder trace from which the measurements were read subsequently in computer readable form with the aid of a Ferranti digitising table.

The only corrections made to the data before plotting (by means of a computer-linked plotter) and statistical analysis were background removal and the subtraction of a linear trend due to machine drift, as represented by readings on standard minerals at the beginning and end of each traverse. The importance of absorption, fluorescence, and atomic number corrections was assessed by calculations on selected results using the formulae of Salter (1970). Errors due to fluorescence and the atomic number correction were found to be less than 1%, while those due to absorption were much greater (up to 31% in the case of Mg). For the larger errors, however, the maximum difference in the size of the errors for different concentrations was only 5%, which would not make an important difference to the apparent variability of the chemical concentration. As the primary interest in making the chemical measurements was to observe the nature of variations in the concentrations rather than their absolute values it was not considered necessary to make the error corrections referred to above. It may be noted that the identification of cycles by Fourier analysis, used in this study, depends not on absolute values but on their variations about a mean.

The traverses were between about 8 and 15 mm in length and were normally made in sets of two or three along adjacent parallel lines, about 200 μm apart, in order to assess the lateral continuity of the variations within the lamination. Because two elements were recorded together in each traverse they are plotted together as an illustration of the relationships between the various elements.

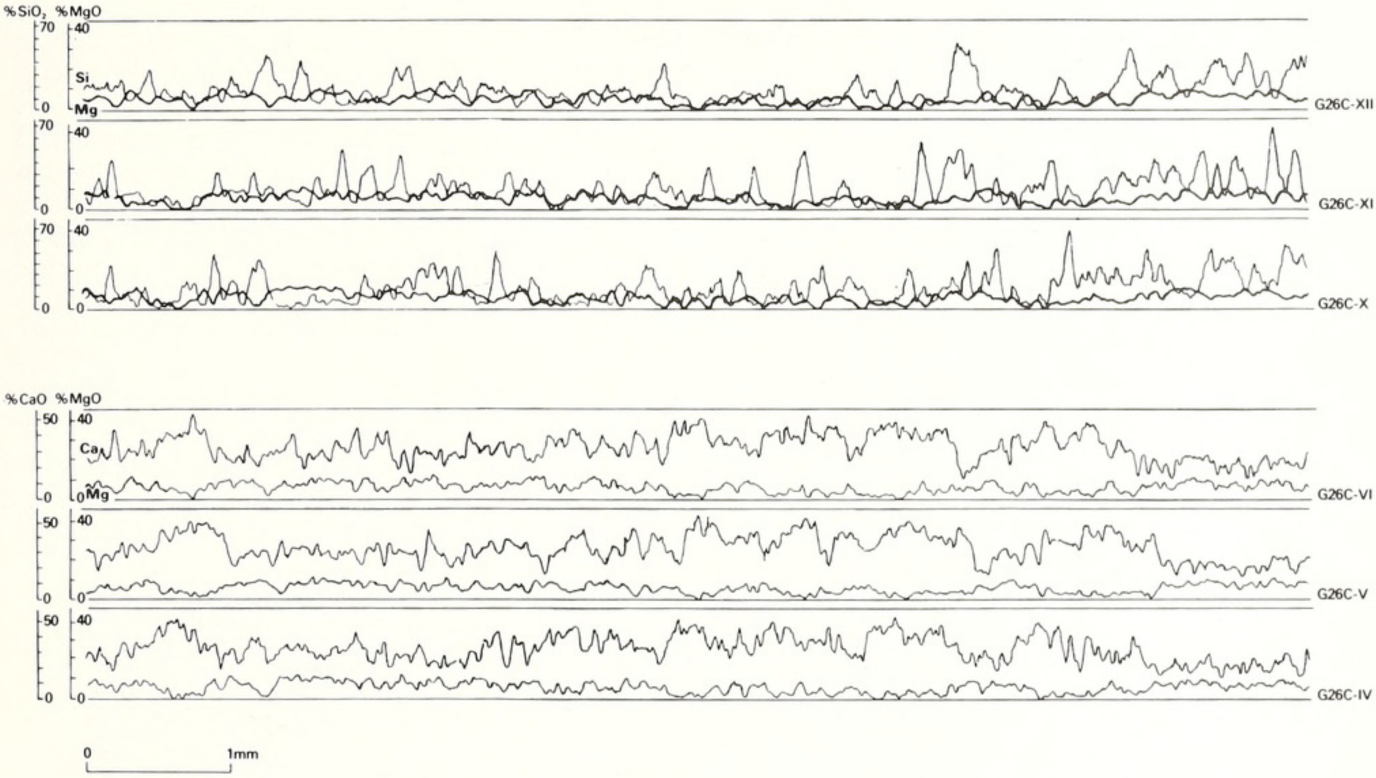


TEXT-FIG. 6. Thin section of Hearne Formation stromatolite (GSM 77329) showing changes in the pattern of lamination along a sequence, × 3·3.



TEXT-FIG. 7. Thin section of Hearne Formation stromatolite (GSM 77323) showing a very uniform development of micritic lamination, × 1·6.

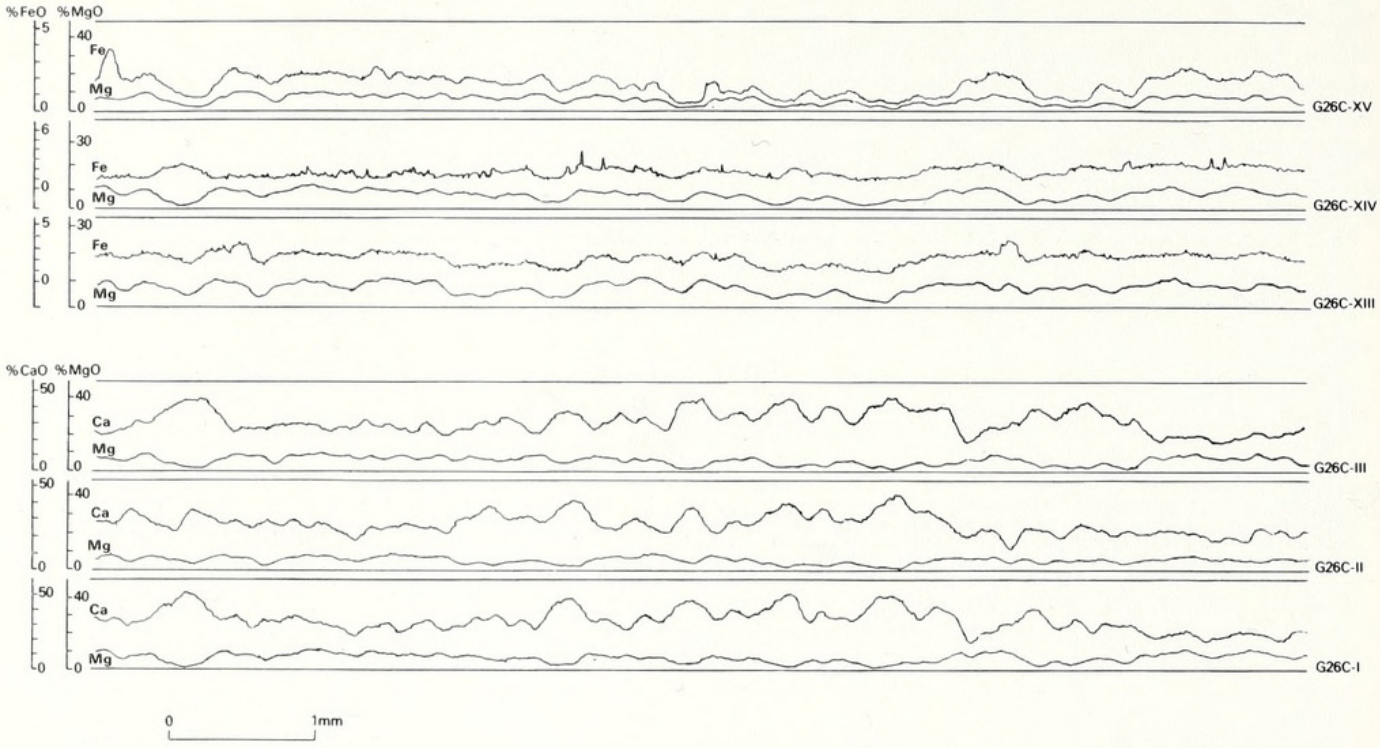
The ease with which adjacent parallel traverses can be correlated, and therefore the degree to which the chemical variations in the traverses may be said to be laminar properties of the specimens, was found to be closely related to the size and shape of the electron probe beam. Traverses made with a spot diameter of 30 μm or less are particularly difficult to correlate with each other, while with larger probe sizes the traverses appear more regular in their variation and more consistent from one to another. This can be attributed to the fact that the peaks in the traverses using the small spot sizes are related to individual mineral grains while, with their greater areal coverage, the larger probes produce traverses in which the peaks represent the association of adjacent mineral grains of a similar composition which characterize and define individual, at least partially continuous, laminae.



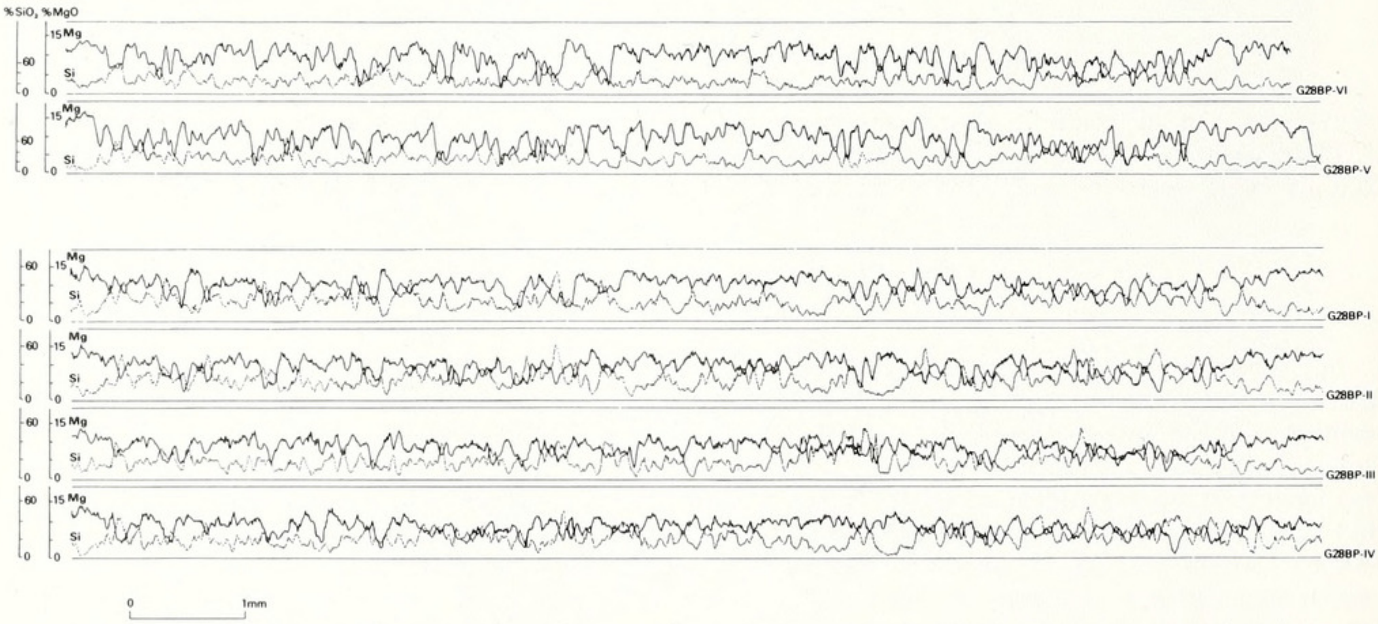
TEXT-FIG. 8. Parallel electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77322), recording the elements Si and Mg, and Ca and Mg. The traverses within each set of three are about 200 μm apart and employed a line probe of 200×40 μm oriented parallel to the lamination for the Ca/Mg traverses, and a round probe of 70 μm diameter for the Si/Mg traverses

In an attempt to increase the chances of recording such laminar continuity of mineral distribution, many traverses were made using a line probe oriented approximately parallel to the lamination. Illustrations which demonstrate the greater sensitivity of the line probe to the laminar structure are given in Rosenberg and Jones (1975). The use of a line probe of dimensions about 200 by 40 μm, which is comparable in width to the narrowest visible laminar couplets, results in traverses which are not simply correlated in their details, but which have broad peaks which are easily correlated (text-fig. 8). Traverses made with bigger lines, about 400 by 150 μm (text-fig. 9), emphasize the correlation of the broader peaks, while obscuring any variation which may represent smaller scale lamination. Information about the chemical nature of the lamination will be gained most economically by using a narrow line probe, since this will record both high and low frequency variations. The broader scale variation can then be examined by digital filtering of the high frequencies from the data ('smoothing' it) which has a similar effect to increasing the width of the line probe (text-fig. 16).

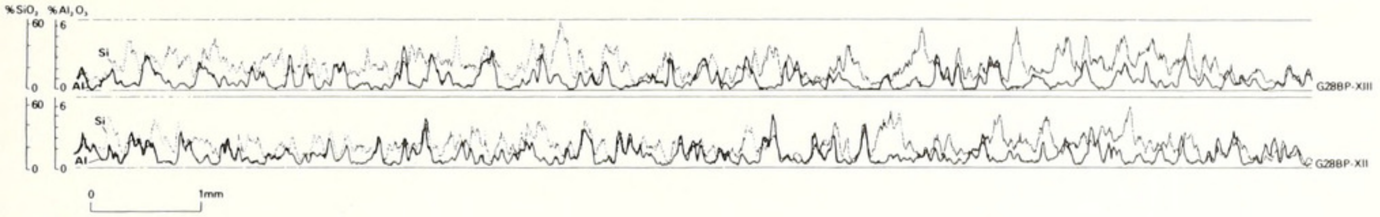
All the elements studied display major variations in their concentration along the length of the traverses. A consistent relationship is apparent between a number of the elements. Thus there is a uniformly negative



TEXT-FIG. 9. Parallel electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77322), recording the elements Fe and Mg, and Ca and Mg. The traverses within each set of three are about 500 μm apart and employed a line probe of dimension 400×150 μm oriented parallel to the lamination.



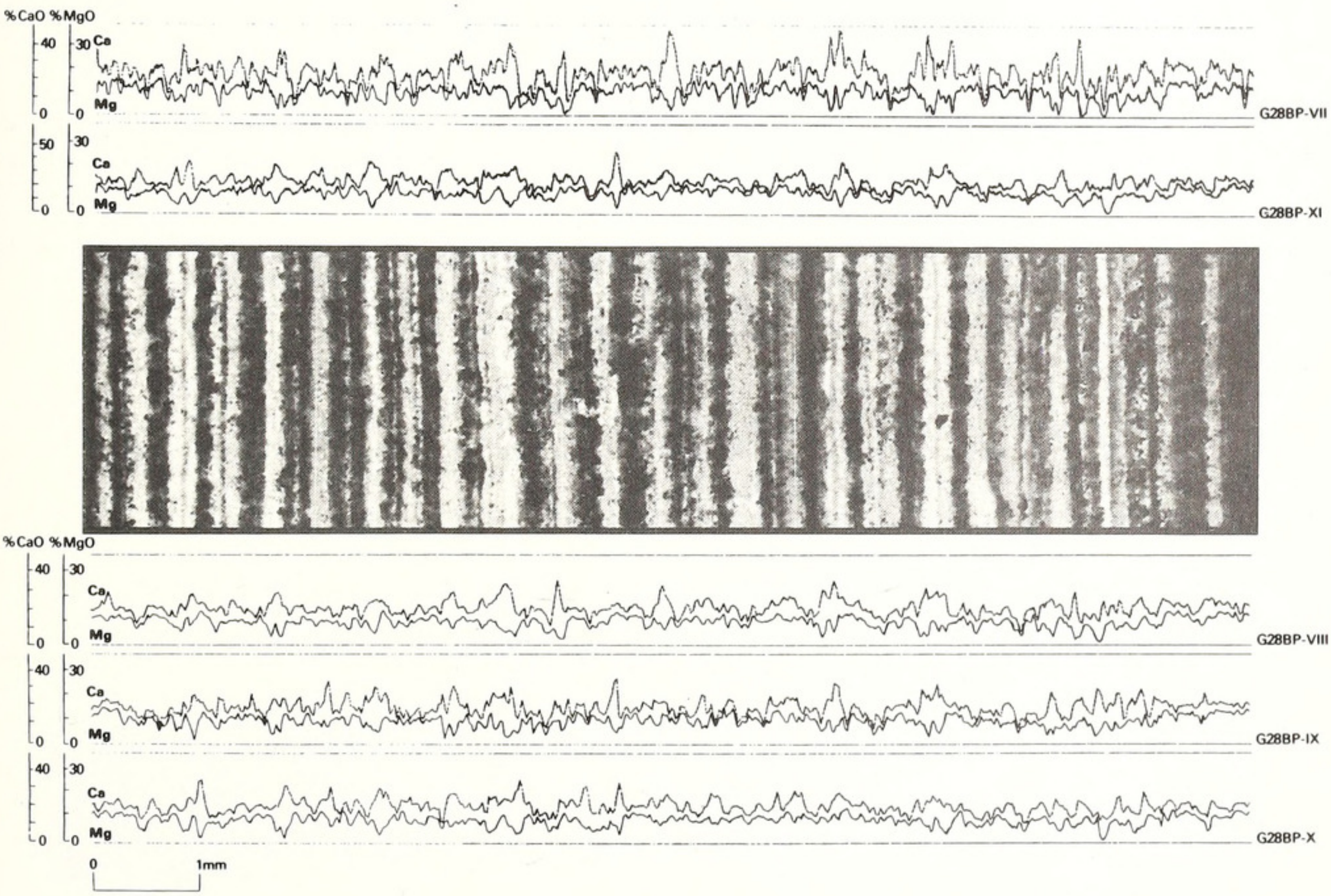
TEXT-FIG. 10. Parallel electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77325) recording elements Si and Mg. Traverses G28BP-I to IV employed a 200×40 μm line probe and are 200 μm apart from each other. Traverses V and VI employed a 40 μm diameter probe, and V was positioned between I and II, while VI was 300 μm away on the other side of traverse I.



TEXT-FIG. 11. Parallel electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77325) recording the elements Si and Al. The traverses employed a line probe of dimensions 200×40 μm oriented parallel to the lamination,

correlation between Mg and Si (text-figs. 8, 10), and usually between Mg and Ca (text-figs. 8, 9). Iron (text-fig. 9), though rather erratic, tends to correlate positively with Mg (i.e. as haematite, in addition to its presence in dolomite). Si and Al are also usually positively correlated (text-fig. 11).

Comparing graphs for the traverses for Si and Mg, and for Ca and Mg, with photographs of the laminae analysed, at the same scale, reveals a general association between Mg peaks and dark laminae, while Ca and Si peaks correspond sometimes with dark and sometimes, in general more frequently, with light laminae (text-figs. 12, 13). The relation between Mg and dark laminae is most consistent in the almost totally micritic specimen GSM 77325 (text-fig. 12), whereas exceptions often occur in the coarser grained GSM 77320



TEXT-FIG. 12. Electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77325) for the elements Ca and Mg, with a photomicrograph of the area of the traverses, to the same scale. Traverses G28BP-VIII, IX, and X employed a 200×40 μm line probe and were made by spot counting at an interval of 20 μm, while VII and XI were made directly on to a pen recorder trace, which was digitized at an interval equivalent to 6 μm. Traverses VII and XI employed 40 μm diameter and 200×40 μm probes respectively and were made along approximately the same line as VIII and X respectively.

(text-fig. 13), particularly in the case of coarse veins of dolomite visible in the latter. The antithetic relationship between Si and Mg is, however, maintained within the coarser grained specimen. In text-fig. 12 Ca appears in places to be positively correlated with Mg. In these situations Si is found to be relatively high in concentration, while the ratio of Ca to Mg is lower in the peaks than in the troughs so that there is still a limited antithetic relationship between Ca and Mg. Relating the peaks in the microprobe traverses to the visually identified laminae, it is apparent that the broader, lower frequency chemical variations are at a similar scale to what has previously been termed the second-order lamination, while the narrower, less consistently related peaks are comparable in scale to the first-order laminae. By means of Fourier spectral analysis, described below, it is possible, using a process of selective frequency filtering, to isolate these two types of variation for a particular element. The result of doing so for Mg is illustrated in text-fig. 16, in which the first-order and second-order variations are graphed separately.

SPECTRAL ANALYSIS OF MICROPROBE TRAVERSES

Cyclical properties of the microprobe traverses were investigated with the aid of Fourier analysis (see, for example, Jenkins and Watts, 1968). The method is essentially the same as is commonly used to identify the periodicities of geophysical data such as fluctuations in the geomagnetic field. Briefly, Fourier analysis consists of reducing a data series $s(t)$ of N sample points into a set of sine and cosine waves of varying frequencies w (specifically the harmonics 1 to m, where $m = (N-1)/2$) and amplitudes a and b, such that

$$s(t) = a_0/2 + \sum_{w=1}^{m} \{a_w \cos(2\pi wt/N) + b_w \sin(2\pi wt/N)\}$$

where

$$a_0 = (2/N) \sum_{t=1}^{N} s(t)$$

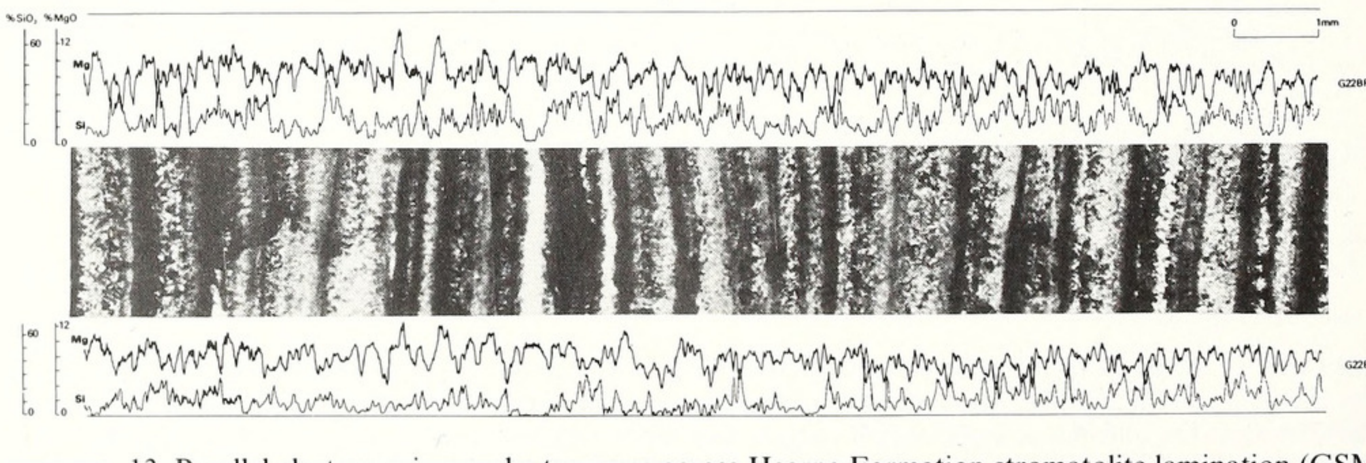
$$a_w = (2/N) \sum_{t=1}^{N} s(t)\cos(2\pi wt/N)$$

$$b_w = (2/N) \sum_{t=1}^{N} s(t)\sin(2\pi wt/N)$$

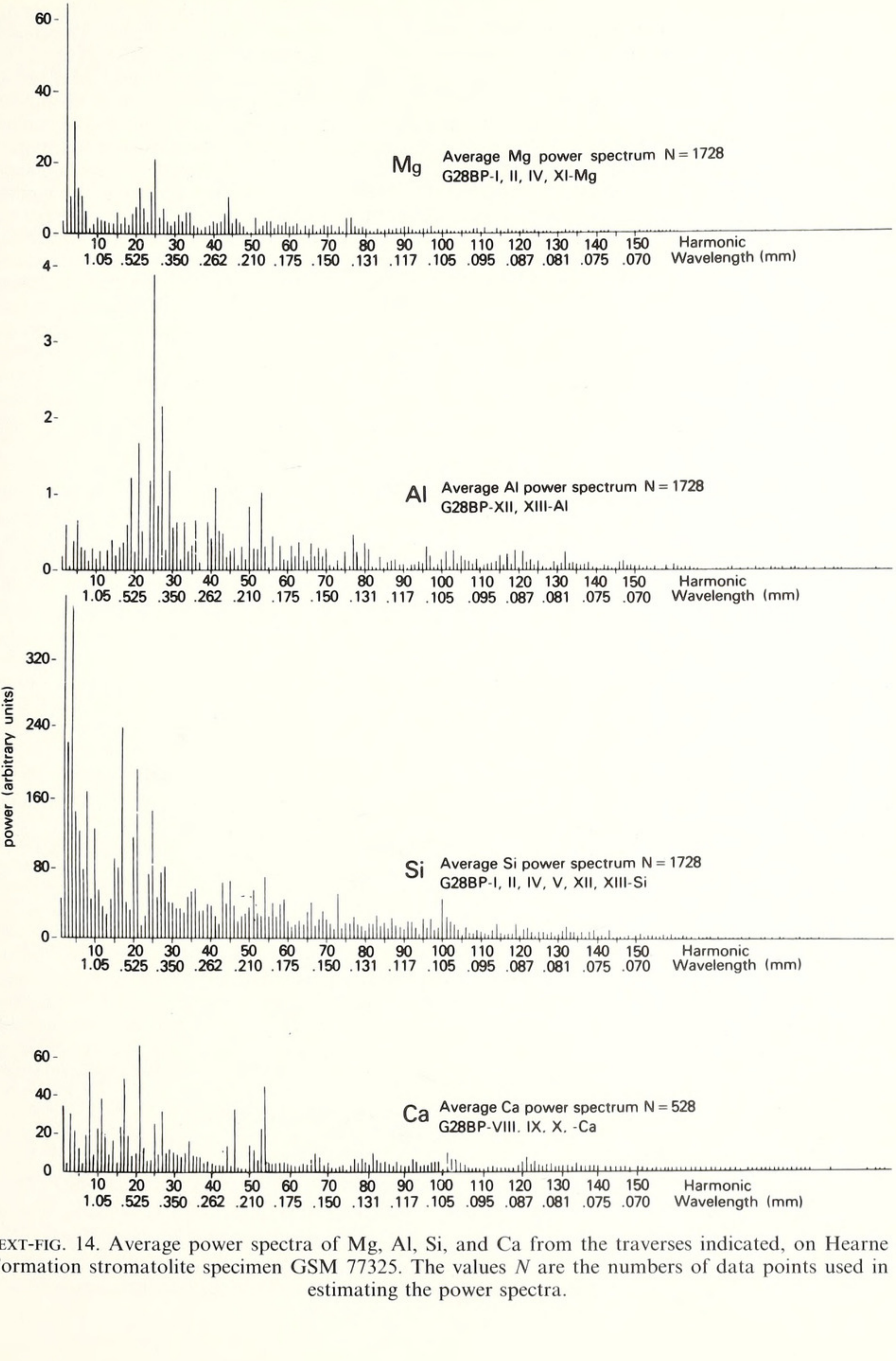
The variance contributed by the individual component frequencies may be assessed in terms of the power spectral function

$$C_w^2 = (a_w^2 + b_w^2)$$

The power spectra of all of the microprobe traverses figured here have been calculated with the aid of an algorithm based on the Fast Fourier Transform (Jenkins and Watts, 1968), and they are individually plotted in Jones (1976). In order to reduce the error attached to values in a spectrum, the individual spectra for a particular element estimated from adjacent parallel traverses may be averaged arithmetically. Several such average spectra which exemplify the main features of those calculated are illustrated in text-figs. 14 and 15.



TEXT-FIG. 13. Parallel electron microprobe traverses across Hearne Formation stromatolite lamination (GSM 77320) recording the elements Si and Mg, and a photomicrograph of the traverse area at the same scale. The traverses employed a line probe of dimension 200×40 μm oriented parallel to the lamination.

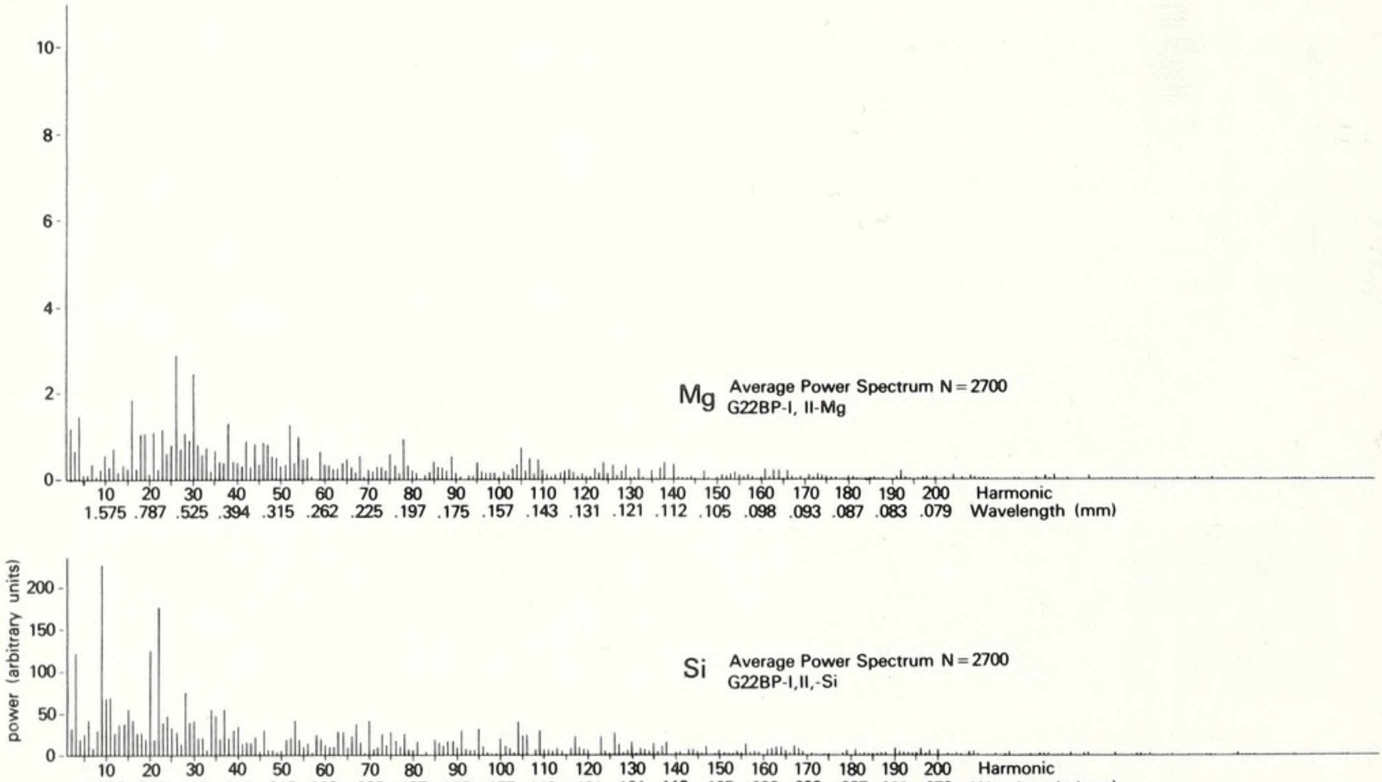


TEXT-FIG. 14. Average power spectra of Mg, Al, Si, and Ca from the traverses indicated, on Hearne Formation stromatolite specimen GSM 77325. The values *N* are the numbers of data points used in estimating the power spectra.

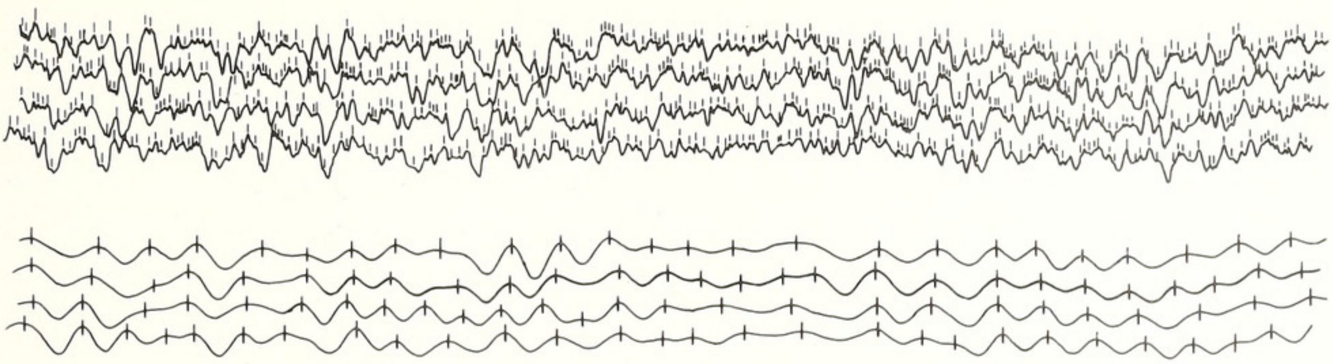
Of the four elements Ca, Mg, Si, and Al, for which spectra are presented, it is apparent that the spectra of two of them, Mg and (to a less proven extent) Al, are simpler with more clearly defined peaks than the other two. The Mg spectrum of specimen GSM 77325 displays major peaks, which are statistically significant (Jones, 1976). The spectrum displays a peak within the first five harmonics, which cannot easily be correlated with any specific visible property of the lamination, and there is also a peak at a spatial period of about 400 μm (about harmonic 25 in GSM 77325). This latter period correlates with a very prominent visible lamination of light and dark layers which is seen in thin section (e.g. text-fig. 3) and which weathers out as troughs and ridges. It is because laminae at this scale can be seen in thin section to be subdivided by finer laminae they are termed second order (see section on petrography). The GSM 77325 specimen spectrum also contains a third but less prominent peak about harmonic 44, i.e. intermediate in frequency between the previously described first- and second-order lamination. This periodicity can be correlated with the appearance in part of the specimen (text-fig. 12) of laminae of about half the normal thickness of the most prominent second-order laminae. The Mg spectrum of specimen GSM 77320 (text-fig. 15) is similar to that of GSM 77325, except that the peak corresponding to the second-order lamination (about harmonic 26) is much more broadly defined, though it centres on the average thickness of the visually identified second-order lamination, which in this specimen appears much more variable in thickness, and is therefore spread over a wider frequency band.

The average Al spectrum (text-fig. 14), calculated for specimen GSM 77325 has only one distinct peak and this is centred at the same frequency as the Mg peak (at harmonic 25) for the specimen, referred to above.

Spectra calculated for Si (text-figs. 14, 15) have a relatively broad distribution of power, but with a peak at the lowest frequencies, and a poorly defined concentration of power which in GSM 77325 (text-fig. 14) is in a wide range centred about two-thirds the frequency of the second-order Mg peak, while in GSM 77320 (text-fig. 15) it is centred at both about half and just over two-thirds the frequency of the Mg peak. The Ca spectra are comparable to the Si spectra in their wide and rather complicated distribution of power. They tend to peak broadly about frequencies half or two-thirds the 'second order' Mg peak, though there is also a moderate amount of power concentrated at the same position as this latter peak (text-fig. 14). Only three spectra have been calculated for Fe, and these were very inconsistent, though they bear some resemblance to the Mg spectra (as is expected from the presence of Fe in dolomite) as well as what appears to be a major random element, reflecting some irregularities in the distribution of haematite.



TEXT-FIG. 15. Average power spectra of Mg and Si from the traverses indicated on Hearne Formation stromatolite specimen GSM 77320. The value N is the number of data points used in estimating the power spectra.



TEXT-FIG. 16. Smoothed electron microprobe traverses G28BP-I, II, III, and IV for Mg from the Hearne Formation stromatolite specimen GSM 77325. (See text-figs. 10 and 12).
The ticks indicate visually identified peaks which may be regarded as first-order lamination (A) and second-order lamination (B).

No single peak in the spectra has been correlated with the finest, first-order lamination. The reason for this is partly its relatively poor definition in the original specimens. Where the finest laminae can be identified in thin section they are often indistinct and discontinuous, and they cannot therefore be expected to contribute a great deal to the total chemical variance, which is measured by the power spectra. Another important factor is that in terms of the total data length of the probe traverses, the finest laminae occur at relatively high frequencies which are very well resolved. Small variations in thickness of these laminae along the length of a traverse will result in a considerable spread in the range of the short period frequencies which represent them. As the first-order lamination is not represented by a distinct peak in the power spectrum it is not possible, using the spectra alone, to make an estimation of the relative frequencies, or ratios, of first- to second-order laminae. Spectral analysis can, however, be used for filtering in order to highlight particular frequency bands on the graphed chemical traverses, such as to facilitate counting the various orders of laminae as represented by the chemical peaks. The ratio of the laminar orders may then be expressed in terms of these peak counts for a particular element. An example of the application of this method is illustrated in text-fig. 16 for Mg traverses on specimen GSM 77325. Part A represents the traverses I, II, III, and IV in which frequencies greater than harmonic 500 have been filtered out. This means that no chemical features smaller than 21 μm can be represented (as the traverse length is 10·5 mm), the assumption being that there is no lamination finer than this scale. The tick marks represent the visual identification of peaks. A number of arbitrary decisions have been taken as to what constitutes particular peaks, but in general peak counting is a simpler, more repeatable, operation than counting laminae under a microscope. The average number of peaks in the four traverses in text-fig. 16A is $173{\cdot}5 \pm 4{\cdot}5$. In text-fig. 16B all frequencies greater than harmonic 35, and hence of wavelength less than 300 μm, have been filtered out, such that all peaks remaining in the traverses may be regarded as equivalent to second-order Mg lamination. The ticks mark off the peaks and the average number for the four traverses is $26{\cdot}5 \pm 1{\cdot}0$ (the errors quoted here are half the maximum difference between the individual counts). Dividing the former average count by the latter gives $6{\cdot}5 \pm 0{\cdot}4$ which provides an estimate of the average ratio of first to second-order laminae for Mg. It may be noted that the average number of peaks counted in text-fig. 16B is a little higher than the value of the power-spectral peak for Mg representing the second order (i.e. harmonic 25). The number of peaks which appear in the filtered traverses is a function of the highest frequencies which have been retained, chosen here somewhat arbitrarily as harmonic 35. If the average power-spectral peak value of 25 were used to calculate the first- to second-order ratio, then the result would be 6·9.

THE GEOLOGICAL SIGNIFICANCE OF THE CHEMICAL ANALYSIS

The relatively simple appearance of the average Mg spectrum (text-fig. 14), from the micritic specimen GSM 77325 (text-fig. 12), with its few, and relatively well-defined, peaks suggests that special attention should be given to this element as an indicator of periodicity. The process of formation of dolomite laminae, whether primary or secondary in origin, has been more strictly linked to some periodic 'governor' than has the formation of for example quartz or calcite. A simple explanation for the difference in the behaviour of Mg from that of some of the other elements is to be found by applying Gebelein and Hoffman's (1973) interpretation of dolomite as the representative of organic rich material. Their work, in combination with that of Davies *et al.* (1975), indicates that decaying blue-green algal organic matter may act as a site for the precipitation of high Mg calcite which may be subsequently dolomitized. It may be supposed then that dolomite laminae were once organic-rich laminae, and that quartz, calcite, and clay-rich laminae are the result of clastic deposition (probably in part selectively controlled by the algae).

The less regular appearance of the Si and Ca spectra, compared with the Mg spectrum (text-fig. 14), can be explained if their deposition, as quartz and calcite, was related to the sedimentary conditions governed by hydrodynamic and meteorological factors. The ratio of quartz to carbonate could not be expected to remain exactly constant; hence the differences in the positions and relative heights of peaks in their respective spectra. The fact that the spectra of the 'clastic' elements Si and Ca peak broadly in the range of, though generally somewhat lower than, the second-order (of lamination) Mg peak can be considered as a direct consequence of a rhythm in organic productivity which imposed itself upon the structure of the lamination. Poorer definition of the rhythm in Mg, as expressed in the spectra, occurs in thicker and coarser lamination, (such as that in specimen GSM 77320, text-fig. 13), where the mechanical sediments appear to have been preferentially deposited and which therefore would reflect any irregularities in sediment supply.

Of the elements which are interpreted as being wholly or partially clastic in origin, Al is remarkable for having a very strong spectral peak at the same position as the Mg peak corresponding to the second-order lamination. This may be attributed to the very fine (illite grade) grain size of the Al mineral, which may have resulted in it having been represented, in suspension, in an approximately constant proportion of the original sediment load. As such its spectrum is representative of what would be the spectrum of the total (interpreted) sediment fraction (which is complementary to the interpreted organic fraction and which therefore possesses the same properties as those displayed by the Mg spectra, though with opposite phase).

Though the power spectra of Fe were found difficult to interpret, it is evident from the plotted probe traverses (text-fig. 9) and from observation that it is usually associated with Mg in micritic laminae, both within dolomite and separately as haematite. Horodyski (1975) has discussed the origin of haematite in carbonate stromatolites from the Middle Proterozoic Missoula Formation and he suggests that it formed from the alteration of iron sulphide precipitated during decomposition of the stromatolite micro-organisms. The association between Fe and Mg in the Hearne Formation might be explained in a similar way. Major departures from the association may be accounted for by later partial mobilization of haematite by pore fluids.

This explanation for the power spectral properties of the major elements recorded by microprobe analysis is supported by the petrography of the lamination. The micritic dolomite-rich laminae are of relatively constant thickness compared with the intervening calcite and quartz-rich laminae, and this is so both in a lateral sense, from one side of a dome to another, and in a vertical sense for successive laminar couplets. The two types of laminae may then easily be envisaged as originating in separate ways, possibly with the heterogeneous quartz, calcite, dolomite, and muscovite laminae resulting from algal trapping and binding of water-borne sediment, while the predominantly dolomite-rich laminae resulted from intervening periods of algal growth accompanied or followed by *in situ* carbonate precipitation. The two modes of growth could perhaps have been characterized by distinct dominant algal species, like the supratidal domes on Andros Island, described by Monty (1967, 1972), where in certain instances active growth of the genus *Schizothrix* alternates with that of *Scytonema*.

CHRONOMETRIC INTERPRETATION OF THE LAMINATION

Relative dating of stromatolite laminae depends largely on analogy with growth in Recent algal mats. Data for the latter are incomplete as there are relatively few published results of experiments designed specifically to determine accretion rates in modern carbonate stromatolites, however, some results are summarized here.

Solar daily lamination, consisting of an organic-rich lamina and a mineral-rich lamina, has been recorded in the sub-tidal zone of the Bahamas and Bermuda by Monty (1967) and Gebelein (1969) respectively, and 'daily calcified films' are present in supra-tidal algal domes on Andros Island (Monty, 1972). Laminar couplets deposited by individual high tides, and therefore with a daily and semi-daily frequency, have been described from the inter-tidal zone of Shark Bay, Western Australia (Davies, 1970), and the inter-tidal zone of Ingraham Lake, Southern Florida (Gebelein and Hoffman, 1968). Park (1973), studying the inter-tidal mats of the Trucial Coast, has concurred with Monty's and Gebelein's accounts of daily lamination, though apparently without any experimental confirmation, and he also suggests that semi-daily tidal couplets might be deposited as well.

Non-daily first-order lamination, with a periodicity of about a week or more, has been recorded (Monty, 1967) in the inter-tidal zone of Andros Island. Seasonal lamination caused by alternations of wet and dry periods is also present (Monty, 1967) in the supra-tidal and fresh-water environments of Andros. Seasonal cycles have been described (Hommeril and Rioult, 1965) in algal mats of the inter-tidal area of the Normandy coast and Brittany, sometimes with two cycles per year corresponding to spring and autumn growth periods. In Shark Bay, Davies (1970) has identified sequences of cyclic bedding in the inter-tidal algal laminated sediments, which he attributes to the annual cycle of winter tides and winds depositing volumes of mud and silt, followed by quieter, summer regeneration of the algal mat growth. Monty (1973) has found that the sub-tidal algal domes and biscuits of Andros, with daily laminae, are also subject to annual cycles in development with a peak of dome abundance during the summer months.

Hardie and Ginsburg (1977) have carried out experiments on the Three Creeks tidal flat area of north-west Andros Island to determine the rate of deposition of the millimeter scale lamination there. They found that the individual tides were not responsible for sedimentation because of their very low sediment load, and that deposition of a sedimentary layer was a relatively rare event which was associated with storms causing bottom sediments to be stirred up and redeposited. In the period of their experiments such events had an average frequency of about three per year. The lamination resulting from this process consists of laterally continuous, muddy ('algal stick on') films up to a few tenths of a millimetre thick alternating with mechanically deposited, discontinuous, well-sorted peloid sand varying between a few tenths of a millimetre and several millimetres in thickness. In his study of the Trucial coast algal mats, Park (1973) has described rhythmic lamination in sub-surface peat sections, consisting of light and dark laminae couplets about a millimetre in thickness, the dark laminae of which are subdivided into about ten or more finer laminae. On the basis of C14 dating he concluded that the coarser lamination had a periodicity of about three per ten years, and the finer of three to five per year. He interpreted the pale sediment-rich laminae as storm deposits separated by periods of algal growth producing the dark laminae.

It is remarkable that none of the studies of Recent stromatolites refers explicitly to the formation of fortnightly 'tidal cycles' which are a characteristic of some marine organisms with an accretionary mode of growth, notably certain bivalves (e.g. Evans, 1972). A partial exception to this is Gebelein and Hoffman's abstract (1968) in which they describe semi-daily tidal lamination, the thickness of which is proportional to the period of submergence by individual tides. Since that period will vary with fortnightly and annual periods (Defant, 1961), these cycles might be expected to be present in preserved sequences of such lamination. An illustration of daily sub-tidal laminae in Monty (1967, p. 19) appears to display a fairly regular alternation of predominantly dark and light laminae, which might be attributed to tidal cycles in sediment supply or algal growth, though Monty makes no mention of such a possibility. Referring to 'Monty's (1965, 1967) algal "biscuits"', Pannella (1972*a*) does identify 'tidal patterns' but he does not illustrate or further substantiate his identification, which cannot therefore be accorded any special weight beyond the observation of clusters of daily laminae in Monty's illustration referred to above.

In attempting to make use of the evidence from the modern stromatolite-forming environments in interpreting the Hearne Formation stromatolites, the presence of a fairly simple structure of lamination combined with the domal morphology, present in the latter, indicate a possible analogy with the sub-tidal domes described by Monty and Gebelein. This analogy is, however, not very close because the prominent division of the laminae into two orders is not properly established in these Recent structures, and there are also thousands of first-order laminae in the Hearne Formation in remarkably uniform successions (as opposed to the Recent domes which apparently represent less than one year's growth, and commonly seem to have less than 100 first-order laminae). If the analogy with the Recent sub-tidal domes were maintained, it would be possible to interpret the first-order Hearne Formation laminae as daily, probably with frequent gaps in their deposition as with Gebelein's Bermudan domes (as opposed to biscuits). The most likely periodicity of the second-order lamination would be fortnightly, since variables such as sediment supply and light intensity might be expected to vary with such a tidal period. If this interpretation is accepted (as it is by Pannella 1972*a* and 1975) then it leads to a further divergence from the analogy with the Recent in that any seasonal or annual periodicity in the Hearne Formation would appear to be very much weaker and less regularly developed than the fortnightly cycle. In particular the storm events, which are such an important feature of the modern environments of stromatolite formation, would not then have any obvious parallel in the Hearne Formation. Where two distinct orders of lamination have been identified by researchers working on Recent algal sediments, the second order is identified as annual (Davies, 1970, Monty, 1973) or supra-annual (Park, 1973, 1976). The annual rhythm in the sub-tidal environment of the Bahamas and Bermuda is so strong as to result in the termination of one season's dome population to be replaced by distinct new domes in the following season.

Some evidence of the preservation potential of fine, daily lamination in Recent deposits has been presented by Park (1973, 1977), who found that 'one burial has occurred and as a consequence of dehydration and decay of the organic matter, the identification of the diurnal microlaminae becomes impossible. Instead one finds alternating laminae approaching the millimetre scale which characterizes so many ancient stromatolites.' (1973, p. 161). In the case of the Trucial Coast sediments, the preservation of discrete laminae seems to be closely related to the presence of sedimentary layers, the deposition of which is 'controlled in large part by the pattern of tides, local currents, and especially storm activity' (ibid., p. 156).

The comparatively durable nature of the algal mats with 'millimetre scale' lamination described by Park in the Trucial coast, by Hardie and Ginsburg in north-western Andros Island, and possibly by Davies in Western Australia, combined with close similarities in microstructure and the occasional presence of multiple orders of lamination, suggest that they are more closely comparable to the Hearne Formation stromatolites than the relatively transient sub-tidal domes described by Monty and Gebelein. Thus it would appear reasonable to base any chronometric interpretation of the Hearne Formation on our knowledge of material of the type described by the former authors. The evidence from these environments, in particular where more than one order of lamination has been described, argues in favour of the very prominent second-order Hearne lamination being due to a seasonal (?annual) rhythm in growth of the algae, possibly accompanied or induced by complementary seasonal maxima in sediment deposition, with the less well-defined first order representing a combination of storm events followed by periods of algal development. If the second-order lamination is annual, then the ratio of first- to second-order lamination based on the Mg chemistry indicates an average of about seven storm sedimentation events per year. On Andros Island and the Trucial Coast the equivalent present-day and Recent numbers have been estimated to be about three (Hardie and Ginsburg, 1977) and three to five (Park, 1973) respectively. The studies of Recent stromatolites do not contradict an interpretation of the Hearne Formation laminae as daily and fortnightly, but they make the storm/seasonal interpretation more probable in the light of our knowledge of the modern processes.

Acknowledgements. This work was carried out with the financial support of a NERC studentship and a grant towards field-work from the Royal Society to Professor S. K. Runcorn, who kindly supervised the research. I have received a great deal of valuable advice from G. D. Rosenberg and M. L. Richards. P. F. Hoffman introduced me to the sampled locality and he and M. Semikhatov assisted the field-work. W. Davison afforded me technical assistance. I am grateful to I. E. Penn, T. V. Loudon, J. McInnes, and W. A. Read for their comments. Publication is with the permission of the Director, Institute of Geological Sciences, where the specimens are stored.

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C. B. JONES

Institute of Geological Sciences
Keyworth
Nottingham NG12 5GG

Original manuscript received 21 December 1979

Revised manuscript received 7 March 1980