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STROMATOLITES AND EARTH—SUN—MOON DYNAMICS

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ABSTRACT

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Inclination of stromatolite columns, caused by nonvertical direction of averaged incident solar radiation, provides a signal for deducing astronomical and geophysical data at time of stromatolite formation. A sample of *Anabaria juvensis* (Bitter Springs Formation, central Australia) shows a sinusoidal growth pattern which, interpreted as an annual signal (obliquity of the ecliptic) with daily production of laminae, indicates ~ 435 days per year, a result consistent with other available estimates. A sample of *Inzeria* from the same formation also shows a sinusoidal pattern and a similar estimate for days per year. Both samples indicate growth rates of centimeters per year. Several laboratory measurement techniques offer systematic procedures for extracting data.

INTRODUCTION

Astronomical observations and analyses of radiation reaching the Earth from distant stars and galaxies have presented scientists with direct evidence of events occurring millions and billions of years ago. However, the history of our solar system, and in particular the history of the Earth—Sun—Moon system is best understood only at its two temporal extremes: the beginnings of the system some 5 Ga ago (based on model studies of distant stars), and the last few thousand years for which there are historical records. The intervening several billions of years of history have left few records of important Earth—Sun—Moon relationships. These, for the most part, can be estimated only by using mathematical models.

In contrast, the early history of the Earth, and in particular its crust, is more confidently understood and can be based on data preserved in the rock record. To these ends, the earth sciences have made use of: (1) geophysical studies such as rock paleomagnetism (Roy, 1983) and the structure

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of the ancient crust (Kröner, 1981; Windley, 1984); (2) geochemical investigations on the chemical evolution of the Earth (Wänke and Dreibus, 1982; Veizer et al., 1982), changes in sedimentary rocks through time (Ronov et al., 1980), evolution of the atmosphere (Walker, 1977) and hydrosphere (Holland, 1984); and (3) paleobiological studies on the evolving biosphere of the early Earth and its interactions with the evolving Earth (Cloud, 1976; Awramik, 1982). As illuminating as the rock record may be for terrestrial Earth history, the little information detected reflecting Earth—Sun—Moon relationships have been primarily based on a very few difficult to interpret paleontological examples (e.g., Wells, 1963; Scrutton, 1964; Pannella et al., 1968; Jones, 1981).

Although difficult to interpret, we feel the paleontological examples provide a unique source of data. Organisms are generally more sensitive to their physical surroundings and responsive to changes than non-vital substances at the surface of the Earth. Skeletal organisms, both fossil and Recent, can record such Earth—Sun—Moon influenced factors as daily, tidal, lunar monthly, seasonal, and yearly cycles (Pannella, 1975). Animal-based data can only extend back some 570 Ma ago to the base of the Cambrian, and leave the bulk of geologic time unrepresented. Becausestromatolites which form in a manner analogous to skeletal organisms have a fossil record almost as long as the rock record itself, with examples extending back some 3500 Ma (Lowe, 1980), they have great potential for extending the data base. Our studies on the late Proterozoic (~ 850 Ma-old) stromatolite *Anabaria juvensis* may provide clear and unambiguous signals with which to better understand the history of the Earth and the Earth—Sun—Moon system and lead to a greater understanding of stromatolite morphogenesis (Vanyo and Awramik, 1982). At present we consider the following types of information on early Earth and Earth—Sun—Moon dynamics potentially available from the study of particular stromatolites:

(1) number of days in the year;
(2) spin rate of the Earth (assuming constant length of year);
(3) tilt of the Earth's axis (obliquity of the ecliptic);
(4) direction of Earth's spin axis (relative to the stromatolite);
(5) days per month (lunar orbital period);
(6) paleolatitude of stromatolite-containing strata;
(7) net rotation of stromatolite-containing strata over intervening time;
(8) relation of the paleomagnetic pole to the pole of rotation;
(9) tidal periodicities;
(10) seasonal frequencies of storms; and
(11) by secondary inference, gross features of climatic patterns.

DAYS PER YEAR AND STROMATOLITES

We use Earth spin rate as an example of a geophysical—astronomical topic of current interest (Munk and MacDonald, 1975; Lambeck, 1980), summarize the difficulties of extrapolating from the current value back to early geological time, and discuss the use of stromatolites to deduce days per year directly.

Edmund Halley (1695, p. 174), as part of a discussion of the identity and location of ancient cities relative to the geography of his time, explained discrepancies in recorded latitudes as a "change in the axis of the Earth" and longitudes (based on lunar positions) as evidence that "the Moon's motion does accelerate". The latitude discrepancies were probably errors, and the longitude discrepancies are more correctly interpreted as an equivalent deceleration of Earth spin rate, but Halley clearly did raise the possibility that Earth—Sun—Moon relationships need not be fixed as had formerly been supposed. Kant (1754) proposed, as a mechanism for Earth retardation, lunar and solar induced tides in the ocean and solid Earth. This is believed today to be the dominant mechanism, but serious discrepancies between observation and theory continue to exist (Gerstenkorn, 1967; Rosenberg and Runcorn, 1975; Brosche and Sündermann, 1978, 1982).

Telescopic measurements were precise enough by 1860 to estimate decade variations in length of day, but these decade variations masked a smaller but longer time scale of mean increase in length of day (Stephenson and Morrison, 1982). Since about 1955, atomic clocks have been used to measure accurately daily variations in the length of day (O'Hora, 1975) which, after the assumption of a constant year, yield variations in days per year and angular spin rate. Modern laser measurements show the Moon is receding from the Earth at the rate of about 4 cm y^{-1} (Stephenson, 1978; Ferrari et al., 1980). Earth spin rate and lunar recession rate are closely related, and the lunar recession rate implies a long term secular increase in length of day. Records of total solar eclipses by early Chinese and Babylonian astronomers have also been used to confirm the secular increase in length of day and lead to estimates of 1.23 to 2.55 ms cy^{-1} mean increases in length of day back to about 700 B.C. (Muller and Stephenson, 1975; Stephenson and Morrison, 1984).

The best of these data when extrapolated backward in time lead to the awkward conclusion that roughly 1.5 Ga ago the Moon was near enough to the Earth that the force and energy of ocean and solid Earth tides would have severely disrupted the Earth's surface — but the geological record disputes any such occurrence. Tides, their interaction with dynamics of the Earth—Moon system, theories of lunar origins, and the many contradictions are reviewed by Goldreich (1972).

Many researchers attribute the discrepancies between provable Earth surface phenomena (e.g., tides and atmospheric changes) and observed retardation rates (and temporary accelerations) to interactions between the Earth's mantle and liquid core (Hide, 1981). The liquid core is adequately massive to produce large perturbations in mantle (i.e., Earth) spin rate, but the inaccessibility of the core has prevented direct observations. This has fostered major disagreements on the actual role of the liquid core —

both its effect on length of day and its relationship to the geomagnetic field (Rochester et al., 1975). Experiments recently completed (Vanyo and Paltridge, 1981; Vanyo, 1984) have demonstrated possible mantle—core interactions and have the potential for resolving some of the disagreements — but it is unlikely that any combination of theory or experiment can extrapolate with any precision over a period nearly one million times longer than available observations. A single good observation of Earth spin rate from the Precambrian would obviously be of immense value (Fig.1), not just for that knowledge itself but also as an aid in helping to interpret correctly the many interrelated phenomena and to provide a base line for new research.

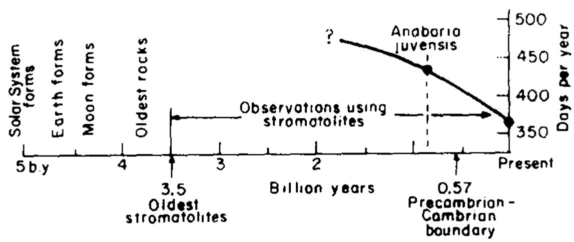


Fig.1. Comparison of solar system and geophysical events with age span of stromatolites (3500 Ma), skeletal fossils (570 Ma), and useful historical records (0.003 Ma). Stromatolites are a potential data source for helping to resolve critical events in Earth—Sun—Moon relationships in the Precambrian.

Paleontological clocks

Interactions between the Earth, the Sun, and the Moon are dominant forces influencing factors affecting the growth of organisms. Many organisms have rhythms, i.e., regularly repeating physiological events, that respond to cycles, i.e., regularly repeating geophysical events (Thompson, 1975). Daily (Pannella and MacClintock, 1968), tidal (Wells, 1937; Palmer, 1973), seasonal (Pannella, 1980), and annual (Dodge and Vaisnys, 1976) cycles have been found to influence growth in a variety of organisms. Accretionary skeletal organisms that grow by the addition of new mineralized material at the skeleton's periphery best record the influence of cycles on rhythms. These have formed the basis of most attempts to deduce early astronomical— geophysical phenomena. Wells' (1963) study on banding in Recent and fossil corals resulted in a methodology for systematically estimating past Earth rotation rates. Counting prominent bands (interpreted as annual) and striations between bands (interpreted as daily) in fossil coral, he concluded that there were between 385 and 410 days per year in the Middle Devonian, about 360 Ma ago. The idea of using other accretionary skeletal fossil organisms or skeletal parts followed: bivalves (Berry and Barker, 1968; Pannella, 1972), brachiopods (Mazzullo, 1971), nautiloids (Kahn and Pompea, 1978), stromatoporoids (Meyer, 1981), fish sagittae (Pannella, 1980) and mastodon tusks (Fisher and Koch, 1983).

This type of research is not without its problems. Probably the best studied invertebrates in terms of deviations from normal shell growth line patterns are the bivalves. With certain bivalves, a daily growth line occasionally is skipped (Clark, 1968); non-daily growth lines can be produced (Evans, 1975); with increasing age there can be fewer growth increments (Hall, 1975); and variations in growth increments within the same species can be caused by latitude and water depth differences (Hall, 1975). Growth patterns representing frequencies of more than one 24-h interval can be found in fish sagittae (Pannella, 1980).

Gould (1980) asked the following questions: (1) how do you know what periodicity the growth lines reflect? ; (2) if the lines are in response to solar cycles, how do you assess the days per ancient month or year?; and (3) how can we be certain that the growth lines reflect an astronomical periodicity? In work on fossil skeletal organisms, numerous assumptions must be made and reference to modern analogs developed. A major criticism of growth line research is the so-called subjectivity in the counting of growth lines, or as expressed by Pannella (1975, p. 262), "Crucial to the accuracy of information of biological growth patterns is the possibility of identifying discrete, recognizable, unambiguous and consistent growth layers representing regular time units".

Stromatolites as clocks

Stromatolites are organosedimentary structures produced by the sediment trapping, binding, and/or precipitation activity of microorganisms, primarily by cyanobacteria (Awramik and Margulis, cited in Walter, 1976, p. 1). Stromatolites grow in a manner analogous to accretionary skeletal organisms in that new material is added on the periphery. However, stromatolites differ from such skeletal organisms as clams in one fundamental way — a stromatolite is built by a complex community involving different microorganisms (Golubic, 1976; Awramik, 1984).

The formation of hard, lithified (mineralized) stromatolites is probably critical for their use as paleontological clocks, but this is not a straightforward, well understood phenomenon. In animals the biomineralization of the shell, or other mineralized part, is under the organism's direct biochemical control (Weiner et al., 1983). With stromatolites the precipitation of mineral matter, principally calcium carbonate, may or may not occur. The mineralization is not a directly biochemically mediated process, but probably a phenomenon physico-chemically induced by the photosynthetic activity of the microorganisms (uptake of CO_2). Also, to make matters more complex, the precipitation of calcium carbonate need not co-occur with cyanobacterial growth of the stromatolites; calcium carbonate precipitation can occur at shallow (mm) depths within a microbial mat (Javor and Castenholz, 1981; Lyons et al., 1984).

In terms of astronomical controls or regulation on stromatolites, the Sun provides the radiant energy used for the growth of cyanobacteria building the stromatolite with rotation of the Earth superimposing day-night cycles. The Moon influences spin rate of the Earth as well as inducing tides. The complex interactions of microbes, sediment, water, sunlight, and Earth rotation all act in concert to generate growth in stromatolites. This potential for stromatolites to record sensitive astronomical and geophysical information was postulated by Vologdin (1961) and Runcorn (1966).

The morphological attribute in stromatolites most likely to record Earth—Sun—Moon driven environmental fluctuations are the laminae (Pannella, 1976). Indeed, the production of laminae *depends* on these fluctuations and is the morphological attribute for which stromatolites received their name (Greek *stroma* layer; Kalkowsky, 1908). The production of laminae requires some kind of rhythmicity that causes discontinuity in the accretionary process (Hofmann, 1973). This rhythm can be either periodic or episodic. Periodicity in the growth of the photosynthetic microbes that build stromatolites is the highest ranking factor for lamination production. In addition to periodic rhythms in growth of the microbes, periodicity in the addition of sediment, periodic decomposition of accreted biogenic materials, and periodicity in diagenetic alterations can modify first order lamination produced by microbes or even produce secondary laminae. The recording of astronomical—geophysical data by stromatolites depends on how well the lamina formation process by microbes can respond to controlling external stimuli and how little the first-order laminae have been altered by secondary processes. Reading the record depends on how well preserved the laminae are and also depends on the ability to recognize first order laminae.

The potential for the columns of stromatolites to record astronomical—geophysical data was explored by Vologdin (1961, 1963) and Nordeng (1963) who postulated that stromatolites should show maximum growth toward and hence be inclined in the direction of sunlight. Inclined columns therefore could be used to determine past positions of the Earth's poles. This work, largely ignored today, has been discredited because column inclination is also controlled to a great extent by local environmental conditions (Hofmann, 1973).

However, we proposed that formation of stromatolite columns can be influenced by incident sunlight, leading to asymmetry of laminae or even a sinusoidal pattern that contains astronomical—geophysical data (Vanyo and Awramik, 1982). The model for sinusoidal column growth requires that the photosynthesizing microorganisms producing the columns grow in relatively clear shallow quiescent water, near the equator and under a nearly cloud-free sky. Local environmental conditions do not control the shape in this model. Given a slightly irregular surface, idealized in Fig.2 as a convex upward hemispherical surface, the specular sunlight, after passing through the air—water surface, illuminates the hemisphere with maximum radiative intensity at the point perpendicular to the rays but approaches zero (except for diffuse light) at the sides. The very existence of the stromatolite carries the implication of favorable conditions for the photosynthetic microbes, which we interpret here as growth related positively to radiative intensity.

At or near the equator, the microbe-controlled growth described for Fig.2 would tend to orient towards the south when the Sun is in the southern sky, gradually turning northward with the change of season and repeating the approximately sinusoidal pattern on a yearly basis. Daily passage of the Sun from east to west is averaged out so that net growth occurs in the north—south plane, preserving in the geological record the spin axis direction of the Earth during that year at that locale.

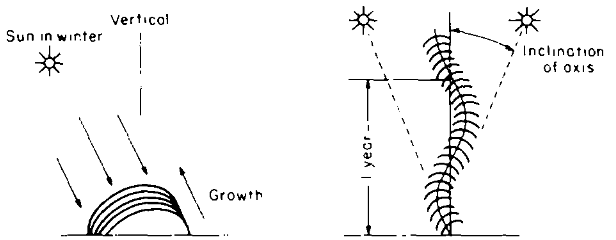


Fig.2. Sinusoidal growth model assuming maximum growth in the direction of averaged incident sunlight. A columnar stromatolite forming near the Equator under optimum conditions may produce sinusoidal structures that preserve important Earth—Sun—Moon relationships and biogeological information.

Obliquity of the ecliptic

The inclination of the column axis relative to net vertical preserves some measure of the inclination of the Earth's axis to its orbital plane (obliquity of the ecliptic). Obliquity of the ecliptic is known to change; at present it is decreasing by about 47″ per century (Wittmann, 1979). It is intimately involved with Earth—Moon dynamics. Attempts to estimate numerically the retrogression in time of Earth—Moon relationships using current information on tidal and other interaction phenomena lead to differing estimates. Mignard (1982) limited obliquity of the ecliptic to between 12 and 24° while in an earlier paper MacDonald (1966) estimated a range from 10 to 30° over the probable history of the Earth—Moon system. Obliquities as high as 56 to 126° in the late Proterozoic have been suggested by Williams (1975) as a possible explanation for the enigma of low latitude glaciation occurring at that time.

The suggestion by Williams is not based on dynamical considerations. It may reflect a hazard always present in interdisciplinary research, i.e., proposing solutions that conflict with knowledge in one field as a substitute for an inability to solve an enigma in another field. We recognize the possibility of the same hazard in our interpretation of the sinusoidal pattern, yet after careful review of the fields of astronomy, geophysics and biogeology we find no significant conflicts. Instead we find general conformity between our preliminary results and the general trends of current research. Anticipating discussions of the next section, counts of the large number of very thin laminae per wavelength raise the possibility of daily production of laminae, with laminae per sinusoidal wavelength then being a record of days per year.

Lunar induced periodicities

Existence of an annual signal independent of laminae anomalies permits periodic events (e.g., lunar tidal phenomena) to be assessed either as events per annual signal or laminae (days) per event. This should help to minimize erroneous inclusion of episodic events into a periodic count.

THE STROMATOLITE *ANABARIA JUVENSIS*

A silicified stromatolite collected in 1965 by Preston Cloud from the Bitter Springs Formation in central Australia and designated *Anabaria juvensis* by Cloud and Semikhatov (1969), was part of a general investigation of the relationship of stromatolite shape to physical factors in a liquid medium. A sample was cut and polished in two perpendicular planes, roughly parallel to the columns' axes, but otherwise random. An approximately sinusoidal pattern of the columns was fortuitously discovered (Fig.3).

Using thin sections of *A. juvensis* columns as "photographic negatives" (see Fig.9), enlarged prints were made. Clear acetate overlays were placed over the prints and lines were drawn on the acetate to mark the originally dark (now light) laminae. Laminae were counted over distances of several centimeters where preservation was best. These counts extrapolated to 409, 435, 454, and 485 laminae per 8.7 cm sine wave with the 435 count based on the best preserved laminae (Vanyo and Awramik, 1982). The count of laminae per wavelength agree well with published estimates of 420—440 days per year at that time based on theoretical extrapolations using tidal friction and core accretion (Munk, 1966). A summary of the measured wavelengths, the angles of intersection of column axes with net vertical, and the laminae per average wavelength is shown in Fig.4.

After correcting for index of refraction at the sea water surface, obliquity of the ecliptic computes to $26°30'$ compared to the present value of $23°27'$. This is consistent with Wittmann's estimate of a currently decreasing value but contrary to the numerical extrapolations of both MacDonald and Mignard who compute a smaller obliquity in the past and contrary to the larger values suggested by Williams for slightly younger Proterozoic times.

Vologdin (1961, 1963) and especially Nordeng (1963) used stromatolite column inclinations to deduce paleolatitudes but do not discuss variation of solar inclination over the seasons. We use other evidence for near equatorial growth of our samples and deduce only seasonal variations (obliquity of the ecliptic). The paleolatitude information requires *a priori* information on original horizontality of stratum at time of stromatolite formation. Both paleolatitude and obliquity information should be present in a given sample provided of course the stromatolite microorganisms were responding to

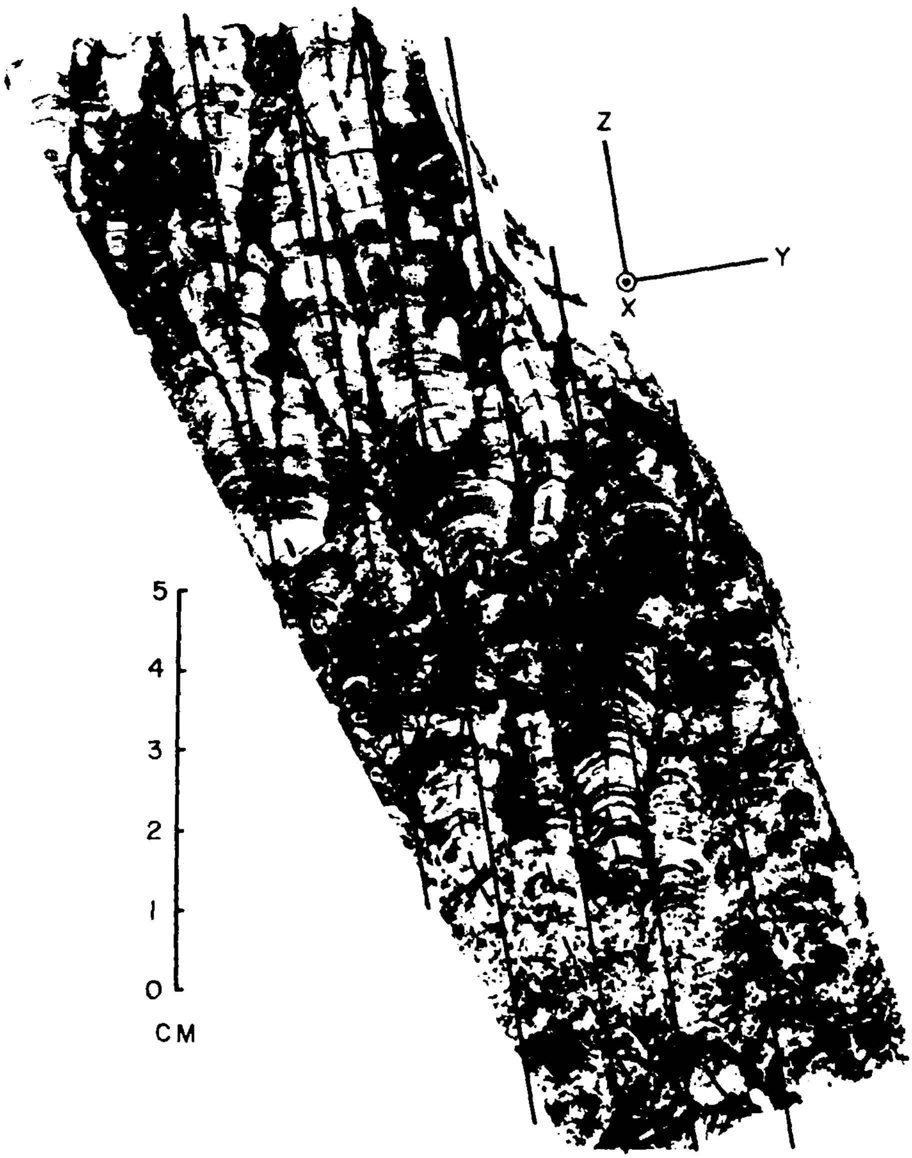
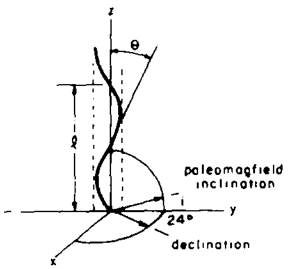


Fig.3. The stromatolite *Anabaria juvensis* showing sinusoidal growth patterns. Dashed lines highlight column axes; solid lines are taken as net vertical. The XYZ coordinate system is used for paleomagnetic analysis (from Vanyo and Awramik, 1982).

direct (specular) solar radiation.* If responding entirely to diffuse radiation, neither type of information would be preserved; as an extreme example, stromatolite formation in Antarctic lakes (Parker et al., 1981).

A further test involved an independent paleomagnetic analysis performed by M. Fuller. The model requirements of growth at low latitude and with the sinusoidal plane aligned true north—south indicate that any paleofield vector should preferentially be nearly perpendicular to the net vertical and nearly aligned with the sinusoidal plane. The paleofield inclination to net vertical indicated a paleolatitude of about 11°, agreeing with more extensive analyses of the underlying Heavitree Quartzite which yielded paleolatitudes of 11°±5.7° (J.L. Kirschvink, written communication, 1982). The paleofield vector also measured about 20° from the apparent sinusoidal (north—south) plane, near enough to represent a typical magnetic declination (Busse, 1978). Both paleomagnetic field tests were thus consistent with model requirements.

These results were naturally suspect in that only one well-preserved sample was available and the phenomenon was apparent for only a maximum of 1.5 wavelengths in the few columns contained in the specimen. These columns do include (semi) periodic anomalies that may be records of tidal events, but the limited opportunity for statistical analysis discouraged a detailed investigation. Placing a high priority on recollecting that or similar stromatolites, in April of 1982 we travelled to central Australia to find the type locality of ***Anabaria juvensis*** described in Cloud and Semikhatov (1969). The locality from which these stromatolites were found had not



$\bar{\ell} = 8.7$ cm, $1\sigma = 0.8$ (6 estimates)

$\bar{\theta} = 19.6°$, $1\sigma = 3.2°$ (9 estimates)
If $\eta = 1.33$, inclination of axis $= 26.5°$

Latitude $= \tan^{-1}(\frac{1}{2} \tan i) = 10°$
(underlying strata paleolat. $= 11° \pm 5.7°$)

Four laminae counts over seperate regions $= 409, 435$ (best), $454, 485$ laminae/$\bar{\ell}$.

Age 850 ± 50 Ma

Fig. 4. Summary of analyses of the *A. juvensis* sample shown in Fig.3. Days per year, obliquity of the ecliptic, and direction of the paleomagnetic pole relative to true north—south at the time of formation of the stromatolite, 850 Ma ago, are part of the recorded data.

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*A September 1984 investigation of microbial stromatolitic growths in geyser and hot pool outflows at Yellowstone National Park, Wyoming, U.S.A., yielded abundant evidence of subaqueous columnar and conical growth forms tilting southerly with 10—20° zenith angles. Southerly growth occurs *independent* of flow direction. The zenith angles approximate the summer ecliptic zenith angles at that latitude. Details will be published elsewhere.

been relocated since Cloud's initial discovery in 1965 (Walter, personal communication, 1982).

Approximately 50 km east of Alice Springs along the Ross River Road at grid reference 218800 (Sheet 5750) of the Undoolya 1 : 100 000 Sheet, we found outcrops mapped as the Loves Creek member of the Bitter Springs Formation to contain silicified *Anabaria juvensis* (Fig.5). The stromatolites were patchily distributed on bedding plane surfaces for 2 km along strike (N50°—60°E) by the southern flank of the ridge a few tens of meters to the north of the road. Several blocks of stromatolite samples were collected and three samples were oriented for subsequent paleomagnetic analyses (in progress). At each of the five small outcrops of *A. juvensis* studied, the sine wave pattern was not apparent on the longitudinally exposed weathered surfaces of the columns. This was also true of the original sample of *A. juvensis*.

Two other Bitter Springs stromatolite localities were investigated within the limited field time available to determine how widespread *Anabaria juvensis* is and to look for evidence of sine wave patterns in other stromatolites of the formation. (1) Katapata Gap, SW corner of SF 53-13 Hermannsburg 1 : 250 000 Sheet, grid reference KP1047. Here Conybeare and Crook (1968) illustrated columnar stromatolites with an apparent sinusoidal pattern in their Plate 40A. We were unable to find the site where the photograph was taken or any sinusoidal patterns in the abundant columnar stroma-

Fig.5. Photograph of an *Anabaria juvensis* site, Bitter Springs Formation, central Australia, ~ 50 km east of Alive Springs. The central portion was oriented *in situ* for north—south and vertical before removal from outcrop. Approximately 5 such outcrops were located and collected from along strike over a distance of about 2 km.

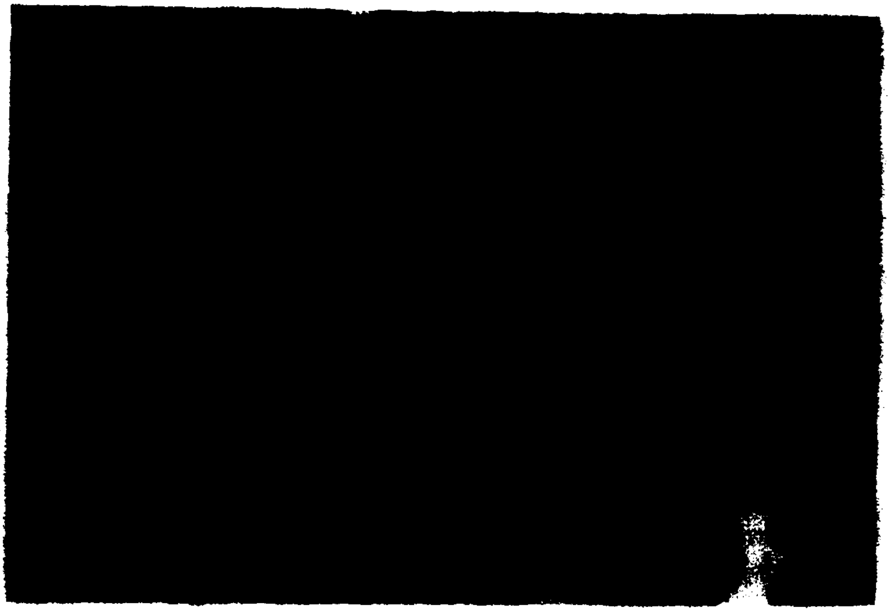

Fig.6. *Acaciella australica* at Katapata Gap ~ 200 km west of Alice Springs. This stromatolite shows an abrupt change from planar mats to a "cauliflower" shape composed of radially arranged subcylindrical columns. Sinusoidal patterns were not visible.

Fig.7. *Inzeria initia* located several km north of the Ross River Station, ~ 120 km east of Alice Springs. This specimen, found lying loose on a steep hillside, shows an obvious sinusoidal pattern. If the pattern was produced by the model shown in Fig.2, a 45 cm y^{-2} formation rate is implied.

tolite *Acaciella australica* Walter exposed in outcrop (Fig.6). (2) 1.5 km NNE of the Ross River Station. Here *Kotuikania juvensis* (Cloud and Semikhatov) was described by Walter et al. (1979) and thought to include the *A. juvensis* of Cloud and Semikhatov (1969). The nomenclatural problem regarding *A. juvensis* is beyond the scope of this paper. Although we did not find morphs that we could identify as *Kotuikania* or *Anabaria*, we did find a sinusoidal pattern in columns of an unattached portion of *Inzeria initia* Walter (Fig.7). This stromatolite is unusual not only because of its obvious sinusoidal pattern, but also because the wavelength is of the order of 45 cm. This would indicate very rapid growth over a period of one year — assuming of course a solar induced sinusoidal pattern. Accretion rates of the order of 1 mm day^{-1} have been observed in modern stromatolites by Gebelein (1969). Preliminary study of slabbed longitudinal surfaces of the *Inzeria* columns indicates laminae of the order of 1 mm thick, again leading to a count of about 450 laminae per wavelength. More precise measurements are anticipated as part of planned research.

LABORATORY ANALYSIS

Except for the *Inzeria* sample, the sinusoidal pattern is not apparent on the surfaces of our unprocessed samples collected in 1982 nor was it on the unprocessed surfaces of the original *Anabaria juvensis* sample. A systematic approach in finding sine wave patterns in columnar stromatolites is needed. We present here various approaches being evaluated in our study of stromatolites. This work is in progress and depends on manageable samples with column diameters on the order of centimeters.

(1) Paleomagnetic field vector and cut method. It has been suggested (Runcorn, private communication, 1983) we use the paleomagnetic test in reverse; that is, first find the field vector and then cut parallel to it. This may have promise; in the original sample we would have been within about 20° of the correct plane, and a second iteration might have been within 5°, close enough for most analyses.

(2) Longitudinal cut method. Spacing six cuts 30° apart, all parallel to column axes, guarantees being within 15° of a sinusoidal plane. This is a variation of a method described by Krylov (1959) for reconstructing the three-dimensional structure of stromatolites from a series of parallel longitudinal sections. Technique 1 depends on preservation of the primary magnetic field vector at the time the stromatolite formed, while technique 2 consumes a large quantity of stromatolite sample.

(3) Transverse cut (slabbing) method. This procedure grinds (or casts) two smooth surfaces on the sample perpendicular to each other and with both approximately parallel to the column axis direction. The sample (say 8 × 8 cm square and available column height) is then sliced with a 2 mm-thick diamond saw at 4 mm intervals from top to bottom leaving a set of slabs each 2 mm thick similar to the procedure suggested by Raaben

(1969). Remnants of the ground or cast smooth surfaces are used as reference planes to measure (x,y) coordinates of each column axis for each 2 mm of column height (z). Both sides of each slab are used for measurements. The loci of points (x, y, z) for each column axis are then used to compute the existence or nonexistence of a sinusoidal pattern for each column in the specimen (only a few columns are exposed on a longitudinal polished surface). The data can be used to compute statistically the best fit sine curve for all columns, assuming a sine pattern exists. Precise estimates of net wavelength and inclination are the final result. Additional portions adjacent to and oriented to the processed sample need to be retained for thin sections (laminae counts) and for paleomagnetic or other analyses. This procedure necessitates careful measurement of slabs from a fixed datum and is time-consuming, with the saw removing approximately half the original material. Figure 8 shows a set of slabs, with cast plaster of paris reference surfaces, ready for measurement.

(4) Grind and photograph method. A more detailed procedure is to grind or cast two perpendicular surfaces as noted before and then to successively grind away the stromatolite from column tops to column bottoms, photographing each ground surface. Provided that ground surfaces are finely spaced and are precisely made, this process can record the information necessary for much more rigorous laminae counts than have been achieved by other reported methods. It also permits very detailed reconstruction of laminae and columnar morphology. Drawbacks with the procedure are that the stromatolite sample is completely destroyed and it is the most time-consum-

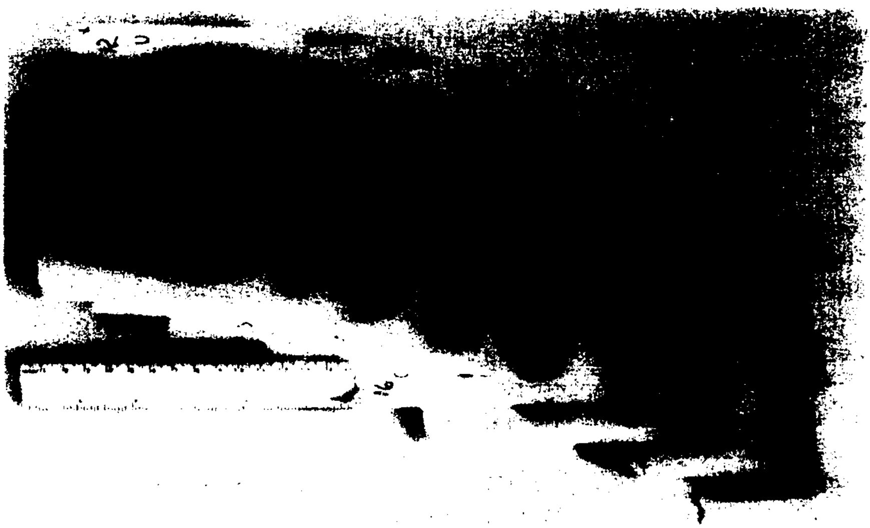

Fig.8. Sample of *A. juvensis* after cutting into parallel slabs, each approximately perpendicular to net column growth direction. The white portion is plaster of paris cast before slabbing to preserve reference surfaces for measurement of column centerline positions.

ing technique. Although a photographic record of the polished surfaces is made, adjacent oriented portions must be retained for other tests. The extremely large amount of information recorded on the thousands of photographs necessitates some type of automated processing and computing capability, a result anticipated and discussed by others (Hofmann, 1976; Zhang and Hofmann, 1982).

Figure 9 is an enlargement from a thin section of our original sample of *Anabaria juvensis* showing the typical convex upward cross sections of nearly hemispherical laminae surfaces. The best preserved of the laminae, shown in the inset, average about 0.2 mm thick. Figure 10 illustrates use of the grind and photograph process applied to a column of idealized laminae of about the same dimensions. Available grinding machines have a feed

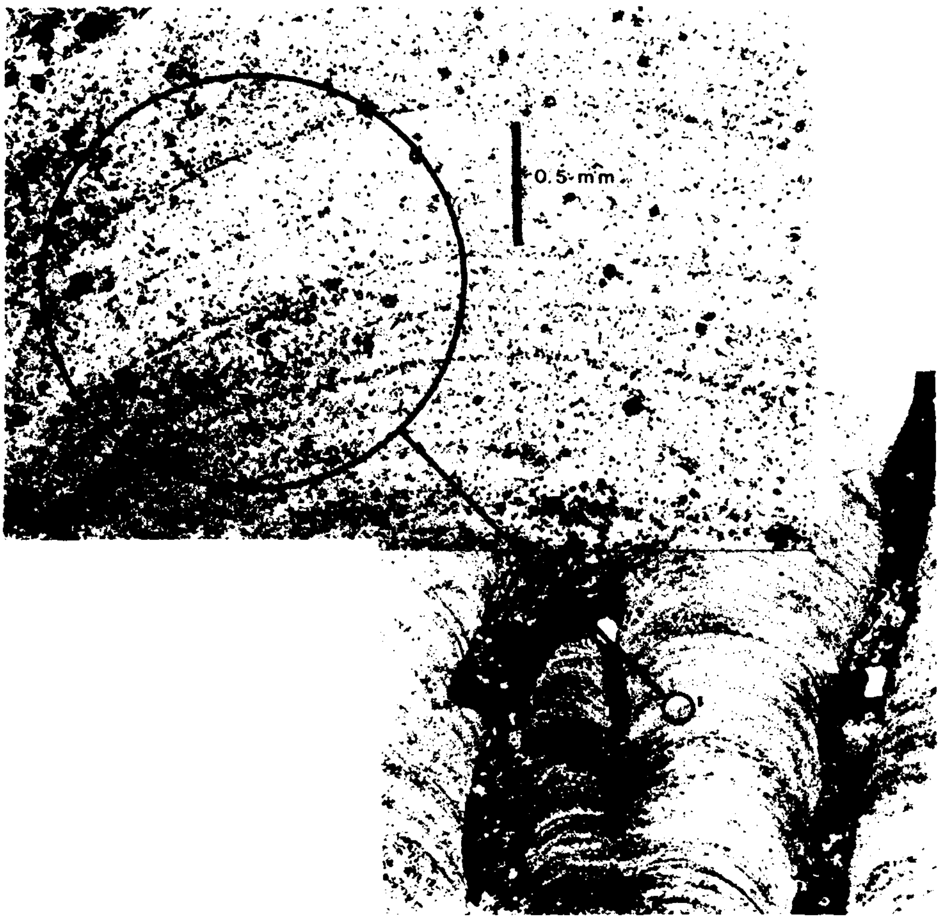

Fig.9. Photomicrograph of a thin section, taken through the largest diameter of column A of Fig.3, of *A. juvensis* showing five well-preserved laminae. The bar equals 0.5 mm (from Vanyo and Awramik, 1982).

accuracy of about 0.001" (25 μm) so cuts taken each 0.004" (0.1 mm) appear reasonable. This is half the laminae thickness on the average, but laminae height (relief) are of the order of 1.5 mm from top to bottom. Each lamina is therefore exposed and photographed up to 15 times in the form of annular rings. The center of the columnar cross-sections designate the column axes with the rings being lines of constant height for reconstructing laminae topology.

The Fig.9 inset enlarges the best of the exposed laminae on that thin

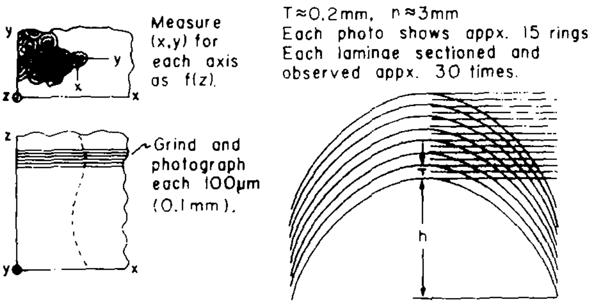

Fig.10. Sketch showing potential use of the grind and photograph process. The best preserved laminae of Fig.9 would show up to 15 rings on a polished horizontal surface; less well preserved laminae and flatter laminar contours have more typically shown less than 6 rings.

Fig.11. Photograph showing half of the oriented specimen of Fig.5 cut into three portions, each showing column lengths greater than the original specimen of Fig.3. Common reference surfaces are preserved using cast epoxy.

section. Most laminae were not so clearly defined; some were partially missing; gaps indicated others were completely missing (these are common observations in other work on laminae counts of stromatolites (Pannella, 1976)). The overall effect was to make laminae counts a difficult and uncertain procedure. The grind and photograph process exposes on the order of 10 times the cross section of each lamina which proportionately increases the chance of finding at least some portion of each lamina for more precise counts.

Figures 11, 12, and 13 show our initial application of the grind and photograph process applied to *Anabaria juvensis*. Figure 11 illustrates a portion of the oriented specimen of Fig.5 cut into three sections each containing full column lengths slightly longer than those of our original *Anabaria juvensis.* Figure 12 shows the central portion of Fig.11 after being fitted with three precise orthogonal cast epoxy surfaces ready for fastening to the table of a surface grinder. One surface sits flat on the grinder table and defines the $z = 0$ plane; the other two surfaces are vertical and are used as the $x = 0$, $y = 0$ surfaces. Figure 13 shows a closeup of a ground surface with the columns exposed as sets of nearly concentric rings. These first tests are partially limited in accuracy due to the quality of the available equipment.

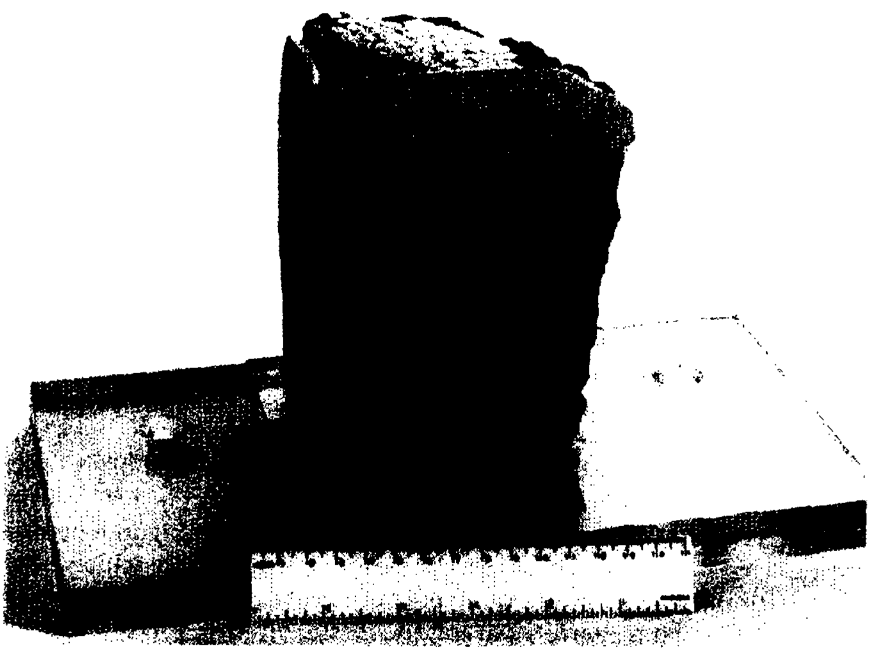

Fig.12. The central portion of Fig.11 with three mutually perpendicular cast epoxy surfaces including a cast epoxy base for attachment to a grinding machine table. A small flat top surface has been ground to show column cross sections.

Fig.13. Close-up of a ground and polished horizontal cross section showing laminae (rings) details. The prodigious amount of information available has, in conjunction with computer processing, the potential for reconstructing both macro and micro aspects of stromatolite morphology.

Two sets of photographs are taken. One set of photographs uses a 35 mm camera with a 50 mm macro close-up lens and high resolution black and white film (Kodak technical pan film 2415, TP 135-36). A photograph is taken after each grind (approximate intervals of 0.1 mm) for detail laminae counts and morphology. We also take photographs at each 1 mm interval with a 3¼" × 4¼" fixed focus oscilloscope Polaroid camera using Polaroid type 665 black and white film. This film provides a negative and a positive print for immediate use.

SUMMARY

There have been numerous attempts to use ancient stromatolites to interpret daily, monthly, and yearly periodicities and to use this information to infer past spin rates of the Earth (see Jones, 1981). Although cyclicity in laminae formation is a real event in stromatolites, the recognition and interpretation of these periodicities in ancient stromatolites has been based on numerological relationships (Pannella, 1975). Our research differs from previous work in that we recognize what could be an unambiguous annual signal, the sinusoidal pattern in the growth cf columns, against which laminae counts, periodic events (e.g., tidal perturbations), and other measurements can be more confidently calibrated. Tests on the validity of the sinusoidal growth pattern model include independent paleomagnetic analyses; these are not subject to uncertainties inherent in the stromatolites themselves.

Our study of the sine wave columns of *Anabaria juvensis* yields several important preliminary results: (1) the obliquity of the ecliptic 850 Ma ago was not significantly different than today; (2) the paleomagnetic pole and the geographic pole positions 850 Ma ago were nearly aligned; (3) stromatolite columns can orient themselves with respect to incident sunlight; (4) preservation of daily laminae is possible in stromatolites; (5) there were a minimum of 410 days per year in the late Proterozoic with our extrapolations varying between 410 and 485; (6) growth rate in some ancient stromatolites may have been great, on the order of centimeters per year; and (7) sinusoidal growth patterns may not be the exceedingly rare phenomenon we thought at first — a detailed analysis of stromatolites from other formations may yield more examples. Careful search for sine wave patterns in additional samples of *Anabaria juvensis* and analysis of morphometric data will either confirm or reject our sinusoidal growth model. We suggest that an unambiguous, non-numerological signal in ancient stromatolites produced by some astrophysical phenomenon and verifiable if only in part by non-stromatolite data, should be sought before the interpretation of laminae and their counts are finalized.

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