

# No heliotropism in Neoproterozoic columnar stromatolite growth, Amadeus Basin, central Australia: Geophysical implications

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## Abstract

An apparent sine wave pattern of columns in a single specimen of the stromatolite *Anabaria juvenis* (subsequently identified as *Kotuikania*) from a Neoproterozoic dolomite unit, originally assigned to the ~850 Ma Bitter Springs Formation, in the Amadeus Basin, central Australia, was interpreted previously as recording heliotropic growth, that is, the non-vertical growth of columns throughout the year controlled by averaged incident solar radiation [Vanyo, J.P., Awramik, S.M., 1985. Stromatolites and Earth–Sun–Moon dynamics. *Precambrian Research* 29, 121–142]. The model of heliotropic growth was used to estimate obliquity of the ecliptic (Earth's axial tilt) and days/year at 850 Ma. Subsequent work, however, casts strong doubt on the heliotropic interpretation. Further field observations and the study of 11 additional specimens of *Anabaria*=*Kotuikania juvenis* from the original locality confirm that the columns typically display strong branching, which produces a common divergence and convergence of columns that is incompatible with heliotropic growth. The rare, apparent sinuosity of columns is seen as the fortuitous product of column irregularity and column branching. Moreover, stratigraphic studies indicate that the host dolomite unit does not belong to the Bitter Springs Formation but caps the younger Cryogenian glaciogenic succession in the Amadeus Basin and hence is ~600 Ma. The previous estimate of ~435 (range 409–485) days/year based on extrapolated counts of laminae in the original specimen of *A.*=*K. juvenis* conflicts with the figure of  $400 \pm 7$  days/year indicated by high-quality palaeotidal data obtained from the late Cryogenian (~640–600 Ma) Elatina–Reynella tidal rhythmites in South Australia. We conclude that inferences concerning Neoproterozoic obliquity and palaeorotation cannot be drawn from the non-vertical growth patterns of the columnar stromatolite *A.*=*K. juvenis*. © 2007 Elsevier B.V. All rights reserved.

**Keywords:** Amadeus Basin; Australia; Neoproterozoic; Stromatolites; Obliquity of the ecliptic; Rotation

## 1. Introduction

The early promise that the Earth's dynamical history could be illuminated through the study of skeletal growth increments in marine invertebrate fossils (e.g.

Wells, 1963; Rosenberg and Runcorn, 1975) has not been entirely fulfilled (Lambeck, 1980; Crisp, 1989; Williams, 2000). Taken at face value, Palaeozoic data imply a catastrophic close approach of the Moon between 1.5 and 2 Ga, for which no geological evidence exists. Scrutton (1978, p. 182) concluded that palaeotidal and palaeorotational values obtained from fossils “should be treated as approximations rather than as precise quantities for mathematical analysis”. Moreover,

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stromatolite growth increments have proved difficult to interpret. Studies of modern stromatolite growth patterns in the Bahamas (Monty, 1967) and Yellowstone National Park, USA (Walter et al., 1976) showed that laminae were not necessarily diurnal or did not form every day. Reid et al. (2000) linked lamination in modern marine stromatolites in the Bahamas to a dynamic balance between sedimentation and intermittent lithification of cyanobacterial mats. Smith et al. (2005) suggested that lamina couplets displayed by peritidal stromatolites at Cape Morgan, South Africa, are annual growth increments representing seasonal environmental fluctuations. Because of the uncertainty in the time-significance of stromatolite lamination, Hofmann (1973) and Lambeck (1980) challenged the veracity of palaeorotational data derived from the growth patterns of Precambrian stromatolites. Consequently, few have ventured to study “palaeontological clocks” in the past 25 years.

Notwithstanding these problems with fossil and stromatolite geochronometry, Vanyo and Awramik (1982, 1985) presented a celestial model for the origin of an apparent sine wave growth pattern in a columnar stromatolite, identified by Cloud and Semikhatov (1969) as *Anabaria juvenis*, from the Neoproterozoic succession in the Amadeus Basin, Northern Territory, central Australia (Figs. 1 and 2). They based their model on one section of a single specimen of *A. juvenis* (Fig. 3) that was collected by Preston Cloud in 1965 from his locality 4 (Cloud and Semikhatov, 1969), ~50 m north of the Ross Highway 36 km east of Alice Springs

(Undoolya 1:50 000 topographic sheet 5750 4, grid reference 223801, latitude 23°41'17"S, longitude 134°14'13"E). The specimen was thought to have come from the ~850 Ma Bitter Springs Formation. Vanyo and Awramik (1982, 1985) argued that the apparent sinusoidal growth pattern indicated heliotropism, that is, the non-vertical growth of columns throughout the year controlled by averaged incident solar radiation. Making due allowance for the refractive index of water, they deduced that the obliquity of the ecliptic (the Earth's axial tilt or the angle between the Earth's equatorial and orbital planes, now 23°27') was 26°30' at 850 Ma. Furthermore, by counting the number of distinguishable laminae over several centimetres and extrapolating the counts to a full sine wave, they obtained estimates of 409–485 laminae, with a figure of 435 laminae based on the best preserved material. Taking the perceived sine wave pattern and laminae to reflect yearly and diurnal growth, respectively, Vanyo and Awramik (1982, 1985) concluded that there were around 435 days/year at 850 Ma.

Following the study of the original specimen by Vanyo and Awramik (1982), they visited the field site but did not find further specimens of *A. juvenis* with apparent sinusoidal columns (Vanyo and Awramik, 1985). Work on additional specimens of *A. juvenis* collected at five exposures was reported as “in progress” by Vanyo and Awramik (1985, p. 133), but the results of this work have not been reported. Vanyo and Awramik (1985, p. 139) viewed their initial findings as “preliminary”, and concluded that “Careful search for sine wave

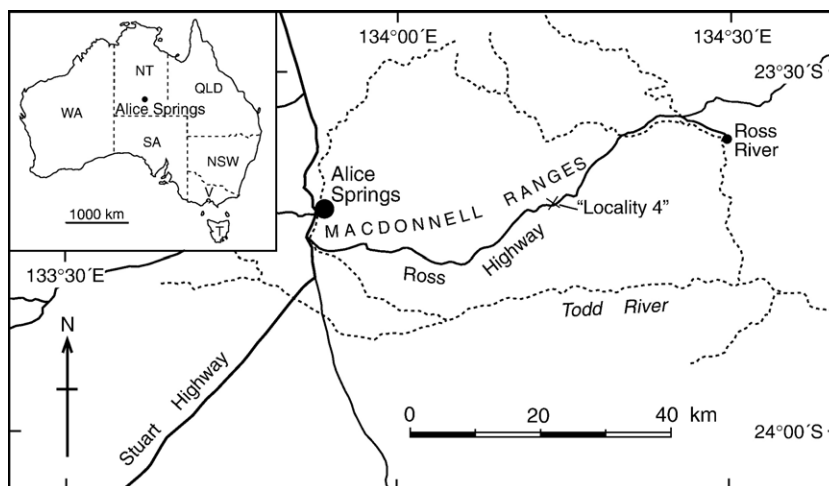


Fig. 1. Locality map of the Alice Springs area, Northern Territory, central Australia, showing Preston Cloud's locality 4 (Cloud and Semikhatov, 1969) where *Anabaria juvenis* occurs just tens of metres north of the Ross Highway (latitude 23°41'17"S, longitude 134°14'13"E). The Alice Springs 1:250 000 Geological Sheet that covers this area (Shaw et al., 1983) is available online free-of-charge at <http://www.geoscience.gov.au/geoportal/250/>.

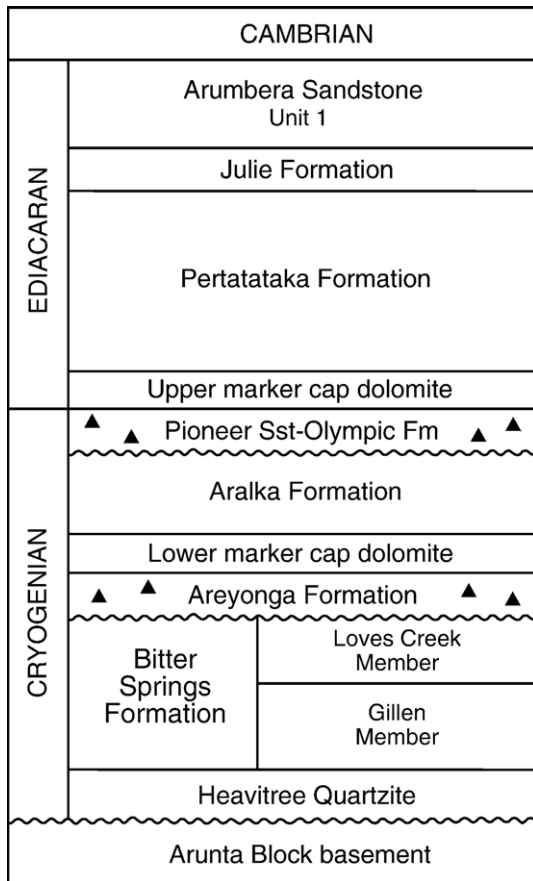


Fig. 2. Neoproterozoic succession in the Amadeus Basin, central Australia (adapted from Preiss et al., 1978; Shaw and Wells, 1983). The succession has a maximum thickness of ~5 km, but in many places is incomplete and the Pioneer Sandstone and Olympic Formation (younger Cryogenian glaciogenic succession) and the “upper marker cap dolomite” rest unconformably or disconformably on the Bitter Springs Formation.

patterns in additional samples of *A. juvenis* and analysis of morphometric data will either confirm or reject our sinusoidal growth model.” They also noted that before acceptance of their interpretation of the stromatolite laminae and counts, verification should be sought through data that are independent of stromatolites.

Despite these cautions, numerous workers (e.g. Wilde, 1991; Eagan and Liddell, 1997; Christiansen and Stouge, 1999; McMenemy, 2004; Oliver and Ronald, 2004) have accepted uncritically the sinusoidal growth model of Vanyo and Awramik (1982, 1985) and the inferences concerning obliquity and days/year at 850 Ma. Additionally, Kusky and Vanyo (1991) analysed the use of the sinusoidal growth model to reconstruct palaeocontinental plate movements and locations. The acceptance and use of such data are premature, however, and further data and tests relevant

to the sinusoidal growth model are desirable. Here we present observations from further field work and the study of 11 additional specimens of *A. juvenis* that we collected from the original locality of Cloud to test the model and inferences of Vanyo and Awramik (1982, 1985). We also discuss sedimentological data that are independent of stromatolite growth patterns, relating to days/year in the Neoproterozoic. Our findings conflict with the sinusoidal growth model and inferences regarding Neoproterozoic obliquity and palaeorotation.

## 2. Stratigraphy and age

Cloud and Semikhatov (1969) placed Cloud’s locality 4 in the Bitter Springs Formation near the base of

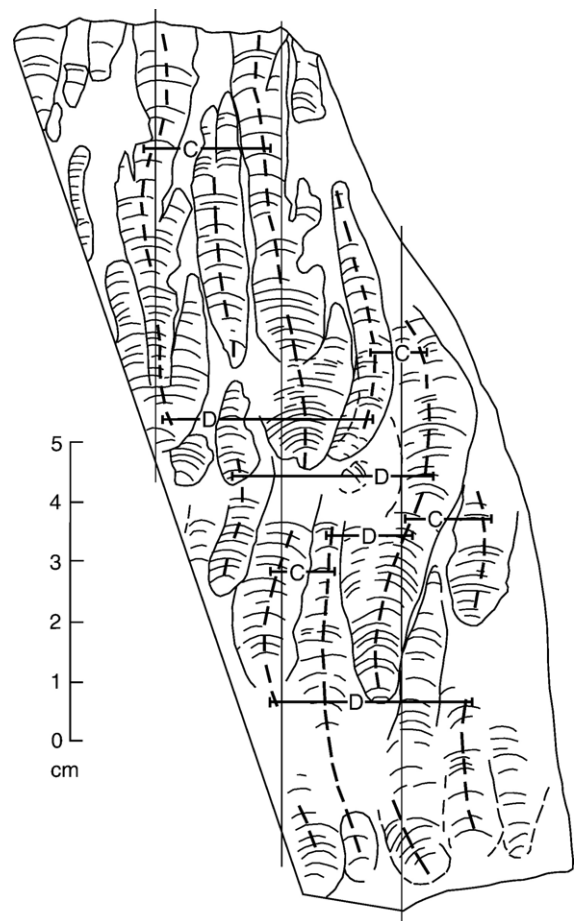


Fig. 3. Identifiable columns of *Anabaria juvenis* traced from Fig. 3 of Vanyo and Awramik (1985). Blank areas represent intercolumn filling. The thick dashed lines, as drawn by Vanyo and Awramik (1985) to highlight column axes, are generalised and traverse several discrete columns. The three long straight lines were taken as net vertical by Vanyo and Awramik (1985). Column branching occurs in several places, and divergence (D) and convergence (C) of column axes is evident at the opposite ends of the horizontal bars.

the Neoproterozoic succession in the Amadeus Basin (Fig. 2). Walter et al. (1979) gave the age of the Bitter Springs Formation as between 900 and 750 Ma, and Vanyo and Awramik (1982, 1985) took an age of 850 Ma for that formation and the stromatolitic unit containing *A. juvenis*. Hill and Walter (2000) and Walter et al. (2000) used new information to deduce an age of ~830 Ma for the Bitter Springs Formation. From bio- and chemostratigraphy, Grey et al. (2005) correlated the upper part of the Bitter Springs Formation with the Rook Tuff in the Adelaide Rift Complex (Geosyncline), South Australia, which has a U–Pb zircon age of  $802 \pm 10$  Ma (Fanning et al., 1986).

The Neoproterozoic succession in the Amadeus Basin contains widespread disconformities and unconformities that mark major stratigraphic gaps, and the Bitter Springs Formation and Ediacaran strata are in close stratigraphic proximity in many parts of the basin. This stratigraphic proximity is evident in regional geological maps (Wells et al., 1968; Shaw et al., 1983; Oaks et al., 1991). Originally it was thought that the Ediacaran Pertatataka Formation directly overlay the Bitter Springs Formation in the northeastern part of the basin where Cloud's locality 4 occurs (Wells et al., 1970), and this locality was placed in the Gillen Member of the Bitter Springs Formation. Subsequent stratigraphic studies (Preiss et al., 1978; Shaw and Wells, 1983) recognised the glaciofluvial Pioneer Sandstone and tillitic Olympic Formation of the younger Cryogenian glaciogenic succession (Fig. 2), which unconformably overlies the Bitter Springs Formation in parts of the Amadeus Basin. The dolomite unit hosting the columnar stromatolite *A. juvenis* occurs widely in the basin and is now regarded as the marker cap dolomite above the Pioneer Sandstone and equivalent strata (Jenkins et al., 1993; Kennedy, 1993; Grey et al., 2005). At Cloud's locality 4 the erosional disconformity at the top of the Gillen Member of the Bitter Springs Formation has a local relief of several metres and is marked by a weakly developed, conglomeratic regolith (Jenkins et al., 1993). A 2–15 cm thick, stromatolitic cherty dolomite overlies the regolith and is conformably followed by red and green shale of the Pertatataka Formation. At "Battery Flat" 1.5 km southwest of locality 4, 10 m of pebble conglomerate and sandstone of the Pioneer Sandstone overlie regolith breccia, or the Bitter Springs Formation with angular discordance, and are succeeded by a 10 cm stromatolitic unit like that at locality 4 (Jenkins et al., 1993). The Olympic Formation and Pioneer Sandstone are correlative with the late Cryogenian glaciogenic Elatina Formation of the Marinoan Series in the Adelaide Rift Complex (Preiss et al., 1978; Preiss,

1987; Jenkins et al., 1993). Hence the stromatolitic, upper marker cap dolomite in the northeastern Amadeus Basin (Fig. 2) may be equated with the Ediacaran Nuccaleena Formation, which constitutes the cap dolomite above the Elatina Formation (Preiss et al., 1978; Preiss, 1987; Knoll et al., 2004; Grey et al., 2005).

The Elatina ("Marinoan") glaciation in South Australia (Mawson, 1949) has not been dated precisely. A maximum age is provided by a U–Pb age of  $657 \pm 17$  Ma for a single zircon grain from the underlying late Cryogenian Marino Arkose in the southern Adelaide Rift Complex (Ireland et al., 1998; Preiss, 2000). Suggested ages of glaciation of  $635.5 \pm 1.2$  Ma (Hoffmann et al., 2004) and near 580 Ma (Calver et al., 2004) are based on U–Pb zircon dating of volcanic rocks in Namibia and Tasmania, respectively, that are associated with diamictites presumed to be coeval with the Elatina glaciation. The temporal relationship of the rocks in Tasmania and the glaciogenic succession in South Australia is unclear, however, and the Tasmanian rocks may be related to the glaciogenic Gaskiers Formation in Newfoundland, which has been dated at ~580 Ma (Bowring et al., 2003). Zhou et al. (2004) gave a lower age limit of  $663 \pm 4$  Ma and Condon et al. (2005) an upper age limit of  $635.2 \pm 0.6$  Ma for the Nantuo glaciation in China, which they equated with the Elatina glaciation. Recent geochronological studies of the preceding "Sturtian" glaciation in South Australia place further constraints on the maximum age of the Elatina glaciation: Re–Os dating gave an age of  $643.0 \pm 2.4$  Ma for black shale that directly overlies Sturtian glaciogenic deposits (Kendall et al., 2006), and zoned igneous zircon from tuff interbedded with Sturtian glaciogenic deposits gave a U–Pb SHRIMP age of ~658 Ma (Fanning and Link, 2006). An estimated age of ~600 Ma for the Elatina glaciation was based on chemostratigraphy (Walter et al., 2000). The above findings together imply maximum and minimum age limits of about 640 and 600 Ma for the Elatina glaciation. Hence the dolomite unit containing *A. juvenis* in the Amadeus Basin is some 200 million years younger than the age taken by Vanyo and Awramik (1982, 1985).

### 3. Stromatolite taxonomy

Cloud and Semikhatov (1969, pp. 1026, 1033) described the shape of columns of *A. juvenis* as "subcylindrical, smooth", the type of branching as "expanding, radiate, multibranching", and the group characteristics as follows: "Bushy colonies consisting of straight or slightly curved columns 5 to 20 mm in diameter, with complicated branching. Before branching columns



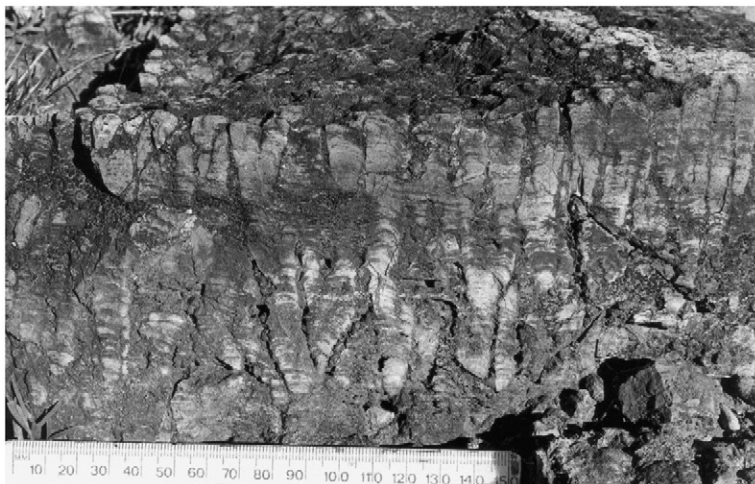


Fig. 4. *Anabaria*=*Kotuikania juvenis* exposed in vertical section at Cloud's locality 4, showing strongly branching and divergent columns. Scale graduated in millimetres.

thicken, then split into thinner columns or finger-like branches which fan out from the locus of branching. Complication and frequency of branching increases upward." A polished surface of the holotype (Cloud and Semikhatov, 1969, their plate 5) shows multiple branching and divergent and convergent columns.

Walter (1972) identified several Neoproterozoic stromatolites from the Amadeus Basin, but did not give a detailed description of *A. juvenis*. He stated (p. 34): "My examination of the holotype of *A. juvenis* revealed markedly divergent branching in the lower part, a

banded microstructure, and a multilaminar wall... No previously described forms of *Anabaria* have markedly divergent branching and the combination of characters listed here indicates classification as a form of *Kotuikania* would be most appropriate. More specimens are needed for complete identification."

Walter et al. (1979, pp. 294–296) provided a detailed description of *A. juvenis* based on a further three specimens from Cloud's locality 4. They found that the morphology and microstructure together indicate a very close similarity to *Kotuikania torulosa* Komar, the diagnosis of which includes active branching and

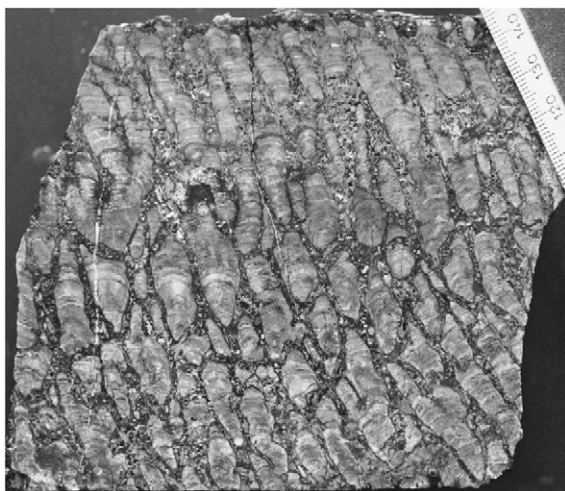


Fig. 5. Section of one of our specimens of *Anabaria*=*Kotuikania juvenis* that is cut at 12° to the mean trend of column axes, showing column branching and apparently short and discontinuous columns. Scale graduated in millimetres. The edge of the scale indicates the mean trend of columns as seen in this section.

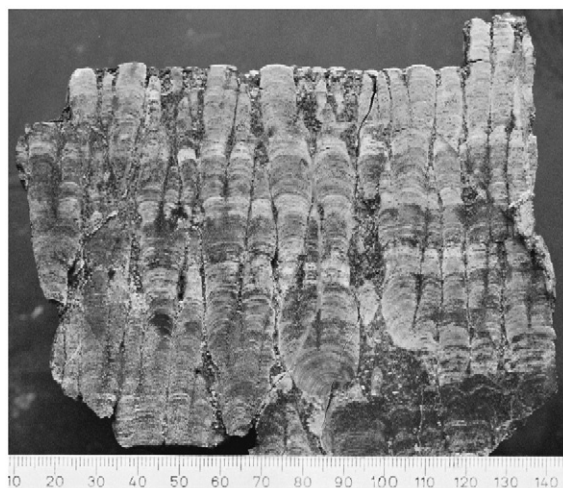


Fig. 6. Section of one of our specimens of *Anabaria*=*Kotuikania juvenis* that is cut parallel to the mean trend of column axes, showing column branching and divergent and convergent columns. Scale graduated in millimetres.

nonparallel axes of columns (Komar, 1964). The specimens from locality 4 have subcylindrical columns that are equidimensional in transverse section. Columns near the base of the bed range from 30 to 50 mm in width and branch moderately frequently, and in the upper part of the bed they are 10–30 mm wide and branch frequently. “Parallel to markedly divergent branching” produces narrow, closely spaced columns and projections. Walter et al. (1979, their Fig. 6, pp. 294–295) provided 11 reconstructions of columns showing “variable branching styles” and “bumpy and bulbous” forms but no apparent sine wave pattern. Laminae, where well preserved, are 50–150  $\mu\text{m}$  thick, steeply convex, and thickly coat column margins. Intercolumn filling comprises mostly detrital quartz grains  $\sim 100 \mu\text{m}$  in diameter and altered carbonate. Jenkins et al. (1993) referred informally to the columnar

stromatolite at this locality as *?Elleria minuta*. Pending further revision of Australian stromatolite taxonomy, henceforth we will refer to *Anabaria*=*Kotuikania juvenis* for the purposes of this paper.

Field observations by us at Cloud’s locality 4 and the study of 11 specimens we collected support the above descriptions of *A.=K. juvenis* and the finding that columns display various attitudes. Column branching is conspicuous in numerous field exposures (Fig. 4). Abrupt changes of thickness of the stromatolitic unit suggest that the regolith on the Bitter Springs Formation formed an irregular substratum, and locally the stromatolites form a dome structure several metres across with surface slopes of  $30^\circ$  relative to the palaeohorizontal and columns on opposite sides of the dome diverging by up to  $60^\circ$ . Our specimens of *A.=K. juvenis* provided 14 sections cut parallel to the mean

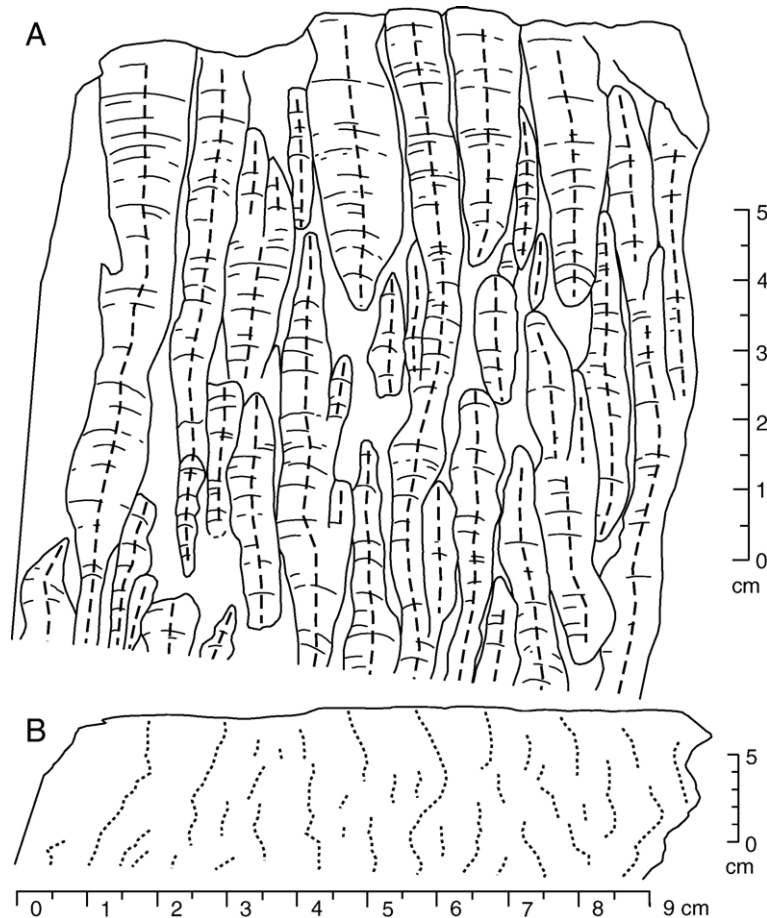


Fig. 7. Sketch of a section of one of our specimens of *Anabaria*=*Kotuikania juvenis* that is cut parallel to the mean trend of column axes. The dashed lines show column axes, and blank areas represent intercolumn filling. The section shows column branching, and divergent and convergent columns, at equivalent stratigraphic levels. Only one column, just to the right of centre, shows an apparent sine wave pattern, but column branching occurs in the two places of maximum curvature. A, horizontal/vertical = 1:1. B, horizontal/vertical = 1:0.25, which emphasises the various trends of the column axes shown in A.

trend of column axes, taken as approximating the palaeovertical, with one specimen having three cuts at angles of 60° and two specimens with perpendicular cuts. One specimen was cut at 12° to the mean trend of column axes. Nearly all the sections display branching columns (Figs. 5–7), with divergence and convergence of columns at equivalent stratigraphic levels evident in numerous places. Columns seen in the section cut at 12° to the mean trend of column axes appear shorter and discontinuous (Fig. 5). Only in one section does a column seem to approximate a sine wave (Fig. 7), but in that instance column branching occurs in the two places of maximum curvature and the same section displays numerous divergent and convergent columns.

## 4. Discussion

### 4.1. The heliotropism problem

Awramik and Vanyo (1986) and Vanyo et al. (1986) reported examples of heliotropism in modern stromatolites in Shark Bay, Western Australia, and Yellowstone National Park, USA. However, some years earlier Walter et al. (1976) sought evidence of heliotropism in stromatolites in Yellowstone National Park but found none, although they identified stromatolites inclined in the direction of water flow. Moreover, stromatolites in Shark Bay display a wide variety of morphologies whose distribution is controlled by physical processes of the local environment (Hoffman, 1976). A small, branching, columnar form occurs along shorelines where a shallow sublittoral shelf gives partial protection from wave action, with the stromatolite columns tilted seaward into the oncoming waves. Chivas et al. (1990, p. 120–121) found that stromatolites in Shark Bay show net vertical growth rates up to 250-fold slower “than those rates postulated by laminae-counting of some Precambrian stromatolites formed in quiescent environments (Vanyo and Awramik, 1982) and warn against interpreting some stromatolite-bearing rock sequences as possible indicators of heliotropism”. The occurrence of heliotropism in modern stromatolites therefore must be viewed as contentious.

Vologdin (1964) was a pioneer in the search for evidence of heliotropism in Precambrian stromatolite growth, and some of the branching stromatolites he illustrated resemble those described here. His research languished until the work of Vanyo and Awramik (1982, 1985). The growth patterns that Vologdin (1964) observed are not consistently developed, however, and we argue here that such patterns cannot be ascribed to heliotropism.

As discussed in Section 1, Vanyo and Awramik (1982, 1985) based their premise of Neoproterozoic stromatolite heliotropism on a single specimen of *A.=K. juvenis*. They argued that one vertical section through the specimen revealed seven stromatolite columns, some of which show an apparent sine wave growth pattern. However, the interpreted column axes drawn by them on a photograph of the original specimen (Vanyo and Awramik, 1985, their Fig. 3), and reproduced exactly in our Fig. 3, display divergence and convergence in numerous places and no consistent sinusoidal pattern. Column branching is evident in several places in their photograph. Our examination of the photograph also suggests the presence of mostly short, apparently discontinuous columns (Fig. 3), a pattern similar to that seen in our section cut at a small angle to the mean trend of column axes (Fig. 5). Vanyo and Awramik (1982, 1985) did not mention the divergence and convergence of columns evident in their section. They thought that a sinusoidal pattern was “superimposed on the branching columns” (Vanyo and Awramik, 1982, p. 1125), but column branching was not mentioned in their later, more detailed paper (Vanyo and Awramik, 1985).

The descriptions of *A.=K. juvenis* by Cloud and Semikhatov (1969), Walter (1972) and Walter et al. (1979), our field observations and study of numerous new specimens, and scrutiny of Fig. 3 in Vanyo and Awramik (1985) demonstrate that the stromatolite columns typically exhibit various attitudes, marked by branching, divergence and convergence. Hence, averaged incident solar radiation cannot have controlled the various non-vertical growth patterns. The rare, apparent sinuosity of columns is seen as the fortuitous product of column irregularity and column branching.

### 4.2. Geophysical implications

We have shown that column growth of the stromatolite *A.=K. juvenis* could not have been heliotropic. Hence, this stromatolite cannot be used to determine palaeo-obliquity, and the value of 26°30' estimated by Vanyo and Awramik (1982, 1985) for the Neoproterozoic obliquity should be disregarded.

As discussed in Section 1, Vanyo and Awramik (1982, 1985) gave an estimate of ~435 (range 409–485) days/year based on extrapolated counts of laminae, taken to be diurnal, for four perceived yearly sine waves in the original specimen of *A.=K. juvenis*. This figure conflicts with that of 400±7 solar days/year indicated by the 60-year-long record of tidal rhythmites — vertically-accreted, laminated sediments displaying periodic variations in lamina thickness reflecting a tidal



influence on deposition — from the late Cryogenian (~640–600 Ma) Elatina Formation–Reynella Siltstone Member in the Adelaide Rift Complex (Williams, 1989, 1998, 2000). The Elatina–Reynella data-set contains a wide range of self-consistent palaeotidal periods and provides the best constrained determination of days/year for the Neoproterozoic. The revised stratigraphy of *A. = K. juvenis* implies that the stromatolitic unit in the Amadeus Basin is penecontemporaneous with the Elatina Formation. Because the growth pattern of the stromatolite columns cannot have been heliotropic, and in view of the conflict with the Elatina–Reynella datum, the figure of 435 days/year estimated by Vanyo and Awramik (1982, 1985) also should be rejected.

Qu et al. (2004), in a study strongly influenced by that of Vanyo and Awramik (1982, 1985), argued that a claimed S-shaped growth pattern in a single, incomplete dome-like stromatolite in China revealed there were 12.9 months/year and 516 days/year and the obliquity was 29.2–30.6° at 1000 Ma. Their photographs of the structure show disturbed laminae passing upward into a fragmentary dome with only part of the top preserved. The claimed S-curve is double an alleged half-cycle and is highly speculative. Moreover, employing equations of celestial mechanics (Williams, 1998, 2000) indicates that 12.9 months/year equates to 394 days/year, not 516 days/year. This major inconsistency shows that the palaeotidal and palaeorotational periods stated by Qu et al. (2004) are invalid, thus casting strong doubt on their entire analysis. The study of Qu et al. (2004) further demonstrates the imprudence of generalising from solitary and fragmentary observations.

## 5. Summary and conclusions

Field observations and examination of 11 additional specimens of the columnar stromatolite *A. = K. juvenis* from a Neoproterozoic dolomite unit in the Amadeus Basin, central Australia (Vanyo and Awramik, 1982, 1985), and stratigraphic studies, indicate the following:

1. The stromatolite columns are strongly branching, producing divergent and convergent columns in numerous places at the same stratigraphic level. Heliotropism cannot have controlled such various non-vertical growth patterns.
2. The rare, apparent sinuosity of columns is seen as the fortuitous product of column irregularity and column branching to accommodate adjacent columns.
3. Contrary to the stratigraphy and age originally assigned to the dolomite unit hosting *A. = K. juvenis* and employed by Cloud and Semikhatov (1969) and

Vanyo and Awramik (1982, 1985), the unit does not belong to the 850 Ma Bitter Springs Formation. Stratigraphic studies (Shaw et al., 1983; Shaw and Wells, 1983; Jenkins et al., 1993; Kennedy, 1993) indicate that the host dolomite unit belongs to the Ediacaran (~600 Ma) marker cap dolomite above the younger Cryogenian glaciogenic succession in the Amadeus Basin.

4. The figure of ~435 (range 409–485) days/year estimated by Vanyo and Awramik (1982, 1985) from counts of stromatolite laminae conflicts with that of  $400 \pm 7$  days/year indicated by a 60-year-long, high quality palaeotidal record provided by late Cryogenian (~640–600 Ma) tidal rhythmites in the Adelaide Rift Complex, South Australia (Williams, 2000).

We conclude that the various non-vertical growth patterns displayed by the Ediacaran, strongly branching columnar stromatolite *A. = K. juvenis* cannot be ascribed to the sine wave growth model and heliotropism advocated by Vanyo and Awramik (1982, 1985). Inferences concerning Neoproterozoic obliquity of the ecliptic and palaeorotation therefore cannot be drawn from the growth patterns *A. = K. juvenis*.

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## References

- Awramik, S.M., Vanyo, J.P., 1986. Heliotropism in modern stromatolites. *Science* 231, 1279–1281.
- Bowring, S.A., Myrow, P., Landing, E., Ramenzani, J., 2003. Geochronological constraints on terminal Neoproterozoic events and the rise of Metazoans. NASA Astrobiology Institute General Meeting. Arizona State University, Tempe. abstract no. 13045.
- Calver, C.R., Black, L.P., Everard, J.L., Seymour, D.B., 2004. U–Pb zircon age constraints on late Neoproterozoic glaciation in Tasmania. *Geology* 32, 893–896.
- Chivas, A.R., Torgersen, T., Polach, H.A., 1990. Growth rates and Holocene development of stromatolites from Shark Bay, Western Australia. *Australian Journal of Earth Sciences* 37, 113–121.
- Christiansen, J.L., Stouge, S., 1999. Oceanic circulation as an element in palaeogeographical reconstructions: the Arenig (early Ordovician) as an example. *Terra Nova* 11, 73–78.
- Cloud, P.E., Semikhatov, M.A., 1969. Proterozoic stromatolite zonation. *American Journal of Science* 267, 1017–1061.



- Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A., Jin, Y., 2005. U–Pb ages from the Neoproterozoic Doushantuo Formation, China. *Science* 308, 95–98.
- Crisp, D.J., 1989. Tidally deposited bands in shells of barnacles and molluscs. In: Crick, R.E. (Ed.), *Origin, Evolution, and Modern Aspects of Biomineralization in Plants and Animals*. Plenum Press, New York, pp. 103–124.
- Eagan, K.E., Liddell, W.D., 1997. Stromatolite biostromes as bioevent horizons; an example from the Middle Cambrian Ute Formation of the eastern Great Basin. In: Brett, C.E., Baird, G.C. (Eds.), *Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications*. Columbia University Press, New York, pp. 285–308.
- Fanning, C.M., Link, P., 2006. Constraints on the timing of the Sturtian glaciation from southern Australia; ie for the true Sturtian. *Geological Society of America Abstracts with Programs* 38 (7), 115.
- Fanning, C.M., Ludwig, K.R., Forbes, B.G., Preiss, W.V., 1986. Single and multiple grain U–Pb zircon analyses for the early Adelaidean Rook Tuff, Willouran Ranges, South Australia. *Geological Society of Australia Abstracts* 15, 71–72.
- Grey, K., Hocking, R.M., Stevens, M.K., Bagas, L., Carlsen, G.M., Irimies, F., Pirajno, F., Haines, P.W., Apak, S.N., 2005. Lithostratigraphic nomenclature of the Officer Basin and correlative parts of the Paterson Orogen, Western Australia. *Geological Survey of Western Australia Report*, vol. 93. 89 pp. Available online free-of-charge at <http://www.doir.wa.gov.au/GSWA/onlinepublications>.
- Hill, A.C., Walter, M.R., 2000. Mid-Neoproterozoic (~850–750 Ma) isotope stratigraphy of Australia, and global correlation. *Precambrian Research* 100, 181–211.
- Hoffman, P., 1976. Stromatolite morphogenesis in Shark Bay, Western Australia. In: Walter, M.R. (Ed.), *Stromatolites. Developments in Sedimentology*, vol. 20. Elsevier, Amsterdam, pp. 261–271.
- Hoffmann, K.-H., Condon, D.J., Bowring, S.A., Crowley, J.L., 2004. U–Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation. *Geology* 32, 817–820.
- Hofmann, H.J., 1973. Stromatolites: characteristics and utility. *Earth-Science Reviews* 9, 339–373.
- Ireland, T.R., Flöttmann, T., Fanning, C.M., Gibson, G.M., Preiss, W.V., 1998. Development of the early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen. *Geology* 26, 243–246.
- Jenkins, R.J.F., Lindsay, J.F., Walter, M.R., 1993. Field guide to the Adelaide Geosyncline and Amadeus Basin, Australia. *Australian Geological Survey Organisation Record* 1993/35. 133 pp.
- Kendall, B., Creaser, R.A., Selby, D., 2006. Re–Os geochronology of postglacial black shales in Australia: Constraints on the timing of “Sturtian” glaciation. *Geology* 34, 729–732.
- Kennedy, M., 1993. The Undoolya Sequence: Late Proterozoic salt influenced deposition, Amadeus Basin, central Australia. *Australian Journal of Earth Sciences* 40, 217–228.
- Knoll, A.H., Walter, M.R., Narbonne, G.M., Christie-Blick, N., 2004. A new period for the geologic time scale. *Science* 305, 621–622.
- Komar, V.A., 1964. Columnar stromatolites from the Riphean of the North Siberian Platform. *Paleontologiya i Biostratigrafiya Vypusk* 6, 84–105 (in Russian).
- Kusky, T.M., Vanyo, J.P., 1991. Plate reconstructions using stromatolite heliotropism: principles and applications. *Journal of Geology* 99, 321–335.
- Lambeck, K., 1980. *The Earth’s Variable Rotation: Geophysical Causes and Consequences*. Cambridge University Press, Cambridge. 449 pp.
- Mawson, D., 1949. The Elatina glaciation. *Transactions of the Royal Society of South Australia* 73, 117–121.
- McMenamin, M.A.S., 2004. Climate, paleoecology and abrupt change during the late Proterozoic: a consideration of causes and effects. In: Jenkins, G.S., McMenamin, M.A.S., McKay, C.P., Sohl, L. (Eds.), *The Extreme Proterozoic: Geology, Geochemistry and Climate*. American Geophysical Union Geophysical Monograph, vol. 146, pp. 215–229.
- Monty, C.L.V., 1967. Distribution and structure of Recent stromatolitic algal mats, Eastern Andros Island, Bahamas. *Annales de la Société Géologique Belgique* 90, 55–100.
- Oaks, R.Q., Stewart, A.J., Deckelman, J.A., Conrad, K.T., 1991. *Geology of the northeastern Amadeus Basin, 1:100 000 scale map (first edition)*. Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia), Canberra. Provided free-of-charge on request by the Northern Territory Geological Survey, Darwin [http://www.nt.gov.au/dpifm/Minerals\\_Energy/Geoscience/](http://www.nt.gov.au/dpifm/Minerals_Energy/Geoscience/).
- Oliver, D.H., Ronald, S., 2004. Evolution of torque in the Earth–Moon system as indicated by invertebrate growth bands. *Geological Society of America Abstracts with Programs* 36 (5), 205.
- Preiss, W.V. (Ed.), 1987. *The Adelaide Geosyncline*. South Australian Department of Mines and Energy Bulletin, vol. 53. 438 pp.
- Preiss, W.V., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. *Precambrian Research* 100, 21–63.
- Preiss, W.V., Walter, M.R., Coats, R.P., Wells, A.T., 1978. Lithological correlations of Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia and Georgina Basins. *BMR Journal of Australian Geology and Geophysics* 3, 43–53.
- Qu, Y., Xie, G., Gong, Y., 2004. Relationship between Earth–Sun–Moon 1000 Ma ago: Evidence from the stromatolites. *Chinese Science Bulletin* 49, 2288–2295 (English edition. Accessible online at <http://scholar.google.com/>).
- Reid, R.P., Visscher, P.T., Decho, A.W., Stolz, J.F., Bedout, B.M., Dupraz, C., Macintyre, I.G., Paerl, H.W., Pinckney, J.L., Prufert-Bedout, L., Steppe, T.F., DesMarais, D.J., 2000. The role of microbes in accretion, lamination and early lithification of modern marine stromatolites. *Nature* 406, 989–992.
- Rosenberg, G.D., Runcorn, S.K. (Eds.), 1975. *Growth Rhythms and the History of the Earth’s Rotation*. Wiley, London. 559 pp.
- Scrutton, C.T., 1978. Periodic growth features in fossil organisms and the length of the day and month. In: Brosche, P., Sündermann, J. (Eds.), *Tidal Friction and the Earth’s Rotation*. Springer, Berlin, pp. 154–196.
- Shaw, R.D., Wells, A.T., 1983. *Alice Springs, Northern Territory, Sheet SF53-14 (second edition), 1:250 000 Geological Series—Explanatory Notes*. Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia), Canberra. 44 pp. [http://www.nt.gov.au/dpifm/Minerals\\_Energy/Geoscience](http://www.nt.gov.au/dpifm/Minerals_Energy/Geoscience).
- Shaw, R.D., Langworthy, A.P., Stewart, A.J., Offe, L.A., Jones, B.G., O’Donnell, I.C., Knight, C.P., 1983. *Alice Springs, Northern Territory, 1: 250 000 Geological Sheet SF53-14, second edition*. Available online free-of-charge from Geoscience Australia, Canberra, at <http://www.geoscience.gov.au/geoportal/250>.
- Smith, A.M., Uken, R., Thackeray, Z., 2005. Cape Morgan peritidal stromatolites: the origin of lamination. *South African Journal of Science* 101, 107–108.
- Vanyo, J.P., Awramik, S.M., 1982. Length of day and obliquity of the ecliptic 850 Ma ago: preliminary results of a stromatolite growth model. *Geophysical Research Letters* 9, 1125–1128.

- Vanyo, J.P., Awramik, S.M., 1985. Stromatolites and Earth–Sun–Moon dynamics. *Precambrian Research* 29, 121–142.
- Vanyo, J.P., Hutchinson, R.A., Awramik, S.M., 1986. Heliotropism in microbial stromatolitic growths at Yellowstone National Park: geophysical inferences. *Eos* 67, 153 and 155–156.
- Vologdin, A.G., 1964. Stromatolites and phototropism. *Doklady of the Academy of Sciences of the USSR* 151, 196–198 (Translated from *Doklady Akademii Nauk SSSR* 151, 683–686, 1963.).
- Walter, M.R., 1972. Stromatolites and the biostratigraphy of the Australian Precambrian and Cambrian. *Special Papers in Palaeontology* 11 (190 pp.).
- Walter, M.R., Bauld, J., Brock, T.D., 1976. Microbiology and morphogenesis of columnar stromatolites (*Conophyton*, *Vaccerrilla*) from hot springs in Yellowstone National Park. In: Walter, M.R. (Ed.), *Stromatolites. Developments in Sedimentology*, vol. 20. Elsevier, Amsterdam, pp. 273–310.
- Walter, M.R., Krylov, I.N., Preiss, W.V., 1979. Stromatolites from Adelaidean (Late Proterozoic) sequences in central and South Australia. *Alcheringa* 3, 287–305.
- Walter, M.R., Veevers, J.J., Calver, C.R., Gorjan, P., Hill, A.C., 2000. Dating the 840–544 Ma Neoproterozoic interval by isotopes of strontium, carbon, and sulfur in seawater, and some interpretative models. *Precambrian Research* 100, 371–433.
- Wells, J.W., 1963. Coral growth and geochronometry. *Nature* 197, 948–950.
- Wells, A.T., Forman, D.J., Milligan, E.N., Stewart, A.J., Shaw, R.D., Kruger, N.L., 1968. Alice Springs, Northern Territory, 1: 250 000 Geological Sheet SF53-14, first edition. Bureau of Mineral Resources, Geology and Geophysics (now Geoscience Australia), Canberra.
- Wells, A.T., Forman, D.J., Ranford, L.C., Cook, P.J., 1970. Geology of the Amadeus Basin, central Australia. Bureau of Mineral Resources, Geology and Geophysics Bulletin, vol. 100. 222 pp.
- Wilde, P., 1991. Oceanography in the Ordovician. In: Barnes, C.R., Williams, S.H. (Eds.), *Advances in Ordovician Geology*. Geological Survey of Canada Paper, vol. 90-9, pp. 283–298.
- Williams, G.E., 1989. Tidal rhythmites: geochronometers for the ancient Earth–Moon system. *Episodes* 12, 162–171.
- Williams, G.E., 1998. Precambrian tidal and glacial clastic deposits: implications for Precambrian Earth–Moon dynamics and palaeoclimate. *Sedimentary Geology* 120, 55–74.
- Williams, G.E., 2000. Geological constraints on the Precambrian history of Earth’s rotation and the Moon’s orbit. *Reviews of Geophysics* 38, 37–59.
- Zhou, C., Tucker, R., Xiao, S., Peng, Z., Yuan, X., Chen, Z., 2004. New constraints on the ages of Neoproterozoic glaciations in south China. *Geology* 32, 437–440.