Paleontological Evidence of Variations in Length of Synodic Month since Late Cambrian

Abstract. *The values of length of synodic month, obtained from tidally controlled periodical growth patterns in mollusks and stromatolites for several geologic periods, indicate that the deceleration rate of the earth's rotation has not been constant. Two breaks in slope, in the Pennsylvanian and Cretaceous, may be related to changes in distribution of continents, oceans, and adjacent shallow seas.*

The scanty paleontological evidence on the number of days per year and per synodic month in the geological past now available in the literature (*1–3*) has been accepted and used by geophysicists as support for their astronomical calculations and theories on the earth-moon system (*4*). The evidence seems to confirm the assumption that the tidal torque has affected the earth's rotation rate in a uniform fashion and that the slowing down is in agreement with the rate of 2 milliseconds per century extrapolated from modern observations (*5*). The paucity of paleontological data renders this conclusion highly speculative, and much more data must be gathered before it becomes tenable. Although preliminary, the results presented here may help to provide a firmer foundation for geophysical theories.

Before we discuss the data, it would be appropriate to pose the question: how reliable and precise is the information derived from paleontological clocks? Circadian rhythms regulate almost universally the world of living matter, and it is reasonable to think they may leave a record in the skeleton of continuously growing organisms. In fact, there is a large enough body of information on growth bandings in many taxons to justify the conclusion that daily growth increments are a widespread feature in the organic world. Do these daily bandings, however, record solar or synodical time? From experiments on bivalve mollusks (*6*) it is safe to conclude that solar time is the basic unit reflected in the increments and that synodical time, at least in intertidal and shallow subtidal bivalves, is expressed in the thickness of the increments. During periods of particularly favorable time, such as summer-spring tides, the mantle of certain bivalves expands outward and deposits a ridge. In other bivalves ridges are formed once every synodic month. Generic, specific, and individual differences should be carefully weighted in interpreting the growth patterns. Breeding events, which in many organisms seem to be related to moon phases and to tides, also leave a record on the growth patterns and may be useful in detecting synodical periodicity. When dealing with fossils, however, difficulties arise. Poor preservation, ambiguity of growth patterns, and lack of modern representatives make the counts of growth increments highly subjective. In general, growth patterns record fewer increments than actual days. The gaps in the record, which are randomly controlled by the environment, affect the degree of precision of the information since there is no way to establish the ratio for each specimen. The degree of resolution required by geophysicists is higher than the precision obtainable from the paleontological-clock method when based on the few data so far gathered. Hopefully, with the use of many different taxons, not only corals or bivalves, integrated data will be gathered and the resolution of the method will be enhanced.

Our paleontological evidence for the length of the synodic month is listed in Table 1. Most of the data were obtained from bivalves, the exceptions being the cephalopod counts for the Lower Pennsylvanian and the stromatolite counts for the Upper Cambrian. For control and comparison, counts from the Recent bivalve *Mercenaria mercenaria* from New England are also shown. Counts of growth patterns clearly incomplete or difficult to interpret have been omitted. Due to the difficulty of finding countable seasonal patterns in mollusks older than Cretaceous, only synodic-month patterns are considered here. For each specimen the average number of days per synodic month, the standard deviation, and the standard error are tabulated. The average value of 29.17 for the Recent is 1.0 percent less than the actual value for the synodic month. The ratio of 29.53 to 29.17 should be used to correct all the other values for bivalves, but, considering the variations of the averages, we did not dare to assume that this ratio is constant and characteristic for bivalves. Because we are more concerned with the shape of the curve that can be drawn from these data than with the absolute values for the geological past, we thought that the correction could be omitted.

Part of the data in Table 1 has already been published (*6*); some have been complemented with more counts and some are new. The change in the length of the synodic month for the Miocene, based on counts from one specimen of *Mercenaria campechiensis ochlockoneensis* that shows the same shell structures and growth patterns as the Recent *M. mercenaria*, is higher than the one predicted by astronomical calculations. Also the values for the Eocene and Upper Cretaceous are higher than those predicted. The figure of 29.65 days per synodic month (*3*) for the Upper Cretaceous is in agreement with the expected astronomical figure but much lower than ours. The discrepancy of the two figures, obtained from fossils approximately of the same age, may be due to a subjective bias in counting. It is impossible to say which of the two figures is closer to the actual value. However, all our values, including those for the Cretaceous, were obtained with the same degree of subjectivity and, if biased, are all biased in the same way. The relation among them should stay constant. The point for the Middle Triassic is less reliable than the others because it was obtained from specimens that show many disturbances and interruptions in deposition. The ratio between the actual number of days and the number of growth increments is probably much higher than the one obtained for the Recent *M. mercenaria*. The Pennsylvanian figure is based mainly on counts from *Conocardium*, an exceptional bivalve in every sense including preservation and clarity of growth patterns. Specimens of *C. herculeum* from Belgium have provided the counts for the Mississippian. Their unique preservation, due to the formation of a protective silicified cortex around islands of original shell material that retains magnificent growth patterns (Fig. 1A), allows accurate counts. The Mississippian point should be considered highly reliable and weighted almost as much as the one for the Recent. The questionable figure for the Devonian, from counts in poorly preserved *Conocardium* specimens, compares well with Scrutton's (*2*) figure of 30.59 days per month from corals. Finally, the point for the Upper Cambrian was obtained from counts in a stromatolite. Daily growth bandings in stromatolites are arranged in unequivocal periodic patterns (Fig. 1, B and C) and should provide another paleontological clock extending back in time 3 billion years (*7*). Growth patterns are commonly discontinuous and irregular and the chances of finding complete yearly records are slim. Yet tidal and synodical patterns are generally clear, and they are easily recognizable when incomplete. If the incompleteness of the record is a definite limitation for

Table 1. The mean number of days per synodic month from Late Cambrian to Recent based on growth-increment counts. Approximate absolute ages estimated from Kulp (*10*). For construction of the best-fitting curve (Fig. 2), subjective weights on a scale from 1 (questionable) to 10 (reliable) have been given to the average for each major geologic interval. Abbreviations: S.D., standard deviation; S.E., standard error; fm., formation; Ls., limestone; Sh., shale; YPM-IP refers to material in the collection of the Division of Invertebrate Paleontology, Peabody Museum, Yale University.

Taxon	YPM-IP locality*	YPM-IP specimen number	Synodic-month patterns (No.)	Days (total No.)	Increments/month (mean)	S.D.	S.E.	Weight
			Recent					
Mercenaria mercenaria (Linnaeus)	A-7267, Cape Cod	26310	25	727	29.08	±1.22	±0.24	
M. mercenaria	A-7267, Cape Cod	26307	19	562	29.58	±1.35	±0.31	
M. mercenaria	A-6843, Cape Cod	26305	42	1217	28.98	±0.87	±0.13	
M. mercenaria	A-7267, Cape Cod	26312	24	703	29.29	±1.04	±0.21	
M. mercenaria	A-7267, Cape Cod	26309	16	467	29.19	±1.05	±0.26	
M. mercenaria	A-6834, Cape Cod	26304	18	524	29.11	±0.90	±0.21	
			Mean of all counts:		**29.17**	±1.06	±0.09	10
			Upper Miocene, 18 million years ago					
M. campechiensis ochlockoneensis (Mansfield)	A-4633, Choctawhatchee fm.	26376	65	1911	**29.40**	±0.97	±0.12	3
			Upper Eocene, 40 million years ago					
Crassatella mississippiensis Conrad	Vicksburg, Miss.	26377	38	1126	29.63	±0.97	±0.16	
			Middle Eocene, 46 million years ago					
Cardita planicosta (Lamarck)	Claiborne fm.	26380	50	1498	29.96	±0.88	±0.12	
			Mean of all Eocene counts:		**29.82**	±0.93	±0.10	8
			Upper Cretaceous, 72 million years ago					
Limopsis striatopunctatus Evans and Schumard	A-1006, Fox Hills fm.	26322	18	534	29.67	±1.03	±0.24	
L. striatopunctatus	A-1008, Fox Hills fm.	26801	29	868	29.93	±1.16	±0.22	
L. striatopunctatus	A-1008	26802	15	446	29.73	±0.70	±0.18	
Cucullaea nebrascensis Owen	A-343, Fox Hills fm.	26381	19	574	30.21	±1.03	±0.24	
Tancredia americana (Meek and Hayden)	A-724, Fox Hills fm.	26382	18	540	30.00	±0.84	±0.20	
			Mean of all counts:		**29.92**	±1.00	±0.10	7.5
			Middle Triassic, 205 million years ago					
Palaeoneilo lineata Goldfuss	St. Cassian Beds	26803	17	507	29.82	±1.24	±0.30	
P. lineata	St. Cassian Beds	26804	17	506	29.76	±1.15	±0.28	
Cardita crenata Goldfuss	St. Cassian Beds	26805	10	293	29.30	±1.25	±0.40	
			Mean of all counts:		**29.68**	±1.20	±0.18	1
			Upper Pennsylvanian, 290 million years ago					
Conocardium sp.	A-6505, Vilas Sh.?	26383	17	521	30.65	±0.70	±0.17	
Conocardium sp.	A-6505, Vilas Sh.?	26378	78	2337	29.96	±0.83	±0.09	
Conocardium sp.	A-6505, Vilas Sh.?	26384	15	448	29.87	±0.52	±0.13	
			Lower Pennsylvanian, 305 million years ago					
Cephalopod sp.	3449/1, Kendrick Sh.	26323	9	272	30.22	±1.20	±0.40	
			Mean of all Pennsylvanian counts:		**30.07**	±0.84	±0.08	4
			Lower Mississippian, 340 million years ago					
Conocardium herculeum Koninck	Carboniferous Ls., Tournay	26806	66	1998	30.27	±1.30	±0.16	
C. herculeum	Carboniferous Ls., Tournay	26807	72	2193	30.46	±1.28	±0.15	
			Mean of all counts:		**30.37**	±1.28	±0.11	9
			Middle Devonian, 380 million years ago					
Conocardium bellum Cooper and Cloud	5179/64 Alpena Ls.	26808	30	916	**30.53**	±1.25	±0.23	2
			Upper Cambrian, 510 million years ago					
Stromatolite	Conococheague fm.	13849	18	568	**31.56**	±3.15	±0.74	2

* Localities are further defined: Cape Cod, Mass.; Choctawhatchee fm., Fla.; Vicksburg, Miss.; Claiborne fm., Bells Landing, Ala.; Fox Hills fm., S. Dak.; St. Cassian Beds, St. Cassian, Italy; Vilas Sh.?, Okla.; Kendrick Sh., Ky.; Tournay, Belgium; Alpena Ls., Mich.; Conococheague fm., Md.

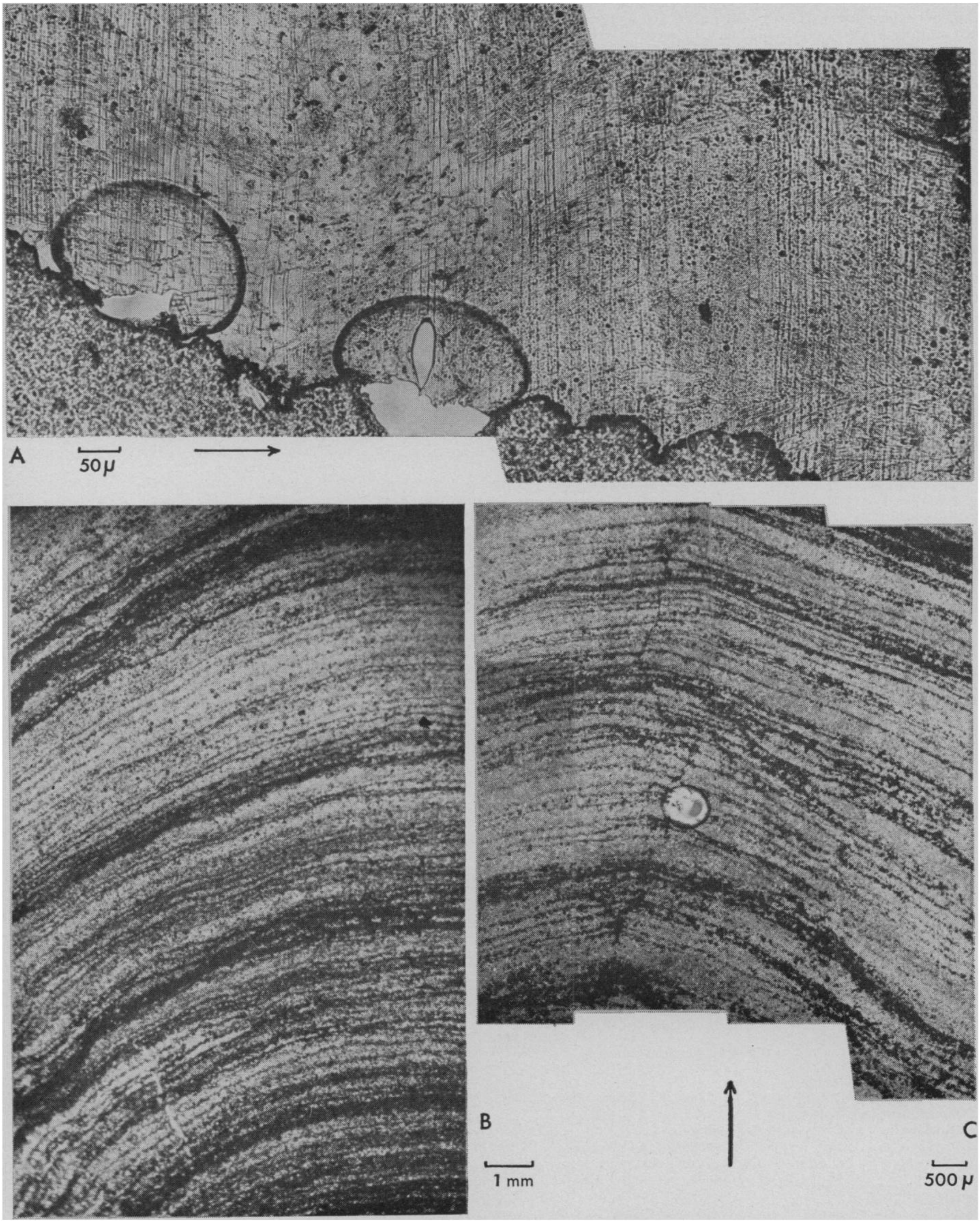

Fig. 1. Lunar periodicity expressed in growth patterns of daily increments in fossil marine organisms. Arrows indicate direction of growth. Given below are the initial magnifications of the microscope lens system. All photographs are of acetate peels (*6*). (A) *Conocardium herculeum* Koninck. Outer complex-prismatic shell layer, with growth increments almost at right angles to surface of maximum growth; Lower Mississippian, Carboniferous Limestone, Tournay, Belgium; silicified cortex bounds area of preserved increments; × 125; hypotype, YPM-IP No. 26807-i. (B and C) Stromatolite from Upper Cambrian Conococheague formation, Funks Farm, Maryland; hypotype, YPM-IP No. 13849-c. (B) Lunar-month periodicity dominant; × 6. (C) Fortnightly periodicity dominant; × 18.

their accuracy, their good preservation and abundance in rocks where no other fossils are available make stromatolites a useful paleontological tool especially for Precambrian evidence of synodic-month variations.

In order to ascertain their statistical significance, the data have been fitted by a polynominal of the form

$$L = A_0 + A_1T + A_2T^2 \ldots\ldots A_nT^n$$

where L is the length of the lunar month in days, and T is the absolute geological age in millions of years. A least-squares fitting program was used to fit polynomials of increasing degree, from 0 to 7, to the nine data points. Examination of the "F ratio" (*8*) for each successive fit indicated that the most likely fit was of order 4 (coefficients up to A_3) (Fig. 2).

On the basis of this analysis it would appear that the slowing down of the earth's rotation has not taken place at a uniform rate. Two major breaks in slope allow a tripartition of the curve: two parts with a slope higher than the predicted one, between Upper Cambrian and Pennsylvanian and between Upper Cretaceous and Recent, and one part with a slope lower than the predicted one between Pennsylvanian and Upper Cretaceous. This latter part of the curve spans more than 200 million years with only one insecure control point for the Middle Triassic. Even though any speculation on the trend of the curve within this span is premature, the end points indicate that from Pennsylvanian to Upper Cretaceous the slowing down has been negligible. It is tempting to relate the changes in slope to some hypothetical events in the earth's history. For instance, if the slowing down since the Late Cambrian is attributed mainly to the loss of energy due to tidal torque in shallow seas (*5*), then a different distribution of continents and oceans, and continental shelves and shallow seas would affect the amount of energy dissipated and the rotation rate of the earth. The idea that continental breaking down has not been a uniform process but has taken place in episodes of rapid drift, with little or no drift in between, has been suggested (*9*). The high slope between the Cretaceous and Recent could be attributed to the rapid drift episode of the Upper Cretaceous, which probably increased the tidal dissipation by broadening the proto-Atlantic and to the rise of the Alpine orogenic belt which created widespread shallow seas open to oceanic water masses. The lower rate of slowing down between Pennsylva-

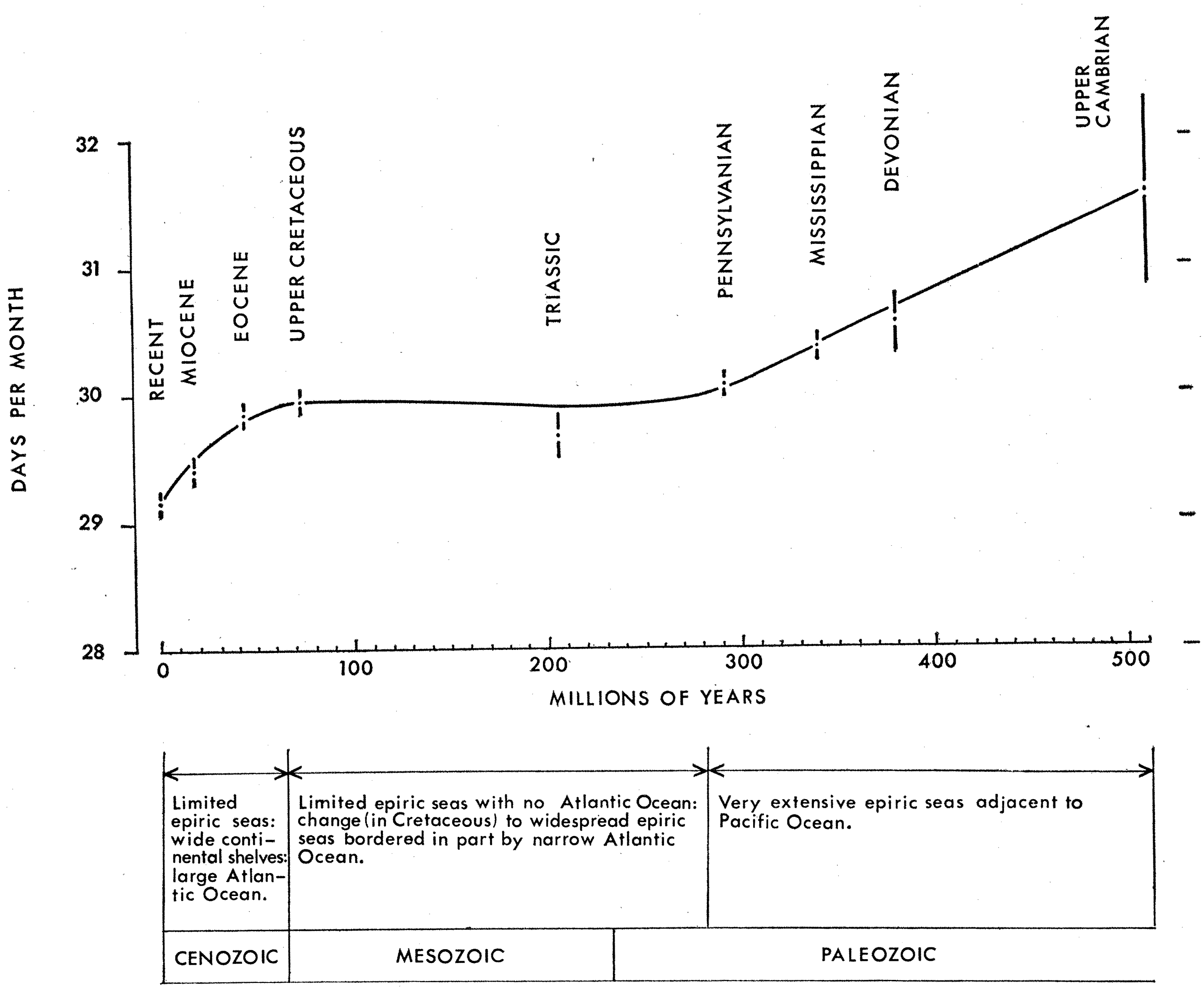

Fig. 2. Variations in the length of the synodic month through geologic time. The error bars show the standard error for each point. With each point weighted as shown in Table 1, the best-fitting curve is a fourth-order polynominal. The Pennsylvanian point, including the nine Lower Pennsylvanian counts (reliability weight of 1), is plotted at the Upper Pennsylvanian position.

nian and Cretaceous could be somehow related to the phenomena that caused the longest and most persistent period of worldwide regressive seas during Late Permian, Triassic, and Jurassic. The only way to account for large tidal dissipation rates in pre-Pennsylvanian time, when the Atlantic was not yet formed, would be the presence of extended shallow seas connected with the Pacific Ocean. Paleogeographic maps do show shallow seas along the rim of the Pacific in Asia and in the Americas.

Other assumptions, as speculative as this of the slowing down due mainly to tidal dissipation in shallow seas, can be made; but no matter what theory one likes best, the changes in slope must be related to events that profoundly affected the earth and that left other observable clues. The paleontological evidence presented does show, however, that the deceleration rate has not been constant through time, and that, by using the growth patterns of organisms, it will be possible to shed light on events that affected the general distribution of oceans and continents in the past.

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Pollen Grains in Lake Sediments: Redeposition Caused by Seasonal Water Circulation

Abstract. *Annual pollen deposition per unit area measured in sediment traps is two to four times greater than deposition measured in surface sediment cores. The difference is due to repeated redeposition of pollen from the sediment surface during seasons of water circulation. This process reduces variations in the percentages of different pollen types in sediment, but causes differences in the total amount of pollen accumulated in various parts of the lake basin.*

The numbers and kinds of pollen grains preserved in lake sediments depend on the surrounding terrestrial vegetation. Consequently fossil pollen grains, in stratigraphic sequence, provide a vegetation record through time. Factors affecting distribution of pollen grains within lake basins are important to paleoecology. These factors could distort the usual relation between vegetation and pollen content of sediments.

We have studied processes of sedimentation in lakes by measuring the deposition of pollen grains onto the lake bottom. This involves measuring not only deposition, but also resuspension and redeposition. Pollen redeposited from the sediment surface and new pollen entering the lake from the air were measured separately, permitting assessment of the effect of the redeposition process on distribution of pollen grains within the basin.

The studies were done at Frains Lake, Washtenaw County, Michigan. Frains is approximately 200 m wide and 500 m long, with one symmetrical basin 10 m deep in the center. There are no significant inflowing or outflowing streams. The lake is surrounded by a gently rolling landscape, now largely under cultivation. Meadows are immediately adjacent to the lake.

Two methods of measurement were used. The first measures net accumulation in the sediment. Short cores that include the mud-water interface and the uppermost 50 cm are taken, and they are divided into 2-cm segments which are analyzed separately. From its pollen content, sediment deposited at the time of land settlement and forest clearance is identified. Around Frains Lake this occurred in 1830, 138 years ago. The change in vegetation cover resulted in a sharp decline in tree pollen, especially oak, and a sudden relative increase in pollen from weedy herbs. Ragweed (*Ambrosia*) pollen was especially affected, increasing from less than 1 percent to about 30 percent of the total (Fig. 1).

After the time horizon is identified deposition since then can be measured. The number of pollen grains in the sediment above the forest clearance horizon is determined by assaying quantitative portions of the sediment (*1*). The cross-sectional area of the core is known, and therefore pollen accumulation per square centimeter can be computed. Dividing by 138 years gives the estimate for average annual deposition of pollen grains per unit surface area since forest clearance. Pollen deposition rate has been measured in this manner at eight stations within Frains Lake. The rate was lowest (1200 grains per square centimeter per year) in sediment near shore deposited in water less than 1 m deep. Intermediate rates, 8,000 to 14,500 grains per square centimeter per year, characterized stations at intermediate water depths, whereas the highest rate (21,000 grains per square centimeter per year) was observed in deep water near the center of the basin.

In the second method pollen deposi-

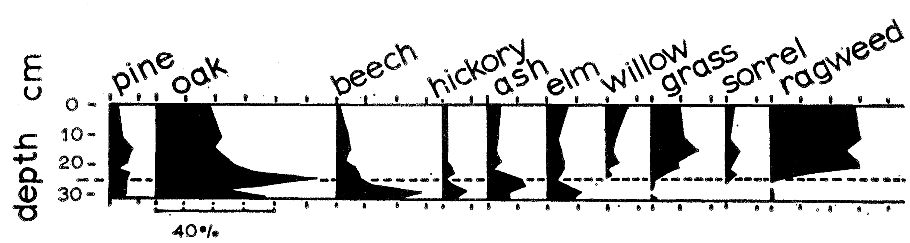

Fig. 1. Percentages of the major pollen types in samples from a short core from the sediment surface in Frains Lake. The dashed line at 25 cm has been drawn across the diagram at the forest clearance horizon, deposited 138 years ago. The percentages are plotted on the scale indicated for oak.