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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11. Supported by the NASA grant NGR-07-004-034. We thank Drs. C. O. Dunbar and K. M. Waage for discussions on paleogeography. Material on which this study is based is in the collections of the Division of Invertebrate Paleontology, Peabody Museum, Yale University (YPM-IP), New Haven, Connecticut. A letter after a specimen number indicates a peel from the original specimen.
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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-

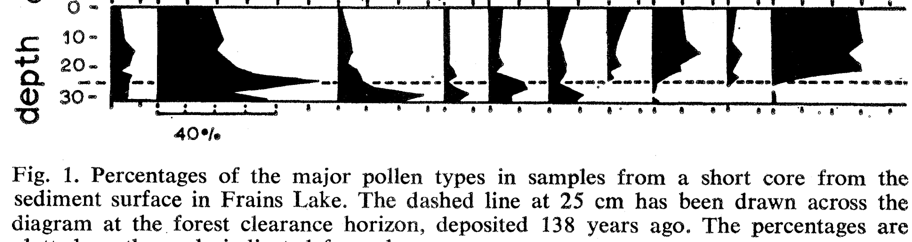

Fig. 1. Percentages of the major pollen types in samples from a short core from the sediment surface in Frains Lake. The dashed line at 25 cm has been drawn across the diagram at the forest clearance horizon, deposited 138 years ago. The percentages are plotted on the scale indicated for oak.

tion is measured directly in sediment traps—gallon bottles, with mouth area 90 cm^2, suspended in wire cages 2 m above the lake bottom between anchors and submerged floats (Fig. 2). A rope attached to the trap is picked up at shore and followed out to the trapping station, where the trap is lifted vertically to the surface and brought aboard a small boat. The sediment in the trap is seldom stirred up by this process. A new bottle is placed in the cage which is lowered gently to the lake bottom for continued sampling.

At the laboratory the sediment in the trap is concentrated on a filter, prepared for pollen analysis, and assayed for pollen (*2*). Pollen deposition per unit area is calculated by dividing the estimated number of grains in the trap by the cross-sectional area of the trap mouth. This result is divided by the length of the sampling period, to obtain pollen deposition per unit area per unit time (*3*).

Sediment traps have been used in Frains Lake over the past 3 years. The yearly rates of pollen deposition measured in traps near the center of the lake range between 40,000 and 81,000 grains per square centimeter per year. This is two to four times greater than the rate of accumulation measured in the sediment.

The two methods of study gave different results. One explanation might be destruction and decay of pollen over a period of years, gradually removing pollen from the sediment on the lake bottom. To test this idea I calculated the pollen content in a number of samples relative to the amount of inorganic sediment (measured as milligram of ash weight). Inorganic sediment here is largely silt and clay. If decay of pollen is occurring in long-term samples, the destruction should be detectable as a change in the numbers of pollen grains relative to the amount of inorganic sediment. To the contrary, the calculations showed no differences in the ratios of pollen grain numbers to ash weight in short-term and long-term samples. Trap samples collected continuously during the last 2 and 3 years had 250 and 750 pollen grains per milligram of ash weight, respectively. Sediment core samples, including portions from the entire thickness of sediment accumulated since forest clearance 138 years ago, were similar, averaging 650 pollen grains per milligram of ash weight (except the core from water $<$ 1 m deep, where there were only 40 grains per milligram of ash weight). This result disproves the explanation that removal of pollen from sediment by diagenesis causes the lower accumulation rates measured in sediment cores.

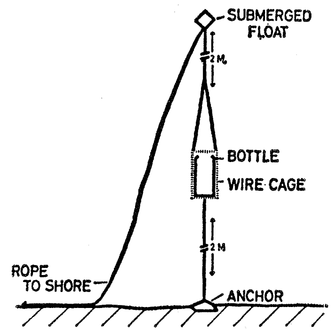

Fig. 2. Sediment trap. [Reproduced, with permission, from *Bull. Geol. Soc. Amer.* **78**, 850 (1967)]

A second explanation for the discrepancy in trap and core results is erosion of pollen-bearing sediment from the lake bottom, resuspension in the lake water, and subsequent redeposition onto the lake bottom. If this occurred, the traps would measure each episode of deposition and redeposition, but none of the episodes of erosion, since the sediment once in a trap would be protected. If the process occurred repeatedly the traps could give quite different results from the net accumulation measured in sediment cores.

To test this hypothesis, deposition was measured in sediment traps for short intervals throughout the year. If erosion and redeposition occurred, it should happen most in the fall and in the spring when the thermocline breaks down and water circulation occurs (*4*).

Sampling continued from August 1965 through July 1966 (Fig. 3A). The lake water was thermally stratified during the summer; circulation first occurred in late September or early October, continuing until January when the lake water froze over. The ice melted in late March, overturn and mixing again occurred, with thermal stratification developing gradually in early summer.

Pollen deposition occurred throughout the year, but varied in amount from one season to another. In July and August only five grains were deposited per square centimeter per day. During February similar rates were observed in traps hung below the ice. [The higher rate during the winter (Fig. 3A) is the average for a longer interval, from a trap that was in the lake for several weeks before a continuous winter ice cover formed.] Much higher rates, from 200 to 1000 grains per square centimeter per day, were observed during the

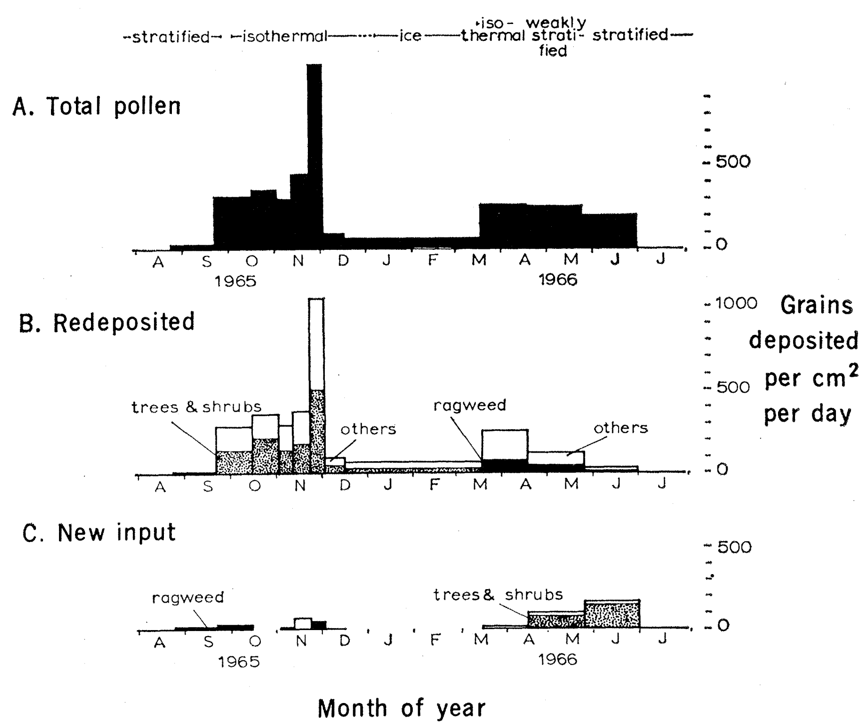

Fig. 3. (A) Pollen deposition rates (grains deposited per square centimeter per day) in sediment traps in Frains Lake from August 1965 through July 1966. (B) Redeposited pollen in sediment traps. Stippled bars, tree and shrub pollen; black bars, ragweed pollen (the out-of-season category within the redeposited pollen component). (C) Input of pollen from the air. Stippled bars, tree and shrub pollen; black bars, ragweed pollen.

fall and spring. The high rates, in every case except June, were correlated with absence of thermal stratification of the lake water.

Correlation of heavy pollen deposition with water circulation implies that redeposited sediment is the source of much of the pollen in traps. Some pollen must be entering the lake each year from the air. This pollen is also deposited into the traps, where it is mixed with pollen redeposited from sediment. The question then is, how much of the pollen deposited into traps is from each source?

Redeposited pollen includes all the pollen of types not observed in the air at that season (*5*), plus some pollen from in-season types redeposited from previous years. In the first category were ragweed pollen in the spring, and tree and shrub pollen in the autumn. Their amounts were used to estimate the amounts of pollen in the second, in-season category (Fig. 3B), by the use of the ratios between pollen types observed in late fall and winter when all (or most) pollen is redeposited. This assumes constancy of the ratios of pollen types within the redeposited component. The amount of redeposited pollen of both categories (Fig. 3B) was subtracted from the total, and the remainder was considered new input from the air (Fig. 3C). New input is high in September, when ragweed is shedding pollen, and in May and June, when the trees, especially oak, are in flower. An exception to correspondence with observations of pollen in the air is the influx of new pollen in November (Fig. 3C). Apparently this is an error resulting from small variations in the ratios of redeposited types, perhaps caused by redeposition of sediment from different parts of the basin (*6*).

A total of 65,000 grains per square centimeter was deposited into the traps during 1965–66. Of these 54,000 (about 80 percent) are redeposited from sediment, whereas only 11,000 or 20 percent represent new input to the lake. Presumably the amount of each component varies from year to year, depending upon the weather, which affects the intensity of water circulation during overturn, and the intensity of flowering of the vegetation. The estimated new input for 1965–66, 11,000 grains, corresponds roughly to the average annual accumulation rate of pollen in deep water estimated from the sediment cores —8,000 to 21,000 grains per square centimeter.

Erosion, resuspension, and redeposition of sediment are quantitatively important in Frains Lake. Presumably redeposition is important in other lakes as well, although basin morphometry, surrounding topography, and the presence or absence of forest cover may affect its intensity. At Frains the ratio of deposition, as measured in traps, to net accumulation, as measured in sediment cores, shows that pollen grains are deposited an average of two to four times before being buried deeply enough to escape further disturbance. This conclusion applies to the sediment in the deepest portion of the basin. In shallow water near the lake shores disturbance is still more extensive. This interpretation is supported by studies of variation in pollen percentage assemblages within the lake basin (*7*). These show that pollen percentages in shallow water sediment most closely match the redeposition spectrum observed in traps near the lake center.

After it is eroded, resuspended sediment is mixed more or less evenly in the water and deposited again over the entire basin. Trap samples at different stations are generally similar, at Frains Lake and in three lakes studied previously (*3*). At Frains, traps suspended at intervals between the water surface and sediment surface at three stations in the lake during spring overturn indicated evenness of vertical mixing in the water column, not only for pollen, but for organic and inorganic constituents of the sediment as well (*8*). Because sediment in shallow water is apparently stirred up and resuspended more frequently or more extensively than sediment in deep water, the net result of repeated resuspension, mainly from shallow water sediment, followed by redeposition over the entire basin, is movement of material from shallow to deep water. This explains the difference in accumulation rates measured in sediment cores in different parts of the basin.

Redeposition has important implications for pollen analysis of ancient sediment. It results in accumulation of different amounts of pollen in different parts of the basin. This must be taken into account when vegetation interpretations are attempted for rates of pollen accumulation observed in the fossil record (*9*). A change in the intensity of redeposition could change rates of pollen accumulation through time. An increase in intensity, for example, would increase the movement of sediment from shallow to deep water, lowering accumulation rates for all pollen types and for total sediment in shallow water, and increasing their rates of accumulation in deep water.

Redeposition also affects pollen percentage assemblages, the usual basis for paleoecological reconstructions. At Frains Lake pollen percentages in shallow-water sediments differ from those in deep-water sediments. The differences are apparently caused by differential input of pollen. At least there is no evidence that sorting of pollen types according to their different settling rates occurs during resuspension and redeposition, since pollen percentages in traps during overturn are similar at different stations and at different levels in the water column. Since redeposition moves pollen from shallow-water environments to deep-water environments, it will have the important effect of reducing the lateral variations in pollen percentages, thus making a single sediment core more nearly representative of the entire basin.

A final important result of redeposition is mixing of pollen entering the lake each year with pollen deposited in previous years. This reduces vertical variations in pollen content of the sediment caused by annual variations in the intensity of flowering of the various plant species. As the result of the mixing brought about by redeposition, each sediment sample in a vertical profile represents a kind of running average of several years' deposition, making it easy to discern long-term changes in pollen sequences (*10*). The process of redeposition may be largely responsible for the uniformity and consistency of pollen content that has made lake sediment such favorable material for paleoecological study.

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1. Sediment samples were assayed by the *Eucalyptus* pollen addition method [W. S. Benninghoff, *Pollen Spores* **4**, 332 (1962)].
2. The portion slide method [M. B. Davis, *Ecology* **47**, 310 (1966)] was used for trap assays. Known quantities of *Eucalyptus* pollen were added to each trap at the start of the concentration procedure. These were counted on the portion slides together with the native pollen, and the percentage recovery used as control for loss of pollen from the sample during laboratory preparation. No losses were discovered, except for four traps used in April, May, and June 1966 and early August 1965. The estimated pollen deposition rates for these months are therefore minimum rates. Higher rates would not change the general

conclusions, even for August 1965 where a doubled rate would still be negligible relative to other months of the year.

3. M. B. Davis, *Bull. Geol. Soc. Amer.* **78**, 849 (1967). Experiments with traps of different sizes showed that the number of grains captured was directly proportional to the cross-sectional area of the trap opening. This result justifies expressing the results as deposition per unit area. At Frains Lake the sum of pollen deposition at one trapping station during two successive sampling intervals (a total of 3 weeks) was the same as deposition into a single trap left in place during the entire 3-week period at a replicate station. This result argues against gain or loss of pollen from traps during collection, and supports the contention that traps measure deposition continuously during sampling.
4. W. Tutin, *Mem. Ist. Ital. Idrobiol.* **8**, 467 (1955); E. Gorham, *Limnol. Oceanogr.* **3**, 291 (1958); W. P. Mueller, *Invest. Indiana Lakes Streams* **6**, 1 (1964).
5. I thank Dr. W. R. Solomon for information on the kinds of pollen present in the air during this period at the University Hospital in Ann Arbor, 12 km from Frains Lake.
6. In the subtraction method pollen is assumed to be available to enter the lake only within the flowering season. Massive input of pollen deposited onto vegetation surfaces earlier in the year has been observed in a small pond in Denmark [H. Tauber, *Rev. Paleobot. Palynol.* **3**, 277 (1967)], but this phenomenon does not appear important at Frains Lake, which is surrounded by meadows and therefore exposed to the wind. Twigs collected from willow shrubs growing along the shores were devoid of pollen in March 1968 and therefore could not have served as a source for ragweed pollen during the spring season of heavy pollen deposition. Another source for out-of-season pollen is surface run-off from the surrounding meadows during periods of heavy rainfall. I assume this source to be relatively unimportant since the surrounding slopes are gentle, grass-covered, and without a drainage network of streams.
7. Surface samples of shallow-water sediment in Frains Lake contain higher percentages of ragweed (31 percent), willow (12 percent), and aquatic plant pollen (6 percent of terrestrial plant pollen) than deep-water sediment (20, 4, and 2 percent, respectively).
8. Written results of experiments in which traps have been placed at various levels between the water surface and the sediment surface at Frains Lake are in preparation. The mixing of pollen and sediment throughout the water column that they indicate shows that turbidity currents moving close to the lake bottom are not primarily responsible for the redeposition described here.
9. M. B. Davis and E. S. Deevey, *Science* **145**, 1293 (1964); M. B. Davis, *Rev. Paleobot. Palynol.* **2**, 219 (1967); M. Tsukada, *Botan. Mag. Tokyo* **79**, 179 (1966); D. R. Whitehead, in *Quaternary Paleoecology*, E. J. Cushing and H. E. Wright, Jr., Eds. (Yale Univ. Press, New Haven, 1967), p. 237.
10. R. B. Davis, in *Quaternary Paleoecology*, E. J. Cushing and H. E. Wright, Jr., Eds. (Yale Univ. Press, New Haven, 1967), p. 143, has emphasized burrowing by benthic animals as a mechanism for mixing sediment. There seems little question that benthos also mix the sediment at Frains Lake. But at Frains Lake, and presumably many other lakes, physical mixing appears to be more important, especially as physical processes can cause lateral as well as vertical movement of sediment.
11. Contribution No. 94 from the Great Lakes Research Division, University of Michigan. Supported by NSF grants GB 2377 and GB 5320. I thank J. M. Beiswenger and L. B. Brubaker for technical assistance and W. C. Kerfoot for reading the manuscript.

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Wedge Dislocation as the Elastic Counterpart of a Crystal Deformation Twin

Abstract. *A crystal deformation twin may be visualized to form and grow by the movement of partial dislocations only if the twinning dislocations are especially distributed to give an invariant shear. One consequence of this requirement is that, if a critical resolved twinning stress exists in the same sense for twinning as for slip, this stress depends on the reciprocal thickness of the twin. This type of model for twinning may be developed through the use of relatively unknown disclinations, in particular, the wedge dislocation.*

There are six general types of elastic dislocations which may be introduced into any doubly connected body, such as a hollow cylinder (*1*). The relative displacements Δu_i of the cut surfaces when these dislocations are produced may be expressed as

$$\Delta u_i = b_i + d_{ij}\, x_j \qquad (1)$$

where $i,j = 1,2,3$; b_i is a polar vector which specifies the relative translation of the surfaces; d_{ij} is an axial vector which specifies their relative rotation; and x_j is the position vector. Only two of the three dislocations characterized by b_i, their Burgers vector, are unique, and these, which are termed edge and screw dislocations, are widely used in theories of crystal plasticity. Only two of the three dislocations specified by d_{ij}, which are now called disclinations corresponding to a rotation parallel or normal to the dislocation line, are also unique. The screw disclination, or wedge dislocation, is shown in Fig. 1. These dislocations have not been used very much in crystal deformation theory. In their case, the residue of the displacement integrated around a circuit containing the dislocation axis is proportional to the radius of the circuit. This report is a description of the procedure by which dislocations of type b_i may be used to model a crystal deformation twin. Because of the invariant rotation which characterizes disclinations, they may be used also to develop a model for twinning.

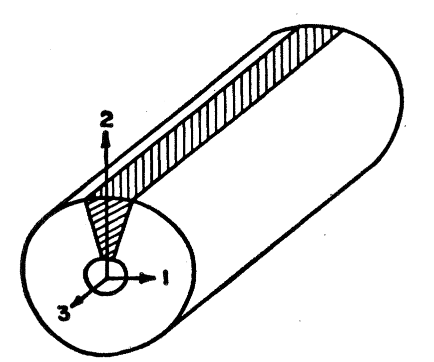

Fig. 1. Screw disclination or wedge dislocation.

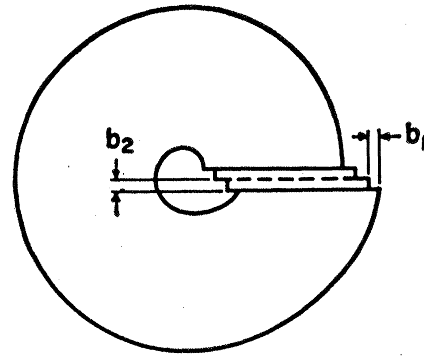

Fig. 2. Model of a crystal deformation twin utilizing partial dislocations.

A number of the features of a crystal deformation twin (*2*) have been modeled as in Fig. 2. The twinned volume is enclosed within the solid horizontal lines of the cylindrical section shown on the right side of the figure. The twin is composed of successively aligned dislocations, each having a partial lattice-displacement vector b_1 separated in the vertical direction by the interplanar spacing b_2. The twinning shear, γ_{12}, is given by the ratio (b_1/b_2). The stress-concentrating properties of this model for a twin have been described in terms of a multiple Burgers vector dislocation (*3*). The work W_e done by an external shear stress σ_{12}, when the twin is produced on the set of surfaces Σ_S by displacements u_{1S}, is given by

$$W_e \approx \int\int_{\Sigma_S} u_{1S}\, \sigma_{12}\, d\Sigma_{2S} \qquad (2)$$

in which $d\Sigma_{2S}$ is an elemental vector component of the set of cut surfaces,

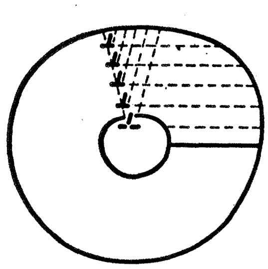

Fig. 3. Simple shear displacements which form a (wedge) twin.