Enhanced Positive Cloud-to-Ground Lightning in Thunderstorms Ingesting Smoke from Fires

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Smoke from forest fires in southern Mexico was advected into the U.S. southern plains from April to June 1998. Cloud-to-ground lightning (CG) flash data from the National Lightning Detection Network matched against satellite-mapped aerosol plumes imply that thunderstorms forming in smoke-contaminated air masses generated large amounts of lightning with positive polarity (+CGs). During 2 months, nearly half a million flashes in the southern plains exhibited +CG percentages that were triple the climatological norm. The peak currents in these +CGs were double the expected value. These thunderstorms also produced abnormally high numbers of mesospheric optical sprites.

Smoke transported from massive fires in Mexico during spring 1998 (*1*) appeared to have a substantial influence on the electrical characteristics of thunderstorms over the central United States. Specifically, major departures from typical climatology were observed in +CGs. The U.S. National Lightning Detection Network (NLDN) routinely reports the time, position, polarity, and peak current of the first stroke in each detected CG flash (*2*). Once considered rare, +CGs have been found to make up about 10% of all NLDN flashes, though there is considerable seasonal and geographical variability. The understanding of cloud electrification in general and the production of +CGs in particular is limited. Higher +CG percentages occur during the cool season along the West Coast and in New England and southern Canada (*3*). Some types of summer storms in the central United States, including certain supercell hail and tornadic storms, can exhibit elevated +CG percentages (>50%) over areas of <10,000 km^2 for several hours. However, widespread episodes of high +CG percentages lasting 6 hours or more are extremely rare (*4–8*). Larger regions of elevated +CG percentages and peak currents can also be found within the stratiform precipitation region of large mesoscale convective systems (MCSs). These +CGs are frequently associated with mesospheric red sprites, transient (<100 ms) luminous glows occurring between 30 and 90 km altitude (*8*). The 1996–1997 nationwide annual average CG peak current was about 27 kA for both polarities. Those +CGs with higher peak currents are more likely to generate sprites (*9, 10*). Climatologically, the +CGs with the highest peak currents (>75 kA) during summer (locally <2 to 3% of the total CG flashes) occur in a band stretching from Colorado into Minnesota (*11*).

A growing body of evidence suggests that natural lightning production may be perturbed by changes in contaminants, aerosols, and possibly the space charge characteristics of the air ingested by the storm. Responses include the nearly total cessation of lightning within a severe storm that ingested military aluminum chaff (*12*). Increases of 40 to 85% in the CG flash rates (undifferentiated by polarity) downwind of many midwestern U.S. urban areas have been reported, although the causal mechanisms were not determined (*13*). Areas of Sweden contaminated by Chernobyl radioactive fallout had increased lightning rates (*14*). In a deliberate attempt to modify storm electrical characteristics, researchers released negative electrical space charge into the base of orogenic convective clouds and reported subsequent anomalous electric fields and ground flashes (*15*). Electric charge generated by small forest fires has been implicated in the production of thunderstorms producing exclusively +CG flashes (*16*). High +CG flash percentages (25 to 50%) have been reported in fire-induced storms, including one within the smoke plume of the 1988 Yellowstone National Park forest fires (*17*).

El Niño–related drought conditions in southern Mexico and Central America resulted in widespread fires in the tropical rain forests during the spring of 1998. More than 10,000 fires consumed more than 4000 km^2 during 3 months in southern Mexico alone (*18*). During most of April, May, and early June, circulation patterns advected much of the dense smoke pall northward into the southern High Plains and states surrounding the Gulf of Mexico, and on occasion into southern Canada (*19*). There were additional excursions eastward into the southeastern United States. The particulate content of the air mass reached >550 μg/m^3 for PM10 aerosols along the Texas-Mexico border (*20*), and visibilities locally reduced to <5 km caused sporadic air traffic delays. The smoke intrusion was halted on 7 June with the passage of a powerful cold front, which brought polar air to the region east of the Rockies. Previously, abnormally warm, summer-like weather had dominated the southern plains. Numerous daily record high temperatures were above 40°C. May temperatures in the southern plains ranked in the 90th percentile of warmth over the past century (*21*).

Throughout our study period (8 April to 7 June 1998), various types of convective systems developing within or on the boundary of the smoke-laden air mass repeatedly produced abnormally high percentages of +CGs (often in excess of 50% throughout their lifetimes). Large convective storm systems can and do ingest substantial amounts of bound-

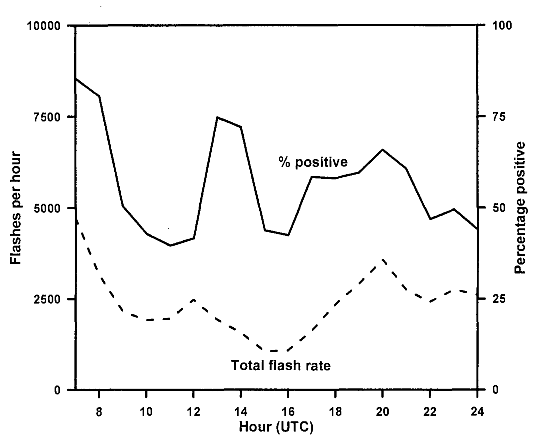

Fig. 1. Hourly distribution of the 43,798 +CG flashes detected by the NLDN from 0700 UTC 15 May to 0200 UTC 16 May 1998 for a series of thunderstorms forming within the smoky air mass extending from Texas to western Ontario.

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ary layer aerosols on a regional scale (*22*). The most spectacular intrusion of Mexican smoke into the United States occurred from 14 to 18 May 1998 in advance of an eastward sweeping Pacific frontal system (*23*). On 15 May, satellite images showed a 1000-km-wide plume of smoke stretching from Mexico into western Ontario, spiraling back into a deep low-pressure system in Minnesota (*24*). Aerosol concentrations (PM10) were >150 $\mu g/m^3$ in St. Louis, Missouri (*20*). Late on the afternoon of 14 May, a family of intense convective storms formed from Texas to North Dakota near the frontal boundary marking the western edge of the smoke. Convective storms swept east and north over the next 36 hours. During the peak lightning activity, 59% of the 43,798 CG flashes recorded between 0700 UTC 15 May and 0200 UTC 16 May 1998 had positive polarity. Flash polarity averaged 77% positive from Kansas southward. The enhanced +CG episode was long-lasting and widespread (Fig. 1). The frontal system continued moving east, causing lesser amounts of convection over the next 48 hours. By 18 May, storms over New England and eastern Ontario commingled with the smoke were still producing high +CG percentages.

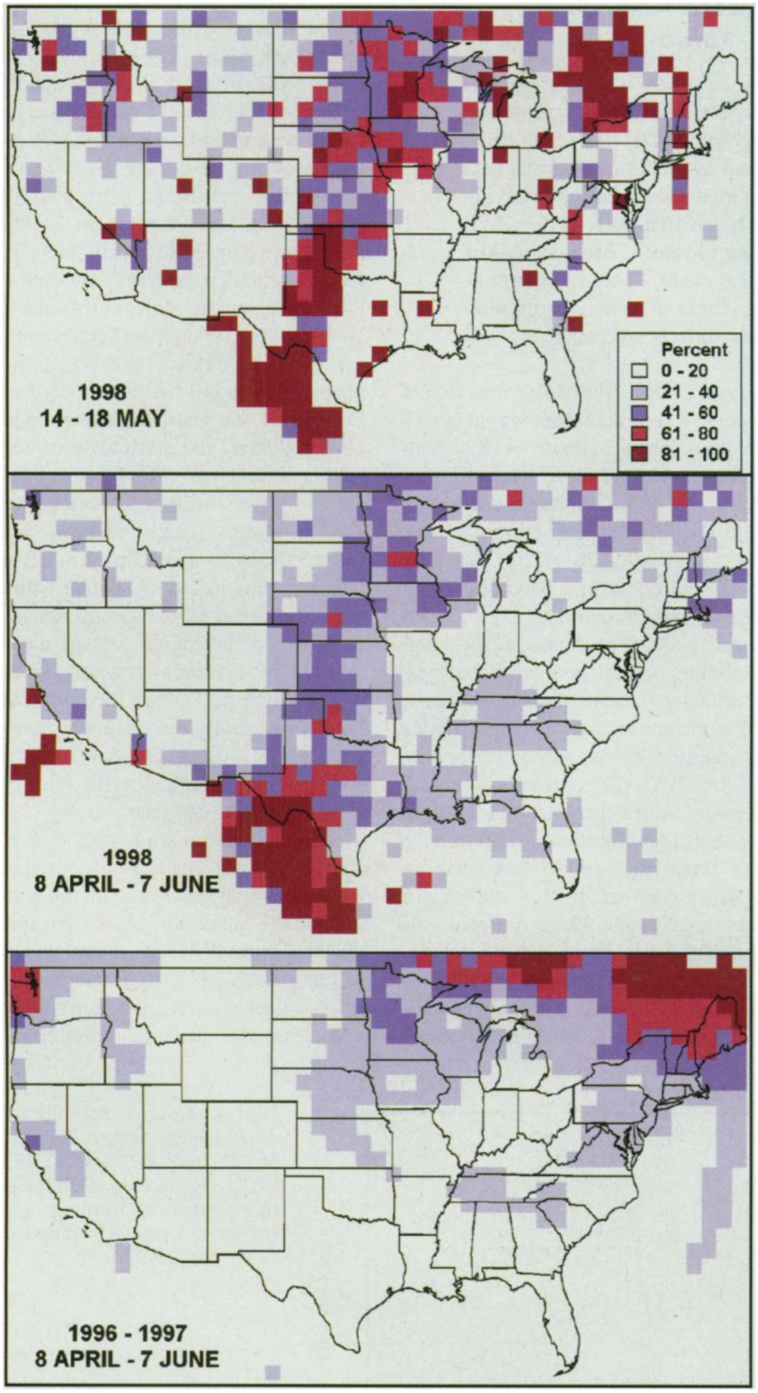

Fig. 2. (Top) Percentage of +CGs measured by the NLDN from 14 to 18 May 1998. Grid cells are 100 by 100 km. **(Middle)** Percentage of +CGs measured by the NLDN during the study period 8 April to 7 June 1998. **(Bottom)** Percentage of +CGs measured by the NLDN averaged for the period 8 April to 7 June 1996 and 1997. Many cells in the western United States and Canada have relatively few flashes.

A map of the percentages of +CGs for 14 to 18 May 1998 reveals that large sections of a swath from Mexico to Ontario experienced values in excess of 40%, with some areas above 80% (Fig. 2A). Over the 2-month period of smoke intrusion during spring 1998, a distinct corridor of greatly enhanced +CG percentages (Fig. 2B) differed markedly from the average values for the previous 2 years (Fig. 2C). In the 1996–1997 composite, the higher +CG percentages were confined, as expected, to the storms of the West Coast, upper Midwest, New England, and southern Canada, which have relatively low flash rates. The 1998 season had approximately the same number of flashes as the average for the prior 2 years (4.4 versus 4.9 million) (Table 1), but the percentage of positive flashes was 48% higher (20.1% versus 13.7%). The average +CG peak current was also 12% larger (30 kA versus 27 kA). In 1998 there were 14 days when the network-wide +CG percentage was ≥25% (days with >10,000 flashes), versus an average of 0.5 days over the prior two seasons. Much more acute enhancements, however, were noted during the period 14 to 18 May when the nationwide +CG percentage reached 40%, the +CGs with large peak current (≥76 kA) rose to 11% of all +CGs, and the average +CG peak current jumped to 42 kA. These values are 2.9, 2.3, and 1.5 times the longer term (1996–1997) levels, respectively.

The 2-month departures are even more pronounced within a smaller southern plains (SP) region (25° to 40°N, 107° to 94°N) (Table 1). The 1996–1997 regional average was 1,401,229 flashes. Developing drought conditions in 1998 suppressed the number of thunderstorms that formed, yet the 424,343 reported flashes in the SP still represented a substantial number. The 1998 SP regional percentage of +CGs jumped to 37%, versus 13% in 1996–1997. There were 15 days when the area-wide +CG percentage was ≥25% (days with >1000 flashes), versus an average of 1 for the prior 2 years. Only 11 of the analysis grid cells (100 km by 100 km) had +CG percentages above 20% (none above 40%) in 1996–1997, whereas 85 cells were above 20% (and 77 above 40%) during 1998.

More striking is that in 1998, the average +CG peak current in the SP region doubled from 22 to 45 kA while the –CG average peak current fell slightly, from 26 to 22 kA. The median and mode of the –CG peak currents remained largely unchanged, while the median of +CGs jumped from 16 to 36 kA and the percentage with large peak currents (≥76 kA) increased to three times the regional long-term value (*10*). The distribution of the +CG peak currents became clearly bimodal. Although the mode of +CGs occurred in the 10 to 12 kA range all 3 years, during 1998 a second maximum developed at 28 to 30 kA. A plot of the cumulative distribution of +CG peak currents in the SP region shows that the 1996 and 1997 distributions were nearly identical, whereas the 1998 distribution skewed toward much higher peak currents (Fig. 3). The percentage of +CGs that had low peak currents (≤10 kA) dropped to 33% of the normal level. The +CG increase appears not to have resulted from greater numbers of +CG flashes with peak currents of <10 kA. This is notable because some of the reported sub–10 kA +CGs result from misclassification of powerful intracloud flashes by the NLDN (*25*). One interpretation of the origin of these differences we have observed is that charge that normally participates in intracloud flashes somehow was reapportioned into the +CG formation process (*26*). The very warm weather during most of this period precludes this being an artifact of the well-known cold weather bias for +CG flashes. The anomaly was most pronounced in northeast Mexico, closest to the smoke source.

Smoke-influenced storms also produced more sprites, according to optical surveillance during the Sprites '98 Campaign from the Yucca Ridge Field Station (*9*). An MCS formed within a smoky air mass over Nebraska on 20 May 1998. It produced a modest 4250 CGs in 208 min, but 62% of these were positive and the average +CG peak current was 40 kA. This storm produced 380 sprites, the highest single-storm total recorded in more than 100 storms in 6 years of observations. The 1.8 sprites per minute rate is double that of the storm with the previous highest sprite rate. There was 1 sprite for every 11 CGs, compared to previous extreme ratios of 1 sprite per 25 to 100 CGs (*8, 9*).

It is clear that in some way the smoke from these fires substantially altered the electrical characteristics of a wide variety of storm types during all phases of their life cycle (*27*). It seems unlikely that any meaningful quantity of electrical space charge could have been advected thousands of kilometers from the fire source. Alterations in cloud microphysical processes by the aerosols is more plausible. Smoke is usually a prominent source of cloud condensation nuclei (CCN). Elevated CCN concentrations affect the droplet size spectrum (*28*), which in turn can affect various aspects of the charge separation mechanisms (*29*). Whether these fires might also have been a source of ice nuclei is still unknown (*30*). Some of the anomalous storms developed in regions where the smoke was not dense enough to be detected by satellite sensors. Inspection of air mass source regions found in these cases, however, shows that boundary layer trajectories most likely passed through the smoke source region (*31*). This suggests that the active agent(s) for these changes may be effective at relatively low concentrations.

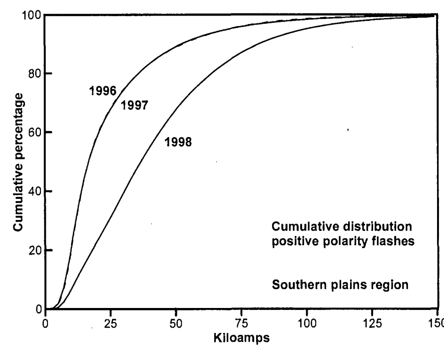

Fig. 3. Cumulative distribution of +CG peak currents in the U.S. southern plains (SP) region for the 8 April to 7 June period of 1996, 1997, and 1998. (The first 2 years are so similar that the curves overplot.)

Table 1. NLDN CG flash statistics.

	1996–97 Entire NLDN 8 April–7 June	1998 Entire NLDN 8 April–7 June	1998 Entire NLDN 14–18 May	1996–97 SP region 8 April–7 June	1998 SP region 8 April–7 June
No. CG flashes	4,809,921	4,401,008	190,990	1,401,229	424,343
No. days ≥25% +CG	0.5	14	5	1	15
% +CGs	13.7	20.1	39.5	12.9	37.3
% +CGs ≤10 kA	21.3	24.7	5.6	15.1	5.1
% +CGs ≥76 kA	4.8	6.9	11.0	4.0	13.1
Mode of +CGs (kA)	11	9	13	11	11 and 29
Mode of −CGs (kA)	17	13	13	17	15
Median of +CGs (kA)	18	19	32	16	36
Median of −CGs (kA)	21	18	17	21	18
Avg. +CG current (kA)	27	30	42	22	45
Avg. −CG current (kA)	27	24	23	26	22

References and Notes

1. Are vast palls of smoke from biomass burning a relatively new phenomenon? The Astronaut Training Manual (Atmospheric Phenomena) prepared by the Earth Science and Solar System Exploration Division at the Johnson Space Center notes that over a 30-year period of space photography, dry-season smoke palls larger than 300,000 km^2 were unusual during the late 1960s but by 1991 were commonly 10 times as large (>3.3 × 10^6 km^2). On the other hand, the 1997–1998 El Niño produced some of the most intense regional droughts of the last several decades in several tropical regions. A strong correlation between El Niño and the Amazon River basin discharge was noted by J. E. Richey, C. Nobre, and C. Deser [*Science* **246**, 101 (1989)], who found that the lowest Amazon flow between 1903 and 1985 occurred in 1926, an El Niño year when the Amazon region experienced extensive drought and fires, as noted by H. O'R. Sternberg [*Geogr. Am.* **69A**, 201 (1987)].
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18. A useful compilation of online information regarding these and other fires has been created by NASA (http://modarch.gsfc.nasa.gov/fire_atlas/fires.html).
19. The Total Ozone Mapping Spectrometer (TOMS) satellite aerosol mapping analyses revealed that on most days between 8 April and 7 June 1998, vast amounts of smoke were drifting north of the latitude of Brownsville, Texas. Smoke coverage was most persistent in Texas, eastern New Mexico and Colorado, Oklahoma, Kansas, and Nebraska. A daily summary of the TOMS aerosol maps for May 1998 can be found at http://capita.wustl.edu/Central-America/reports/SmokeSum/SmokeSum/sld009.htm (slide 9). Also see http://jwocky.gsfc.nasa.gov/mexico.html.
20. Fire-related aerosol observations are summarized at http://capita.wustl.edu/Central-America/Resources/Data/Data.html.
21. Source: NOAA Climate Diagnostic Center.
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23. The extent of the Mexican smoke plume over the southern plains of the United States was vividly

portrayed by the color Sea-Viewing Wide Field-of-view Sensor (SeaWiFS) visible band image at 1800 UTC 14 May 1998; see http://modarch.gsfc.nasa.gov/fire_atlas/MEXICO/SeaWiFS/may1498.jpg.
24. A Geostationary Operational Environmental Satellite (GOES) visible image at 2245 UTC 15 May 1998 showing the massive smoke plume is available at http://cimss.ssec.wisc.edu/goes/misc/980515_2305_g8vis.GIF.
25. K. L. Cummins, personal communication. This conclusion is based on extensive analyses by Global Atmospherics Inc. of the performance of the NLDN since major upgrades were incorporated during 1994–1995.
26. K. L. Cummins, personal communication. The sudden surge of +CGs in the NLDN during April 1998 prompted extensive checks by the Network Control Center staff. No malfunctions were found. Single-sensor data were studied showing storms in the smoky air over southern Texas with 85% positive CGs, whereas other storms in clean air hundreds of kilometers to the north showed 5 to 10% positive polarity.
27. The massive pall of smoke from the 1997 Indonesian fires, occurring in a region characterized by high thunderstorm rates, may have induced a similar response. Unfortunately, political unrest in that nation has temporarily prevented retrieval of data from lightning detection networks covering this area.
28. Increased CCN in forest fire plumes were reported by P. V. Hobbs and L. F. Radke [*Science* **163**, 279 (1969)]. Actual changes in droplet spectra in smoke-contaminated clouds were noted by Y. J. Kaufman and T. Nakajima [*J. Appl. Meteorol.* **32**, 729 (1993)].
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30. Ice nuclei have been documented emanating from numerous urban areas and specific industrial sources. There are very few reports of ice nuclei emanating from biomass fires, but this dearth may reflect a lack of measurements. Increased ice nuclei concentrations in the smoke plume from a coniferous and fir forest blaze were noted by P. V. Hobbs and J. D. Locatelli [*J. Appl. Meteorol.* **8**, 833 (1969)], and smoke from burning Hawaiian sugar cane was found to have enhanced ice nuclei concentrations by R. F. Pueschel and G. Langer [*ibid.* **12**, 549 (1973)].
31. Boundary-layer forward trajectories from the fire regions were operationally produced by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (http://www.arl.noaa.gov/ready/aq.html).
32. Supported in part by NSF, NASA, and the U.S. Department of Energy. Special thanks are extended to Global Atmospherics Inc. and K. Cummins in particular for facilitating the analyses of the NLDN data. We also thank G. Vali and A. Detwiler for suggesting several valuable literature citations.

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Triploblastic Animals More Than 1 Billion Years Ago: Trace Fossil Evidence from India

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Some intriguing bedding plane features that were observed in the Mesoproterozoic Chorhat Sandstone are biological and can be interpreted as the burrows of wormlike undermat miners (that is, infaunal animals that excavated tunnels underneath microbial mats). These burrows suggest that triploblastic animals existed more than a billion years ago. They also suggest that the diversification of animal designs proceeded very slowly before the appearance of organisms with hard skeletons, which was probably the key event in the Cambrian evolutionary explosion, and before the ecological changes that accompanied that event.

There are two seemingly contradictory views about the early history of metazoans. The "Cambrian explosion" scenario is based on Cambrian shelly fossils and Burgess-type lagerstätten. This scenario suggests that animal phyla originated rather suddenly ~540 million years ago (Ma) during the Proterozoic-Phanerozoic transition. This view was first modified by the discovery of Ediacaran fossils of late Proterozoic (Vendian) age in many parts of the world. Although most of these fossils are nonmetazoan [according to the Vendobionta hypothesis (*1*)], the presence of true, but soft-bodied, triploblasts in Ediacaran biota is now documented by worm burrows, by radular markings and body impressions (*2*) of early mollusks, and by phosphatized embryos (*3*). These discoveries lengthened the paleontological record of animals to ~580 Ma. The alternative "slow burn" scenario suggests that animals developed more slowly (*4*)—according to some molecular analyses (*5*), beginning more than 1 billion years ago (*6*).

These two scenarios are not incompatible, because they are based on different concepts. In paleontology, phyla are defined as bauplans that are typified by modern representatives. Because hard skeletons are an essential element of construction in many of these bauplans, it is reasonable to assume that many of them had their origin in the Cambrian skeletonization event. Molecular analyses, in contrast, include any ancestor in the lineage, irrespective of its morphology. Also, the calculated age of the last common ancestor is highly model dependent.

Paleontologists can document the hypothesized pre-Ediacaran animals in the following ways. (i) If it is true that early metazoans were minute larviform planktics (*7*), their remains could be preserved in cherts; so far, however, these cherts have yielded only unicellular organisms. (ii) Larger, but soft-bodied, forms can be expected in black shales, in which only macroalgae have been found so far. (iii) Clastic sediments should preserve the trails and burrows of benthic animals. Pre-Ediacaran trace fossils [summarized in (*8*)], however, are scarce and have not been very convincing. The worm burrows described here suggest that a preservational bias may also be involved in the Precambrian trace fossil record.

Trace fossils are best preserved in sedimentary rocks that have not been metamorphosed. One suitable site for trace fossils is the Vindhyan Supergroup in the Son valley, central India, where continuous sequences of nonmetamorphosed Proterozoic sandstones, shales, and algal limestones can be studied in continuous outcrops (Fig. 1). The Chorhat Sandstone, from which our trace fossils originate, appears to have been deposited in a shallow marine setting. It mainly consists of centimetric storm sands that are topped by oscillation ripples. However, unlike in younger tempestites, event layers have not become cannibalistically amalgamated but remain separated even when there are no mud drapings between them. The reason for this strange behavior is the presence of microbial mats (*9*). These mats transformed the upper millimeters of the sand into a leathery, erosion-resistant coating, so that the next storm sand could, on its sole, form a direct replica of the previous ripples. If the second storm bed was no thicker than the preexisting ripple relief, it filled only the former troughs with starved ripples of a different direction [palimpsest ripples (*10*)].

The matground state of Proterozoic sea bottoms (as opposed to the bioturbational mixground state of later times) has not only been responsible for strange sedimentary structures but may also have led to the strange life-styles (*11*) and preservation (*12*) of Ediacaran organisms and the scarcity of trace fossils in the Proterozoic rocks.

When studying pre-Phanerozoic trace fossils, it is crucial to distinguish true biogenic sedimentary structures from pseudotraces whose shapes are purely (or mainly) formed from physical processes. Among these struc-

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