The Paleobotanical Character of Log Assemblages Necessary to Differentiate Blow-Downs Resulting from Cyclonic Winds

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The traumatic effects of cyclonic winds on forest vegetation are documented for a regional storm front that was accompanied by a localized tornado. Damage was sustained directly in the forest canopy in response to the severity of the winds, especially inflow from behind the vortex. Slight damage to the subcanopy and ground cover was sustained indirectly as the result of canopy litter fall. The orientation of downed and damaged canopy trees parallels that of the path of the tornado, but where the vortex came closest to touching down, trees were oriented perpendicularly to the tornado's route. In assessing an ancient thanatocoenosis (death assemblage) that may be the result of blow-downs, it is important to document the regional scatter of trees in order to determine whether or not the traumatic event represents merely violent windstorms or is the result of cyclonic winds. The recognition of such situations in the rock record would allow for a more detailed assessment of prevailing paleoclimate.

INTRODUCTION

Gale-force winds on terrestrial vegetation are responsible for the traumatic loss of vegetative and reproductive parts that may be incorporated into the fossil record (Gastaldo, 1988; Spicer, 1989). Moderate to severe gusts may selectively dislodge upper canopy parts including flowers/fruits, leaves, and branches (Scheihing, 1980). The energy of many storms is expended in the canopy without affecting the understory (Webb, 1958; Whitmore, 1974), and it has been documented that plants of various growth habits are affected differently by the same storm (Craighead and Gilbert, 1962). Under extreme conditions, canopies may be broken from trunks and/or entire trees may be felled with or without their rootstocks. Large regional blowdowns, extending for up to a mile and one half in one direction, have been documented in various modern climatic regimes (e.g., Anderson, 1964; Dittus, 1985). Wnuk and Pfefferkorn (1987) demonstrate a unimodal orientation for several modern forests affected by windstorms. With the exception of these examples, most data are anecdotal with respect to the orientation of those trees affected in the damaged area. This present report chronicles the events of a severe storm front that passed through eastern Alabama. Accompanying this front was a localized tornado that resulted in considerable damage to the forested areas. The characteristics of the felled trees and their orientations provide insights into the mechanisms responsible for this traumatic event, and the utility of such data sets in interpreting ancient blow downs.

LOCALITY, PREVAILING WEATHER CONDITIONS, AND METHODOLOGY

The city of Auburn is located in eastern Alabama at the contact of the Appalachian Piedmont and the overlying Coastal Plain sediments. On the morning of Thursday, 22 February 1990, at approximately 8:00 am, a severe storm front moved through the Auburn area from the southwest (wind direction 225°), with winds clocked between 54.7 mph (91.2 km/hr @ 8:00 am) and 58.07 (96.8 km/hr @ 8:01 am; near typical rate of thunderstorm speed—Eagleman, 1983). Peak wind gusts were recorded at 64 mph (106.7 km/hr; U.S. National Weather Service, Auburn University Weather Substation). Barometric pressure dropped from 30.16 to 29.94, but no significant drop was recorded on the barogram. During the storm 0.63″ of rain fell. Although no "hook echo" was observed on radar (dual Doppler radar in Montgomery, AL was non-functional at the time), accompanying this front was at least one "weak" tornado that traveled a route from southwest of Auburn to the northeast (Fig. 1).

Immediately after the front passed through the region, the local damage to forested areas was assessed within the city limits (estimated damage $1 million; R. Griffin, City Engineer). The affected areas constitute a trail of sporadic damage beginning approximately 6 km southwest of the center of town, and extending at least 8 km northeast. The heaviest concentration of damage occurred in the north and northwestern portions of the city where the tornado came closest to touching down (see below). At least 780 trees were damaged within the city limits. Orientations of felled trees (n > 300; 286 plotted) were taken throughout the damaged tract, with compass bearing reflecting the direction of the canopy. Trends were

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plotted in Rose diagrams along with the statistic for mean vector using SPLOT (Darden Software) for areas where significant damage was noted to have occurred (Fig. 1).

TAPHONOMIC FEATURES OF STORM-GENERATED ASSEMBLAGE

Both softwood gymnosperms (various species of pines and junipers) and hardwood angiosperms (principally oaks) were damaged throughout the tornado tract. Trees of each wood type were affected similarly somewhere in the region, although softwoods and hardwoods rarely were seen to be affected in the same manner in the same site. In no instance was a path of trees cleared by the tornado activity.

The resultant transported litter assemblage was due to the loss either of canopy parts or an entire canopy. Live and dead branches were traumatically detached from the parent plant and moved up to several 10's of meters in the direction of the advancing front. The distance any individual branch or branchlet was transported appears to be dependent upon the weight of the dislodged plant part and the vegetation density of the site. Canopy litter was transported farther where trees are more open-grown, whereas in forests where a well-developed canopy existed, litter was minimally transported. Large accumulations of traumatically detached canopy parts were not generated by the storm. Rather, damage was sustained by individual trees in response to the rapid movement of the squall line through the area.

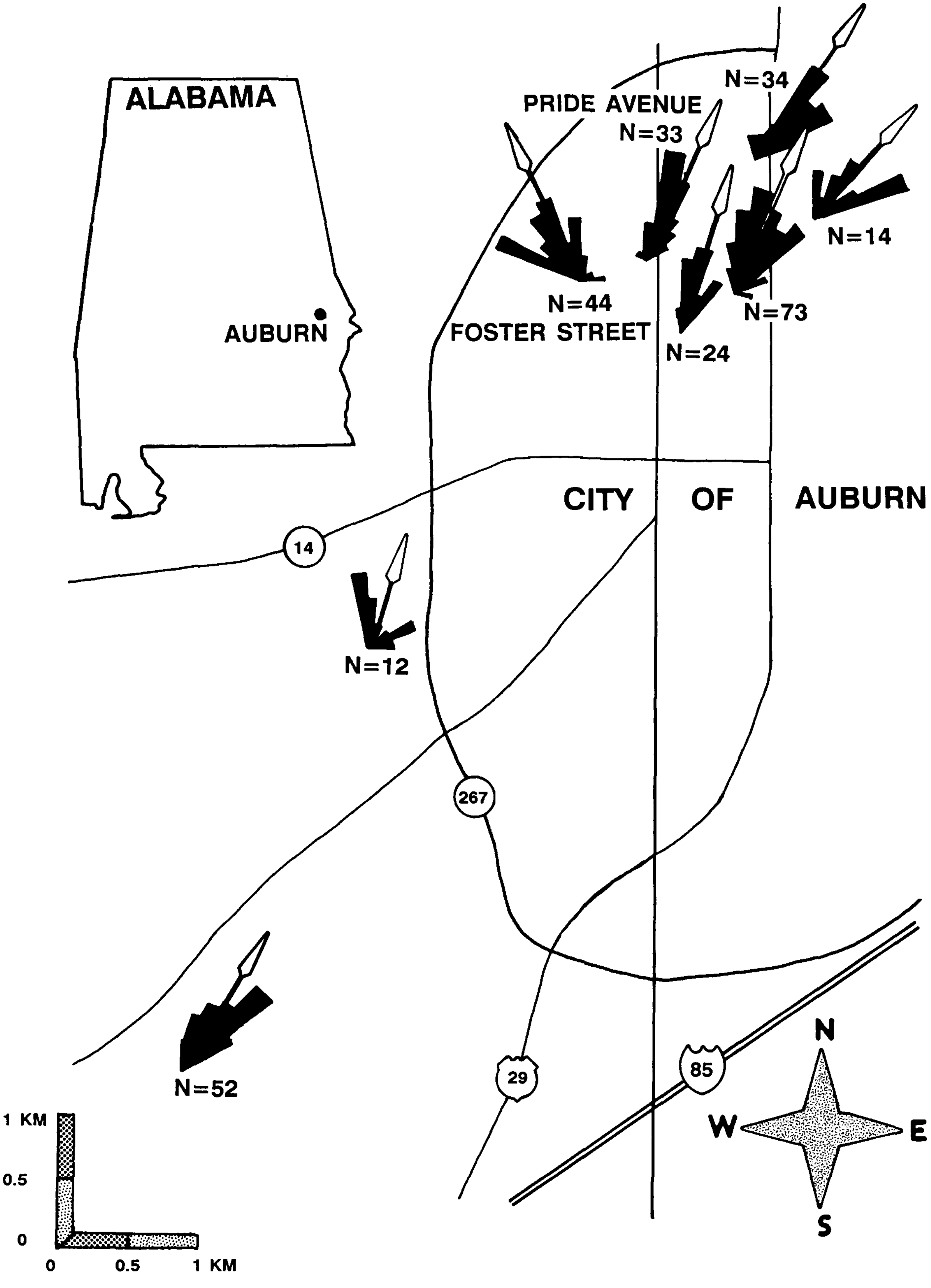
Both the wind stress accompanying the advancing front and that generated by the cyclonic motion caused canopies of trees to be snapped off their trunks. Breakage of tree trunks resulted from one of two factors. Bending stresses are a combination of compressive, tensile, and shear stresses that cause flexure of wood (Panshin and de Zeeuw, 1970). Woods that are subjected to bending stress may react in an elastic or brittle response. Stress that is applied under high winds may subject the wood to conditions that exceed its elastic limit, resulting in breakage. The vast majority of tree canopies were excised in this manner, being bent past the elastic limit of the wood. Once broken, the canopy was transported a short distance in the direction of the winds. Dislodged canopies were transported less than 12.5 m from the source trunk. In other instances, the rotational force of the cyclonic winds appears to have twisted the canopy and trunk in the direction of rotation, causing the trunk to contort and break, leaving the tree base splintered. This type of canopy damage occurred in the areas where the tornado came closest to touching down. Displacement of the tree was generally lateral to the source stump. These tree canopies were found to be lying within a few meters of their original erect position. In neither case were the canopies transported any significant distance from their site of growth.

The most frequently encountered tree response was displacement of the entire plant at the site of growth. This resulted from their being blown over with either a broken or intact rootstock (Fig. 2). Trees were either completely blown over so that they lay flat on the forest floor, or tilted by various degrees from an erect position. Some trunks were suspended above the forest floor. This mode was due to one of two conditions. The canopy of some fallen trees became entangled with adjacent erect trees. In other instances, the branches of the canopy did not break when the tree fell and these held the trunk aloft. Rootstocks were variably affected, but in most cases the larger lateral roots were broken less than a meter from the tree base (Fig. 2). In some instances, tap roots were separated from the tree bases less than 1 m below the ground surface. The extracted root ball retained the surrounding soil, resulting in a depression beneath the dislodged tree. In the three months after the storm, rain has begun to erode the soil from around the roots of some of these trees, whereas in other cases these areas have been colonized by other plants. Depending upon the extent of root damage and the taxon in question, some trees continue to live (e.g., *Quercus, Juniperus*) while others have died (i.e., *Pinus*).

The forest in east Alabama is predominantly composed of Pine, and nearly 95 percent of observed damage was restricted to this genus. Pine trees were either blown-down or the canopy and/or trunk were physically broken by the storm. Most were blown-over exposing their rootstocks. The response of any particular tree in any particular area appears to be the result of the wind conditions operating at the time of impact and the "openness" of the tree. Those on the forest edges are more likely to be blown down than broken. It is common, though, to note both blown-down trees and broken trees in the same location within the forested areas. The differential response of adjacent trees may be due to their position in the canopy and/or a domino effect as displacement of one tree occurs. Only five junipers were found to have been affected, each having been blown-down within a forested area. The remainder of tree damage was confined to the oaks. In most instances these plants were blown over probably because their canopies protruded above the surrounding trees. Oaks whose trunks were broken grew openly or at edges of thinned forest.

Damage to the understory was sustained not as the result of the wind, but as an indirect consequent of damage to the canopy. Falling canopy parts resulted in either the bending or breakage of understory trees. These understory trees also were oriented in the general direction of the storm. Understory trees may be oriented nearly perpendicular to the direction of fall of a canopy tree when the latter has fallen, coming in contact with the side of the former. This occurred infrequently. Overall, the ground cover was minimally damaged and remained relatively undisturbed (Figs. 2, 3).

Orientations of displaced trees generally paralleled the direction of the squall line (Fig. 1). Where several trees were blown over in a single site, they tended to be oriented parallel to each other (Fig. 3). Orientations of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N=44
FOSTER STREET
N=73
N=24
CITY OF AUBURN
14
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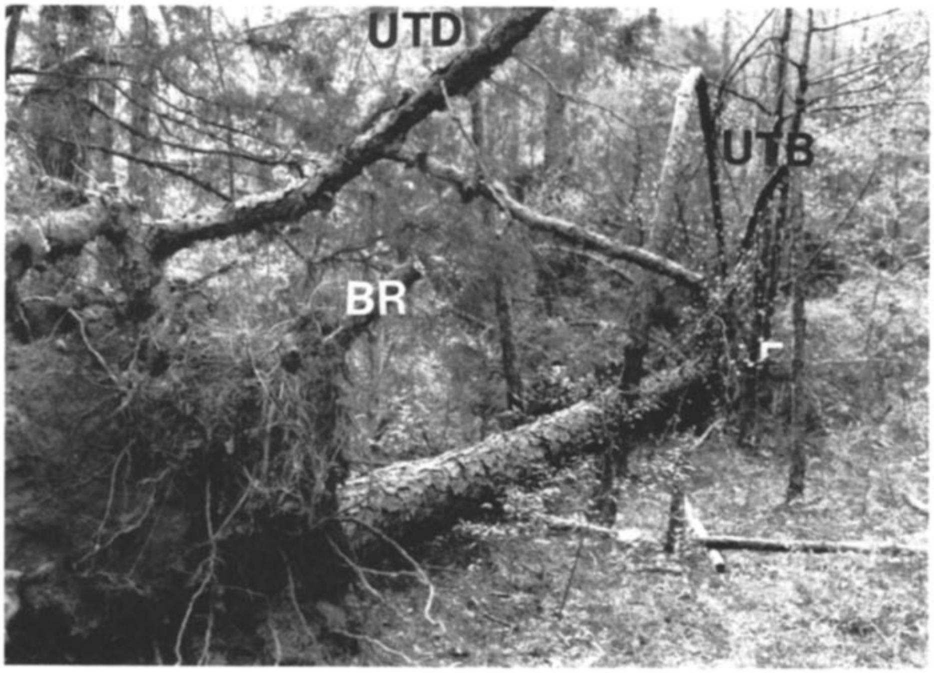

FIGURE 2—Heavily wooded area near Foster Street where mean tree orientation is northwest. Note the uprooted pine with intact rootball. Broken rooting structures (BR) of various dimensions extend from the soil enclosing the rootball. Damage to the understory is the result of tree fall. Understory trees are bent (UTB) in the direction of tree fall, understory tree lateral to the large pine is deflected (UTD) in a direction perpendicular to the fallen tree.

downed trees were directed perpendicular to the storm front only in those sites where the cyclonic vortex extended to near ground level.

DISCUSSION

Severe weather with accompanying gale-force winds (those that may exceed 185 km/hr) is a frequent phenomenon. Damage to terrestrial vegetation occurs often, and orientations of downed trees show a pronounced unidirectional orientation (e.g., Anderson, 1964; O'Cinneide, 1975; DeWalle, 1983; Dittus, 1985). Few such events have been interpreted in the stratigraphic record (Potonié, 1910; Wnuk and Pfefferkorn, 1987), although concentrated accumulations of logs are common particularly in Mesozoic and Cenozoic strata. Blow-downs associated with squall lines in which cyclonic winds have developed can occur under a range of wind velocities. Maximum wind speeds in "weak" tornadoes vary between 40 and 112 mph (67–187 km/hr), in "strong" tornadoes variation ranges between 113 and 206 mph (188–343 km/hr), whereas wind speeds in "violent" tornadoes exceed 207 mph (>344 km/hr). Two or more subsidiary vortices may develop under these extreme conditions. Although the distance over which a tornado can travel may be 10's of kilometers, the width of areas damaged by single funnel tornadoes are generally restricted to less than a kilometer (Eagleman, 1983). Multiple vortex tornadoes, with winds approaching 300 mph (500 km/hr), may leave a complex cycloidal swath of damage over the affected area. Forest blow-downs that occur as the result of such climatic processes can be identified based on orientation and other features of the woody assemblage (xylocoenosis).

Severe thunderstorms develop an organized internal structure within the atmosphere that may extend from their cloud base (approximately 1 km) into the troposphere (heights as great as 17 km). Winds vary throughout this air column with light winds near the base and strong winds at the jetstream (approximately 12 km height). These conditions produce a persistent updraft. Such storms develop vertically through strong wind shear environments, promoting vertical spinning of the air column, and forming a barrier to surrounding airflow (cyclostrophic balance). Air currents form a double vortex within. If, for example, a storm front were moving in a northerly direction, a cyclonic

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FIGURE 1—Locality and generalized city map of Auburn, Alabama. Localities where orientations of wind-damaged trees were measured are plotted as rose-diagrams with the number of measurements noted below. Arrows show vector mean of data set as calculated by SPLOT.

FIGURE 3—Heavily wooded area on Pride Avenue where mean tree orientation is northeast. This site is less than 0.5 km from site in Figure 2. Note the parallel alignment of three large pine trees (P) and two oak trees (O). Damage to the understory in this site includes fracture and displacement from vertical of subcanopy trees. Little damage was sustained by the ground cover.

vortex is produced in the southern part, an anticyclonic vortex is generated in the northern part of the storm. When the cyclonic vortex dominates the system, it begins to simulate a tube extending through the thunderstorm. It is the extension of this tube to the surface that produces a tornado (Eagleman, 1983). The diameter of the funnel is rarely more than a few hundred meters, and it is this scale of resolution that is needed to identify the effects of such atmospheric perturbations.

If all data taken in north Auburn are combined into a single rose diagram (Fig. 4), a justifiable interpretation to explain the tree orientations in the assemblage that extends over approximately 2 km^2 would be a unidirectional windstorm. The combined data diagram is consistent with those published by Wnuk and Pfefferkorn (1987) for tree orientations reported to be the result of unidirectional forces. But, when the distribution of data is assessed within geographical context, it is obvious that the spatial relationships of data sets provide the insight requisite to identify damage in response to cyclonic winds. Areas in which the tree alignment is discordant with the overall pattern of displacement provide the critical evidence for devastation by cyclonic winds. There are two such areas in the present example (Fig. 1). Trees in these groups are oriented northwesterly, a direction nearly perpendicular to that of the prevailing storm trend. If the tornado had touched down, one would expect to find a damaged area in which southeasterly-oriented trees existed. This would be in response to the contact between the rotating vortex and the forest. An analogy would be a spinning top encountering a "grove" of "rooted" wooden dowels. Apparently, the vortex approached the ground at an inclined angle with the southeasterly edge of the funnel somewhat elevated.

In order to discern fossil forest blow downs that were the result of cyclonic winds as opposed to gale-force windstorms, an understanding of both the assemblage features and its spatial resolution are necessary. An assemblage from cyclonic winds would be composed of large trees that are spatially separated from one another. This is in contrast to such accumulations, such as log jams, in which the trees are crowded together within a small geographical area and generally confined to a distinguishable channel form (Degges and Gastaldo, 1988). In cyclonic wind disturbances, the physical features of tree trunks would vary. Depending upon the force of the cyclone and other wind conditions at the time of blow-down, some trees would retain their tree bases (actual blow downs) while others would not (trunk rupture at various heights above ground surface). The lateral roots would decay first due, in part, to their smaller diameter and exposure to oxidizing conditions. The base of the tree would have a higher potential for preservation. There would be little, if any, indication of actual rooting structures attached to the tree base. Erect tree bases, those remnants of ruptured trunks, and rooting structures may be preserved in the original paleosol. The logs would probably not have any type of canopy. Canopy branches

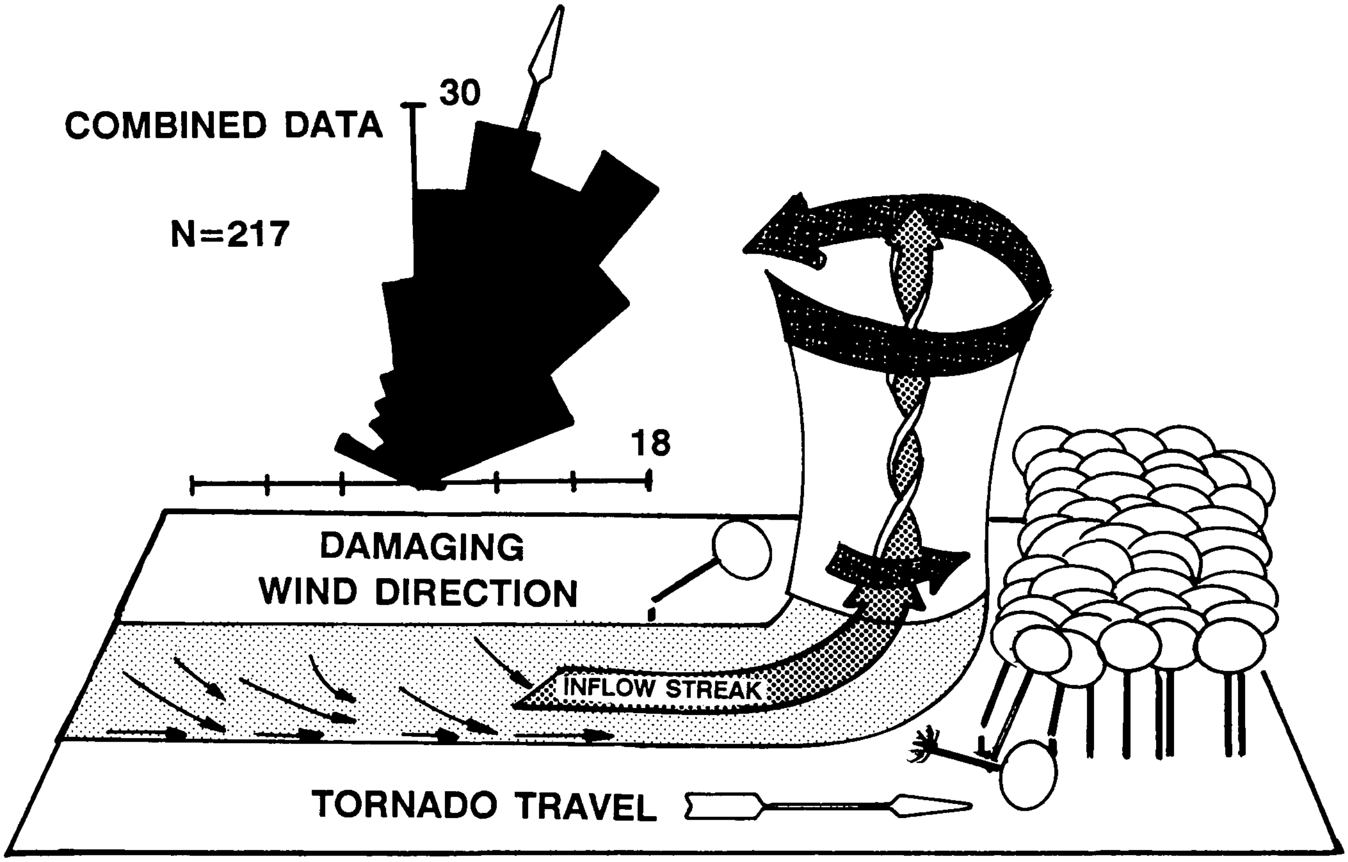

FIGURE 4—Combined data set from localities in north Auburn illustrating the analysis bias when orientations are evaluated out of geographic context. Diagrammatic illustration of advancing tornado depicting the main trend of damage with vegetation lateral to the funnel being displaced perpendicularly to the direction of movement.

would deteriorate more rapidly than the trunk itself and, depending upon the resistance of the wood and diameter of the tree, the trunk may remain on site hundreds of years after canopy deterioration. For example, it is common to find in alluvial swamps of the Mobile-Tensaw River delta, Alabama, prostrate trunks of *Taxodium* that are characterized by a buttressed base but do not possess canopy branches (pers. obs.; see Gastaldo et al., 1989). These trees have resided on the forest floor for several hundreds of years.

In the case of cyclonic wind damage, orientations of the trees within the resultant assemblage would vary geographically across the affected area. Overall, an apparent generalized orientation vector would be found with respect to the alignment of the majority of trunks. Orientations of some trunks in geographically adjacent areas would show some divergence from this composite vector. Such anomalies would be due to at least two factors. First, the orientations of those trees that had been resident on the forest floor before the blow-down event, presumably randomly oriented, would be discordant with the generalized trend. A small number of trees would display this disparative orientation when compared to the predominant vector. Second, orientations of trees that were displaced by cyclonic winds would not conform to the overall trend. This subset would display a preferred orientation perpendicular to that of the generalized vector. A large number of trees would be represented in this subset. As seen in Figure 4, the number of data points that represent damage by cyclonic winds is small when compared with the overall assemblage. In order to evaluate the possibility of the latter, the fossil site would have to be subdivided into quadrats. Orientations of trees would have to be evaluated within and between quadrats. Based on the present example, it is believed that quadrats of 100 m^2 should be the minimum area evaluated. Increasing quadrat sizes and/or restructuring of quadrat boundaries may be used to reevaluate the data afterwards. Only in this way will the possible signature of cyclonic damage be ascertained. Because specific climatic conditions are requisite for cyclone development, such an event recognized in the stratigraphic record would provide evidence for paleoclimatic conditions and refined modelling of past atmospheric circulation.

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