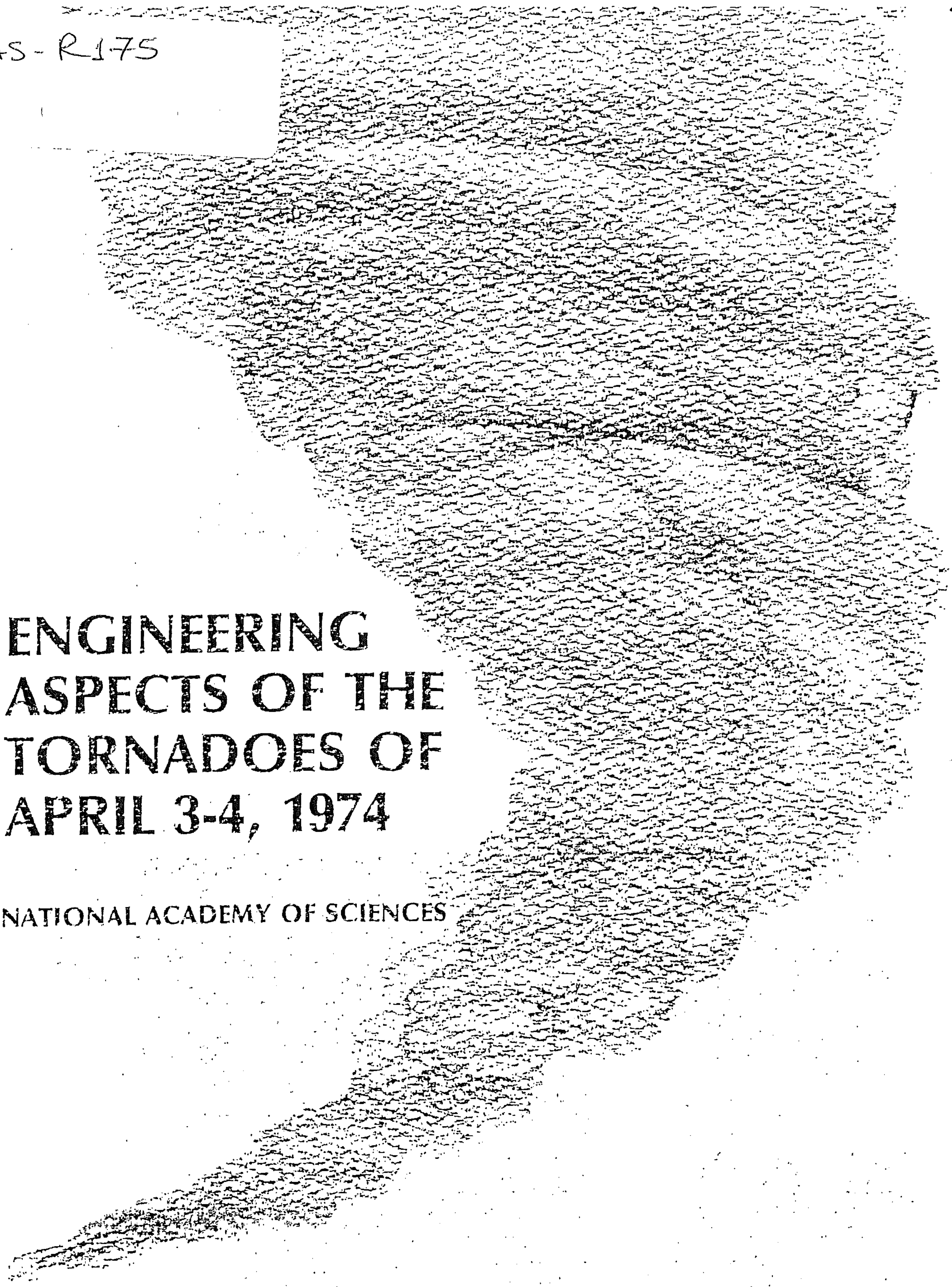

ENGINEERING ASPECTS OF THE TORNADOES OF APRIL 3-4, 1974

NATIONAL ACADEMY OF SCIENCES

ENGINEERING ASPECTS OF THE TORNADOES OF APRIL 3-4, 1974

a report prepared by

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Commission on Sociotechnical Systems

NATIONAL RESEARCH COUNCIL

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1975

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FOREWORD

A part of the mission of the Committee on Natural Disasters of the Commission on Sociotechnical Systems of the National Research Council is the investigation of damage to engineered structures immediately following a natural disaster. Reports of the findings of the investigating teams are published in order to provide engineering disciplines with information that will result in design improvements better to enable engineered structures to withstand the effects of natural disasters.

This document is a preliminary summary and overview of engineering data assembled following the extensive outbreak of tornadoes during the 3rd and 4th of April, 1974. The planning and coordination of the damage inspection visits was carried out by the Institute for Disaster Research at Texas Tech University at the request of the Committee on Natural Disasters. The report contains summary information from field investigating teams representing several universities and organizations. Direct expenses of field investigators and report writers were supported, in part, under a contract between the National Science Foundation and the National Academy of Sciences.

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National Severe Storms Laboratory
National Weather Service Office, Central Region
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ABSTRACT

On April 3, 1974, a series of severe storms generated approximately 100 tornadoes in eleven states throughout the central part of the United States. The total of tornado damage path lengths exceeded 2000 miles (average total path mileage of tornadoes in the entire U.S. is approximately 4000 miles per year). This event represents the largest outbreak of tornadoes in a single 24 hour period in recorded history. The storm killed 330 persons and injured many thousands. A conservative estimate of damage is $500,000,000.

The day after the storms, architects and engineers from various organizations initiated a coordinated effort to document the extent and severity of damage. Field work conducted by these engineers was coordinated with meteorologists. The ground level documentation effort by the engineers was begun under the auspices of the National Research Council Committee on Natural Disasters. Observations made by these engineers are presented in this report. The overall damage documentation and evaluation efforts by professionals from different disciplines have potentials for advancing the state-of-the-art regarding the understanding of tornadic storms and the mitigation of disasters resulting from future storms.

Preliminary general observations by field documentation team members, including their assessments of possible beneficial additional work, are summarized below:

(1) WINDSPEEDS: Several specific storms exhibited extreme windspeeds which appear to be as severe as those occurring in previously documented storms of record. Preliminary analyses of structural damage and missile incidents has not produced any conclusive evidence that ground level (30 feet and less) windspeeds in the April 3-4 tornadoes exceeded 250 mph. Evaluations of damage to several major structures which may provide meaningful windspeed estimates are continuing, and should be given continued support.

(2) METEOROLOGY: Satellite photography, radar data, and meteorological information assembled before and during the tornado outbreak should significantly enhance the abilities of meteorologists to forecast conditions which are conducive to tornado occurrence and to provide warnings in advance of tornado impacts on populated areas. This activity will have a significant influence on the design of structural systems for occupant protection which presume the existence of minimal warning times. Occupant protection activities--warning systems and protection systems--warrant additional coordinated attention by meteorologists and engineers.

(3) STORM CHARACTERISTICS: Many tornadoes in the April 3-4 storms were observed to closely follow the terrain, and to cross ridges and sweep into valleys with little abatement. This type of storm characteristic may have implications for the design of tornado resistant structures located in hilly or mountainous regions. Additional attention to the study of storm characteristics is indicated by the field data; such studies should be of particular interest to the nuclear industry.

(4) STRUCTURAL RESPONSE: Observed damage to fully engineered, marginally engineered, and non-engineered structures serves to reinforce previously established conclusions regarding structural response to extreme winds: (1) fully engineered structural frames perform well, but subsystems (e.g., fill-in walls, large doors) often provide points of initial failure; (2) marginally engineered structures (commercial and light industrial buildings, apartments, motels) are generally poorly coordinated with respect to wind resistance because anchorages and connections between major components frequently fail; and (3) non-engineered structures such as residences exhibit little resistance to extreme winds. However, even in destroyed residences there are, in most cases, small, interior portions of the residence which remain--suggesting beginning points for the design of shelters in residences. Mobile homes, as previously observed, are very poor in their resistance to wind and offer no opportunity for occupant protection. Improvement of design methodology could reduce property damage significantly and implementation of designs for occupant protection in public buildings and private residences will reduce loss of life. Attention should be given to these facets of structural and architectural design.

(5) SCHOOLS: Twenty severely damaged schools in Indiana, Ohio, Kentucky and Alabama will provide valuable information regarding (1) relative responses of several basic structural/architectural systems and (2) opportunities for the development of design criteria for safe havens for school children from the effects of tornadoes. An opportunity exists with these data to significantly advance the state-of-the-art of school design to include tornado protected areas for school children.

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I. INTRODUCTION

The tornadoes of April 3-4, 1974 affected eleven states and Canada, and killed more than 300 persons. More than 100 tornadoes were reported and nearly 100 separate tornado tracks have been mapped. The significance of these storms--termed the worst series of storms and the most significant meteorological event in 50 years--lies in the dramatic signalling to the public of a major, persistent problem in the United States--protection of people and property from the effects of tornadoes and extreme winds.

The meteorological, engineering and architectural professions are faced with a challenge in the formulation of effective and economical warning and protection plans for people and property in advance of storm occurrences. It is the duty of the professional community representing these disciplines to investigate and document damage caused by extreme winds, and to make known conclusions and implications of these investigations to appropriate design groups, code bodies, governmental agencies, and planning authorities. Only by documenting, publishing, and acting upon published recommendations can the extreme winds hazard be mitigated.

This report represents only the first step in the long process of focusing new knowledge about the nature and effects of extreme winds on appropriate responsible agencies and organizations. This preliminary overview of the extent and intensity of the storms will be followed by more detailed reports and recommendations regarding wind hazard mitigation. Hopefully, these initial efforts will lead to the development of pertinent information for cognizant agencies, organizations, and individuals who are responsible for improved building designs and occupant protection.

Section II of the report contains an overview of the storm and its effects. A brief description of synoptic scale meteorological events on April 3-4 is given as background information. Sections III-XI contain nine state-by-state summaries of ground observations by trained professional engineers and architects. Only Virginia and West Virginia which received less tornado activity, relative to the other nine states, are excluded from these state summaries. These summaries serve three principal objectives: (1) to provide an overview of the nature and intensity of the storms at various locations, (2) to summarize data and information that were recorded and are available for additional study, and (3) to present specific recommendations for future study and action. Section XII contains general conclusions and recommendations regarding the conduct of activities which will, hopefully, bring about mitigation of the effects of severe storms on our society.

II. STORM OVERVIEW

The tornado outbreak of April 3-4, 1974, was the most extensive and devastating in history in terms of property damage, and second only to the March 18, 1925, outbreak in terms of lives lost. Meteorologists are currently studying and evaluating data assembled from satellites, from radar records, from surface maps, from weather instruments, and from aerial observations. We can expect the meteorological community to publish widely and in great detail, as this tornado outbreak event has been termed the most significant in 50 years. Because of the anticipated extensive publication activity by meteorologists, this overview of the storms will include only general descriptions of the synoptic (large scale) situation which spawned the storms and of preliminary assessments of the unique combination of factors which contributed to storm severity and extent. Thus, the overview relates to subsequent presentations and includes (1) the synoptic scale weather situation, (2) the location of storm damage tracks, and (3) activities of ground observation teams.

Synoptic Scale Weather Situation - April 3, 1974

Purdom* reported in a preliminary assessment of ATS-III Satellite pictures that early in the day (0800 CDT) of April 3, a weather system extending from southeast Louisiana, northeastward across western Tennessee to southwestern Kentucky, contained a convection due to an upper level impulse. During the day this impulse moved rapidly northeastward through the Ohio Valley, leaving clear air to the rear of the impulse. This clearing allowed the air in the clear region to become more unstable (due to solar heating) when compared to air in surrounding cloudy areas. Additionally, behind the impulse, midtropospheric dry air advection and vigorous subsidence caused drying at middle levels. The low level heating, combined with the drying at middle levels, increased the convective instability of the air behind the impulse--thus making that air very favorable for tornado development.

The surface weather map at 1500 hrs. (CDT) on April 3 reflected an intense low pressure area (829 mb) in eastern Iowa with a cold front trailing from this low pressure area through western Illinois, extreme eastern Missouri, eastern Arkansas, and into Louisiana. Three active squall lines formed ahead of this front in the unstable air, and were producing tornadoes, simultaneously, in Illinois, Indiana, and Tennessee. At this hour the squall lines were located across Illinois from near Springfield to Chicago, across Tennessee, Kentucky, and Indiana from northern Mississippi to Fort Wayne, and across western Georgia and

* Purdom, James W., "Storm of the Month, The April 3, 1974 Tornado Outbreak," NESS Evaluation presented at the Conference on Jumbo Tornado Outbreak, University of Chicago, July 10, 1974.

eastern Tennessee into southeastern Kentucky. These squall lines moved southeastward during afternoon and evening hours producing most of the tornadoes.

Location of Storm Damage Tracks

According to Fujita* more than 2000 miles of tornado induced damage paths occurred within an 18 hour period beginning at 1400 hrs. (CDT) on April 3. Figure 1 summarizes locations of 148 individual tornado tracks located by Dr. Fujita from aerial surveys conducted by his staff and assisted by representatives of the National Severe Storms Laboratory and the University of Oklahoma. All of these damage tracks are oriented, generally, southwest to northeast and range from very short (less than 1 mile) to very long (132 miles). Most of the tornadoes moved northeastward at 40 to 60 mph while the squall lines were advancing toward the southeast. The tornadoes moved with individual cells--not with squall lines.

Unique features of the tornadoes include mountain climbing and canyon crossing paths in Kentucky, Tennessee, Georgia, North Carolina, Virginia, and West Virginia. Most of the tornadoes avoided large cities with the notable exception being Xenia, Ohio. Extensive damage paths in Xenia, in Brandenburg, Kentucky, in Hamburg and Depauw, Indiana, in Sayler Park (Cincinnati), Ohio, and in Guin, Alabama, are cited by Fujita as being particularly noteworthy.

Ground Observation Teams

The Committee on Natural Disasters moved on April 4 to activate ground observation teams. The Institute for Disaster Research at Texas Tech University was alerted and asked to coordinate ground documentation activities. The Institute contacted the Professional Advisory Service Centers (DCPA) at Detroit (Mr. James J. Abernethy) and at Birmingham (Mr. Billy R. Manning). Through preliminary assessments of news media reports and through coordination with these centers, it was decided that (1) the PASC-Detroit would operate in Indiana, Illinois, and Michigan, (2) Texas Tech University teams would go to Xenia-Cincinnati, Ohio, and to Louisville-Brandenburg, Kentucky, and (3) PASC-Birmingham would operate in the Alabama-Georgia-Tennessee area. Mr. Abernethy (PASC-Detroit) and Professor Hanson of the University of Detroit went into the field in Michigan and northern Indiana and coordinated activities in Indiana with Professor Uwe F. Koehler of Ball State University.

The Institute coordination center in Lubbock remained in contact with field documentation teams and with Dr. Fujita at the University of Chicago. As a result of specific damage path data provided by Dr. Fujita,

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* Fujita, T. Theodore, "Jumbo Outbreak of 3 April 1974," published in *Weatherwise*, June 1974.

additional teams of structural engineers were subsequently sent to Alabama, to Georgia, to North Carolina and to Monticello, Indiana. Other investigators were determined to have also been in the field. Table II-1 summarizes the total damage documentation effort known to have been undertaken.

TABLE II-1

KNOWN INVESTIGATIVE EFFORTS: THE TORNADOES OF APRIL 3-4, 1974

Organization	Personnel	Locations Visited
University of Chicago (SMRP)	Fujita, Pearl, Tecson, Forbes, Pasken, Laplaca, Sereno	(All tracks; aerial)
National Severe Storms Laboratory	Golden, Lemon	(All tracks; aerial)
University of Oklahoma	McCarthy	(All tracks; aerial)
Texas Tech University (IDR)	Mehta, McDonald, Croghan, Beason, Goolsby, Minor	Xenia, Cincinnati, Ohio; Brandenburg, Louisville, Kentucky; Guin, Jasper, Decatur, Huntsville, Alabama; Monticello, Indiana (aerial and ground)
University of Detroit (PASC)	Abernethy, Hanson	Windsor, Ontario; Monticello, Rochester, Talma, Angola, Parker, Farmland, Indiana; Hillsdale, Michigan
Ball State University	Koehler, Monk	Monticello, Parker, Farmland, Kennard, Hamburg, Depauw, Madison, Grant City, China, Hanover, Indiana; Xenia, Cincinnati, Ohio (aerial and ground)
Auburn University (PASC)	Manning	Jasper, Guin, Cullman, Hamilton, Moulton, Decatur, Alabama; Blue Ridge, Resaca, Georgia; Cleveland, Etowah, Tennessee; Murphy, North Carolina (aerial and ground)
Bechtel Corporation	Rotz, Yeh, Almouti	Xenia, Cincinnati, Ohio
Stone and Webster	Shanahan	Louisville, Brandenburg, Kentucky; Kirby, Indiana

TABLE II-1

KNOWN INVESTIGATIVE EFFORTS: THE TORNADOES OF APRIL 3-4, 1974 (Cont'd.)

Organization	Personnel	Locations Visited
Dames and Moore	Nicholson, Wode	Louisville, Brandenburg, Kentucky; Xenia, Ohio
St. Thomas University	Goldman	(Aerial surveys)
University of Illinois	Rodda	Illinois tracks
Purdue University	Agee, Church, Morris, Snow	Parker, Farmland, Indiana
NOAA	Epstein	Several locations (to evaluate warning systems)
HEW, Chicago Office	Fisher	Xenia, Ohio (ground)
HEW, Philadelphia Office	Johnson	Xenia, Ohio (ground)

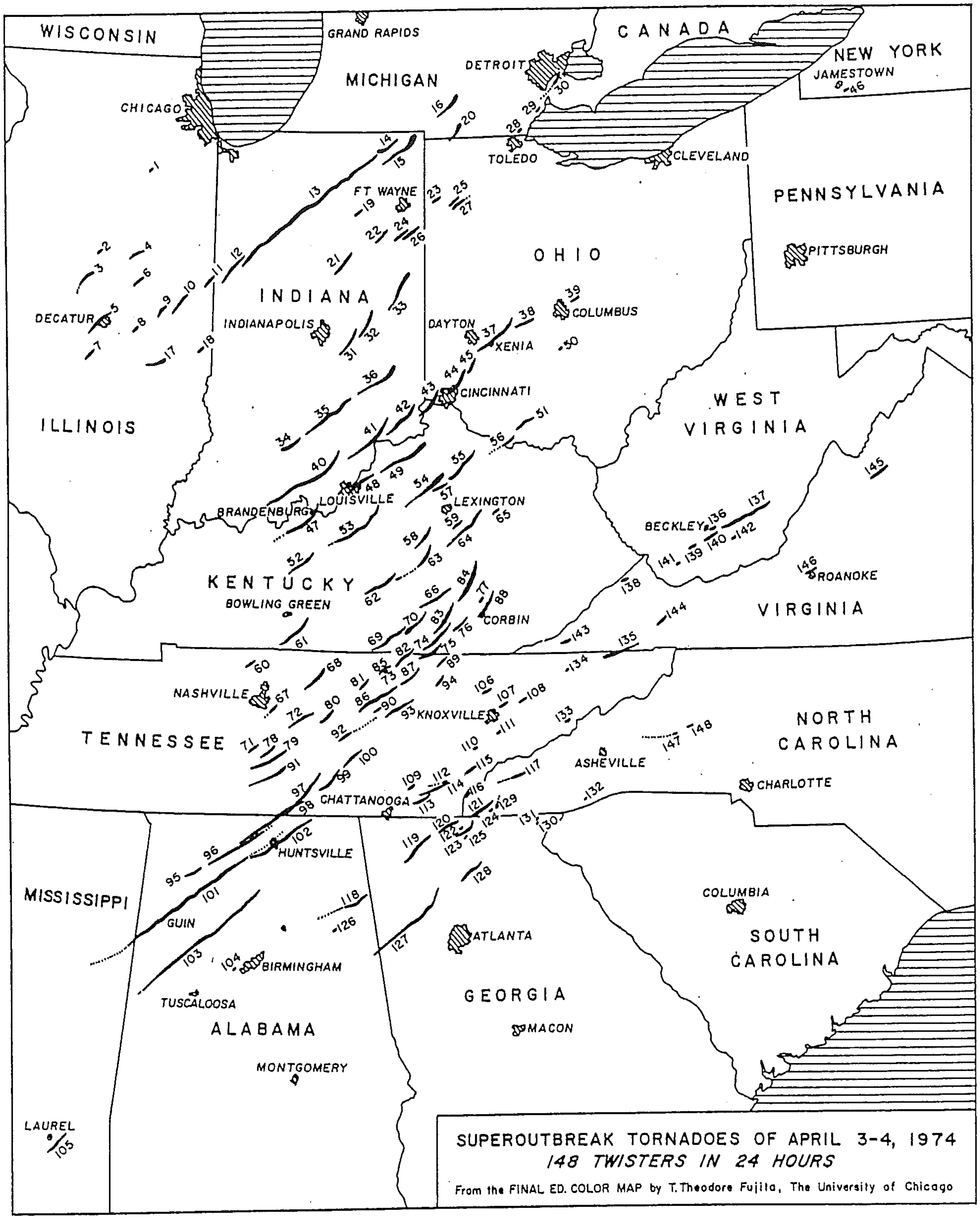


FIGURE 1. PATHS OF 148 TORNADOES ON APRIL 3-4, 1974. (Drawing courtesy T. T. Fujita, The University of Chicago -- updated version supplied in June 1975)

III. MICHIGAN & WINDSOR, CANADA

The tornadic storm of April 3, 1974, generated tornadoes which began at 2:30 P.M. in the midwest states; these storms moved into the southern part of Michigan around 7:30 P.M. Two tornado tracks, each about 300 ft. wide and approximately 8 miles long, were located in Michigan by Dr. Fujita and his associates (Figure 2). These tracks are the northern-most tracks located following the storm of April 3, 1974. Structural damage occurred in Hillsdale, Michigan and in Windsor, Ontario, Canada. In Michigan, 3 persons lost their lives, 23 persons received injuries, and property loss was estimated at $2,000,000. In Windsor (a city located in Canada across the river from Detroit), 8 persons died and 11 persons received injury--all of these casualties occurred in one building failure. Property damage in Windsor was estimated at $1,000,000.

Hillsdale, Michigan

This city of 8,000 people located in the southern part of Michigan was ravaged by tornadic storms about 8 P.M. Most of the damage in this area was restricted to residences. According to initial reports by the Michigan State Police, 67 houses were destroyed and 88 additional houses sustained major damage. Mobile homes in the path of the storm sustained damage by overturning and by impact from flying debris. Some of the mobile homes overturned, tumbled in the high winds, and ultimately disintegrated. A typical disintegrated mobile home and its debris are shown in Figure 3. Two of the three deaths that occurred in Michigan occurred when mobile homes disintegrated. Mobile home parks in this area had received early warnings of the storms. Some of the occupants of mobile homes moved to shelter areas within and outside of the park; thus, warning time may have been responsible for the relatively small number of deaths in Michigan. The mobile home units in the park shown in Figure 4 sustained varying degrees of damage--some of them overturned, some of them disintegrated, and the rest sustained damage due to flying debris. A few of the mobile homes that did not overturn were anchored to the ground. Maximum windspeeds in this storm are judged to be in the 80-120 mph range.

Windsor, Canada

Reports of damage from this city of 180,000 are limited to two structures: a shopping center under construction and the Windsor Curling Club's Ice Rink arena. The one-story structure had a span of about 100 ft. and a wall height of approximately 25 ft. The end wall of the arena collapsed inward and a large portion of the arena roof was blown off as shown in Figure 5 and 6. The structural framing (gabled frames) of the arena did not collapse. The end wall which collapsed was built of concrete masonry blocks and did not have vertical reinforcement. Injuries to 11 persons and 8 deaths occurred in this building when the masonry block wall collapsed on the occupants, burying them in the debris. Maximum windspeeds in this storm are judged to be in the 80-120 mph range.

Indicated Additional Work in Michigan and Windsor, Canada

Deaths, injuries, and damage in Michigan occurred primarily in mobile homes. These types of residential units are susceptible to overturning and disintegrating in high winds if they are not properly anchored to the ground. Additional data should be obtained about these mobile homes and about standards for mobile home parks in Michigan. It would be informative to determine anchorage status of the mobile home units which overturned as well as for the ones which did not overturn. Damage and destruction of mobile homes in windstorms is a national problem, particularly in view of large percentages of mobile homes being used as new residential units. A detailed documentation of the behavior of anchored and unanchored mobile homes in tornadic windstorms will provide valuable information to improve design criteria of anchoring systems.

Deaths and injuries in Windsor, Canada occurred because of the collapse of an unreinforced concrete masonry wall. Additional information should be assimilated regarding this failure to permit further assessment of the safety of persons in high occupancy buildings in windstorms. This collapse is of particular interest because a large number of deaths occurred when a loadbearing wall, which supported a half-span of purlins, collapsed.

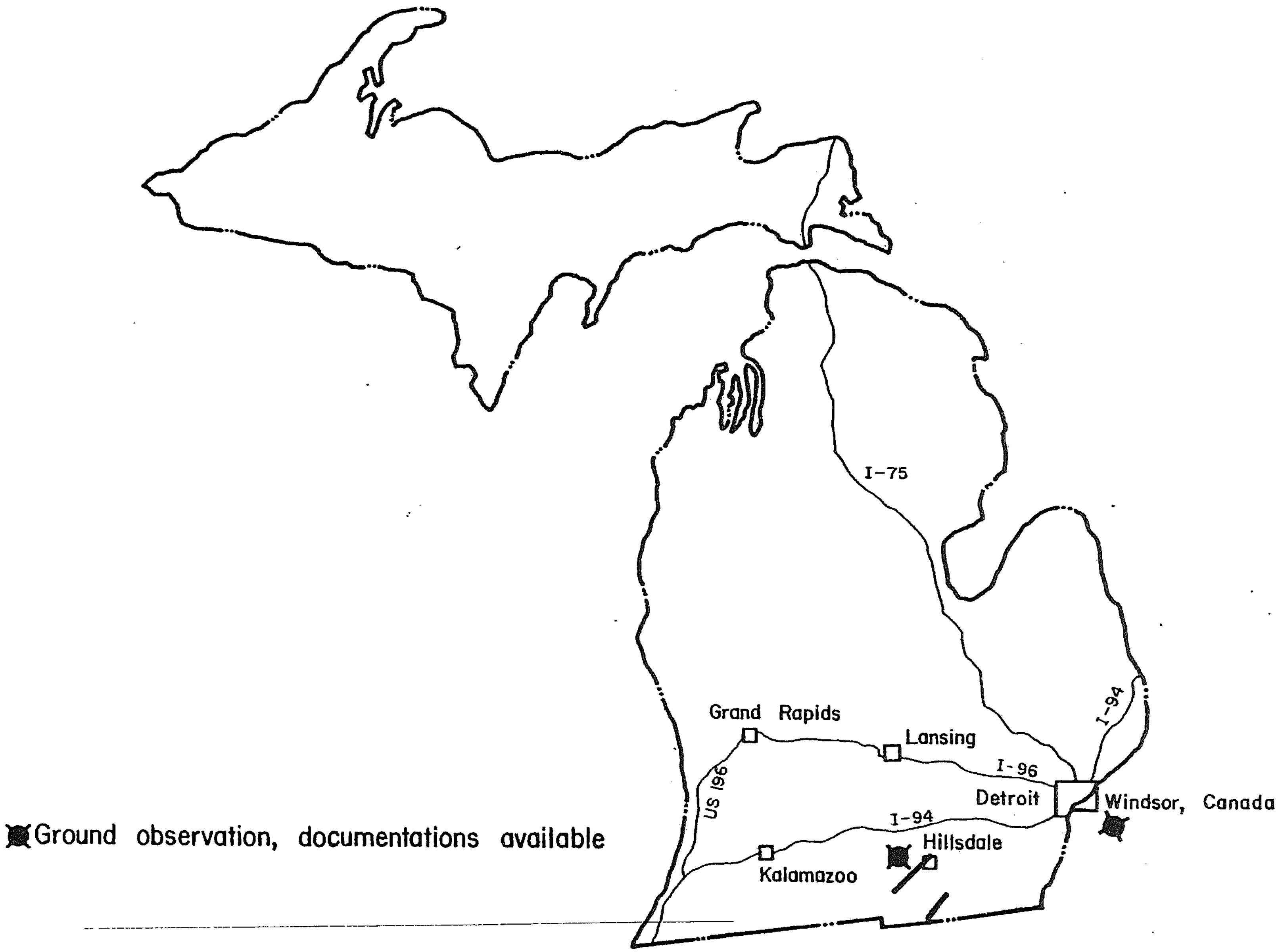


FIGURE 2. MICHIGAN AND WINDSOR, CANADA. Tornado tracks as determined by Fujita.

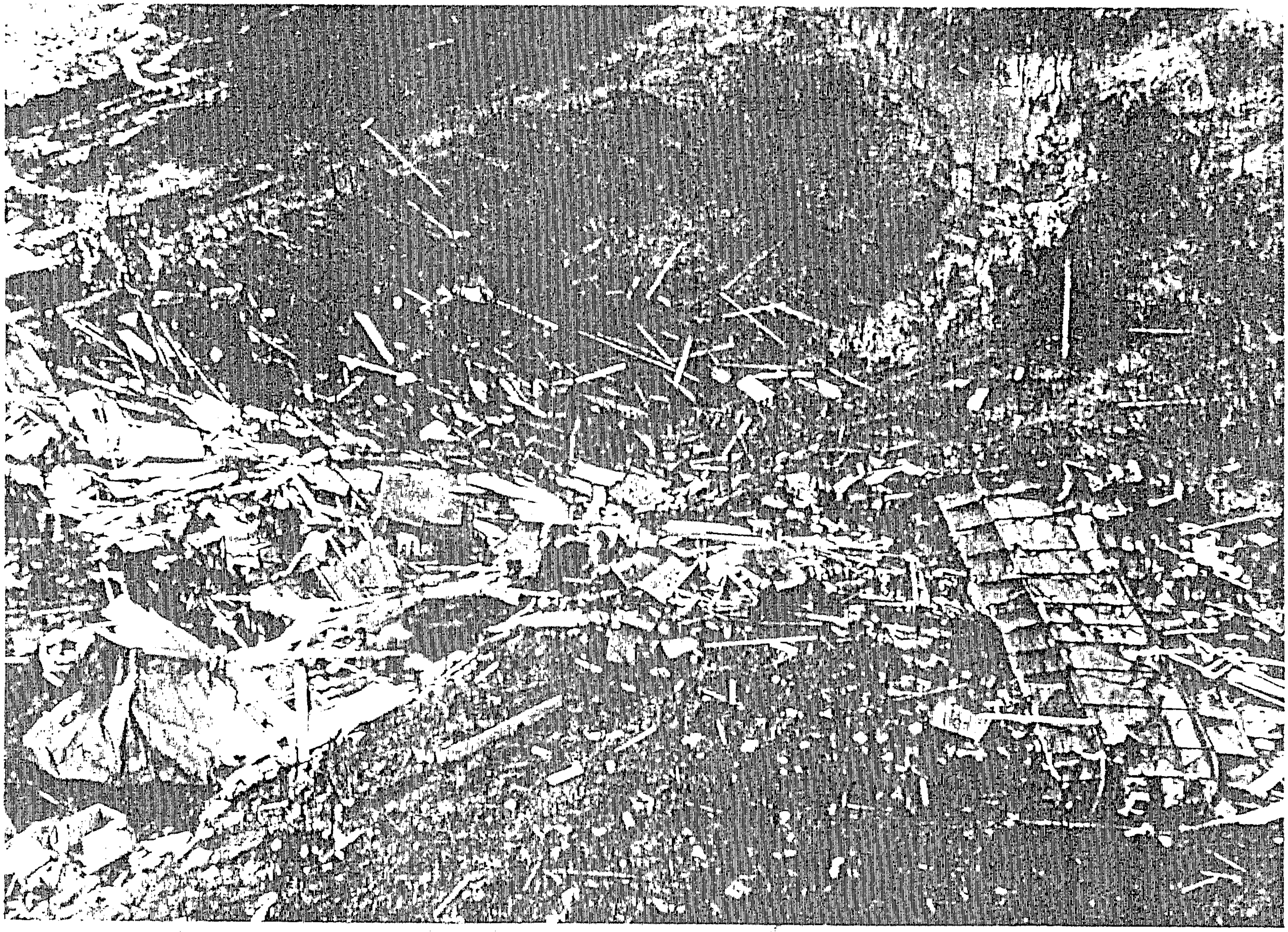


FIGURE 3. HILLSDALE, MICHIGAN. Debris of disintegrated mobile home (photograph courtesy Emergency Services Division, Michigan Department of State Police)

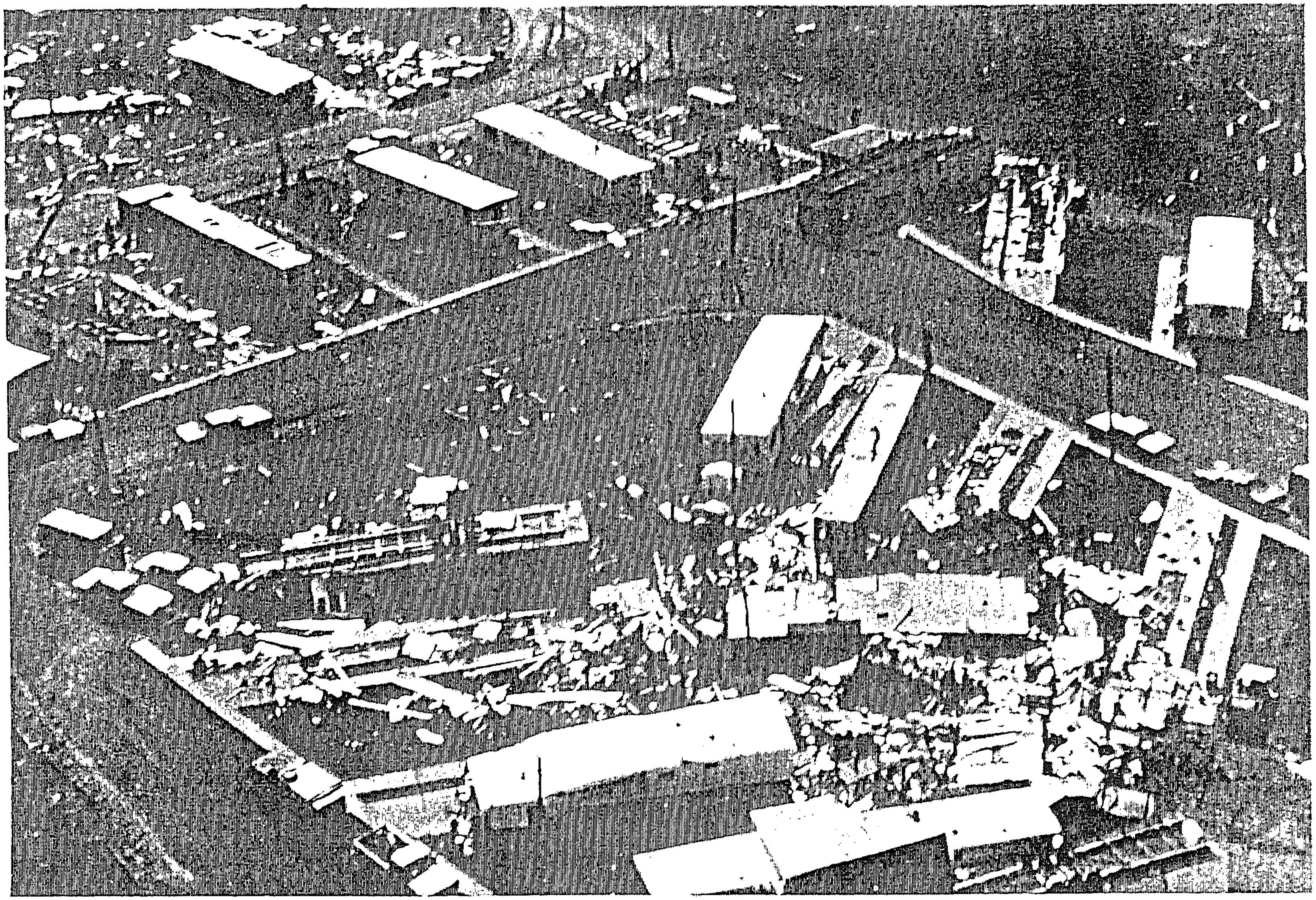


FIGURE 4. HILLSDALE, MICHIGAN. Riley's Mobile Home Park where mobile home units sustained varying degrees of damage. Some residents had taken shelter in the laundry building and outside of the park. (photograph courtesy Emergency Services Division, Michigan Department of State Police)

intersection of Hillsdale Road and Moore Road (still there as of April 2003)
2 miles north of Hillsdale

IV. ILLINOIS

On April 3, 1974, the first tornadoes of the storm system struck in the State of Illinois at about 2:30 P.M. The storm moved through the central part of the State from southwest to northeast. Dr. Fujita and his associates have observed 6 tornado tracks in the State; 4 of these tracks are in virtually a straight line, as shown in Figure 7. According to the Illinois Civil Defense Agency, 2 persons died and 14 persons were injured in these tornadoes. Property damage in Illinois is estimated at $7,000,000. The tornadoes covered primarily rural areas and damaged residences, farm structures and utility lines. Two populated areas, the city of Decatur and the town of Ogden, sustained damage.

Decatur was hard hit by the storm. Structural damage was restricted to residential areas. The Illinois Civil Defense Agency reported that 52 houses were destroyed, 110 houses sustained major damage, and an additional 100 houses sustained minor damage. In most residences, interior, short span rooms remained standing. Closets, interior bathrooms, and hallways (in that order) seemed to be the safest locations for houses without basements. A number of mobile homes were also damaged and destroyed in Decatur. One of the two deaths that occurred in Illinois occurred in a mobile home unit in Decatur.

The town of Ogden is located approximately 12 miles east of Champaign, Illinois on Highway I-74. One person lost his life in this area. The tornado destroyed mobile homes, utility poles, and transmission line towers. Figure 8 shows a collapsed transmission line tower and a snapped utility pole. The tornado also overturned vehicles on I-74 as shown in Figure 9. The tornadoes in Illinois were of narrow paths and they seem to be less intense than tornadoes that occurred in other states on this day. The type of damage shown in Figures 8 and 9 could occur from maximum windspeeds in the 80-120 mph range.

Indicated Further Work in Illinois

It would be desirable to investigate further the behavior of residences, mobile homes, transmission towers, and utility lines in these relatively weak tornadoes. It may become desirable engineering practice in the future to increase wind resistances of certain types of structures by increasing design windspeeds by a small amount above code specified values. There may be an optimum design basis windspeed which would reduce the expected value of damage more than the increase in cost of strengthened construction--measured over the life of the structure. Additional documentation, particularly as to costs of damage to several broad building types, would be extremely valuable to such studies.

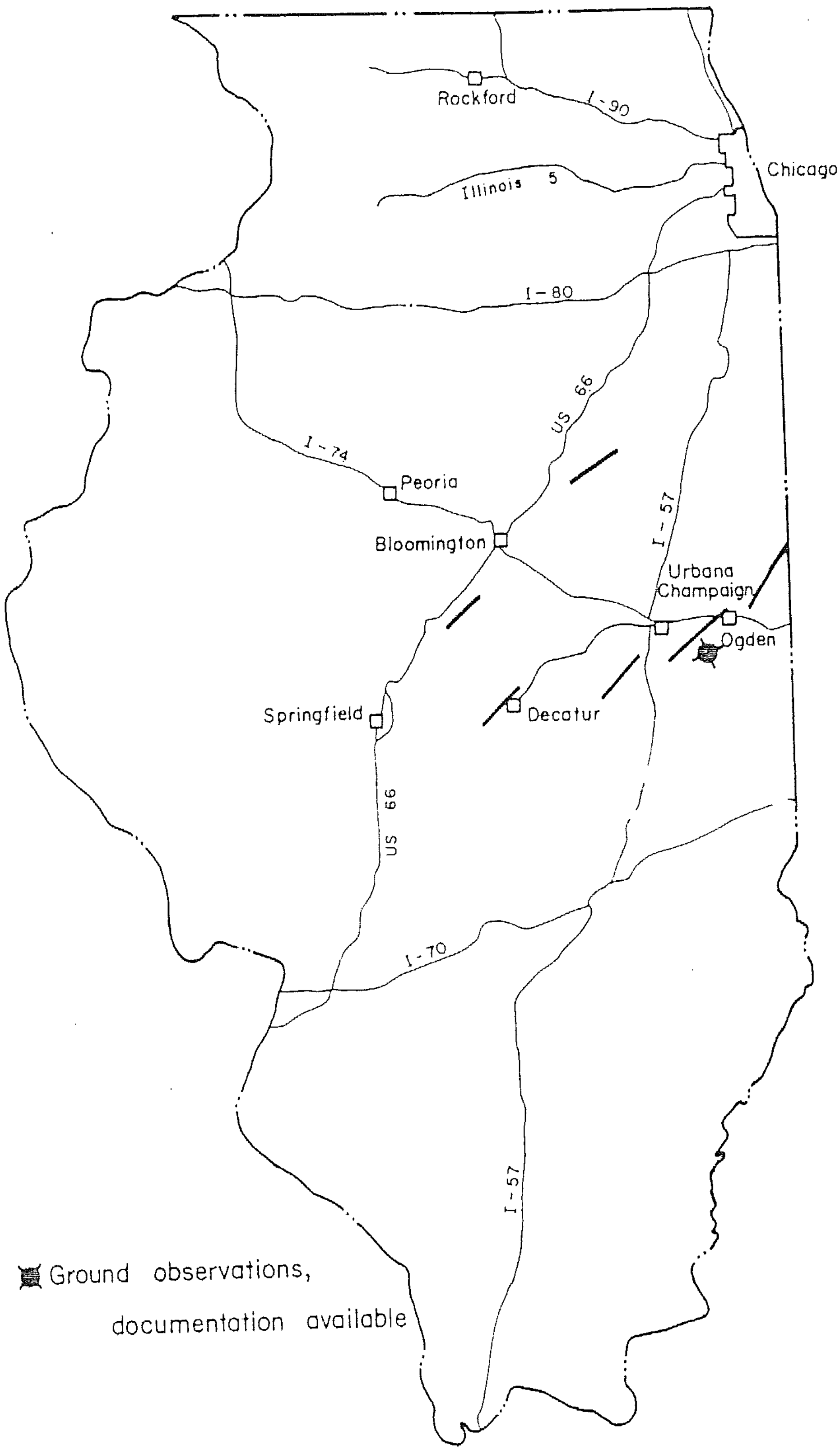


FIGURE 7. ILLINOIS. Tornado tracks as determined by Fujita.

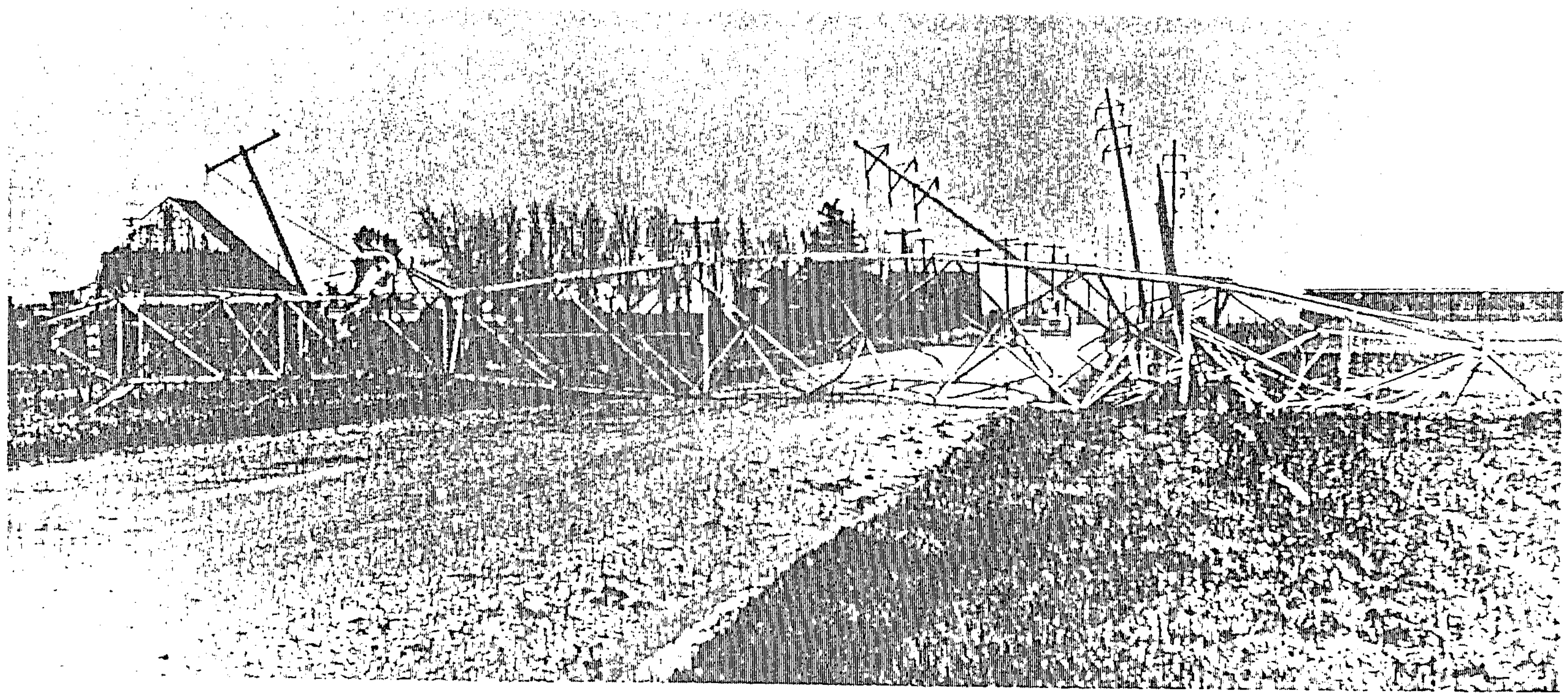


FIGURE 8. OGDEN, ILLINOIS. Collapsed transmission line tower and a snapped utility pole. (photograph courtesy of Champaign News Gazette)

FIGURE 9. OGDEN, ILLINOIS. Overturned vehicles on highway I-74. (photograph courtesy of Champaign News Gazette)

V. INDIANA

A series of tornadoes moved northeastward through the State of Indiana during the afternoon of April 3, 1974. Four well defined paths of damage were examined by aerial and ground observers; these damage paths may have been caused by four or more tornadoes, as suggested by the map by Fujita (Figure 1). The four principal paths of damage in Indiana are located on a map of the State in Figure 10; each path is named after areas which sustained major damage:

(1) Monticello path

(2) Kennard path

(3) Hamburg path

(4) Depauw/Madison path

Damage within the State caused by the April 3 storms has been estimated to be as much as $200,000,000. Included in approximately 1000 casualties are 48 confirmed deaths. Table V-1 contains a summary of deaths and injuries along these four principal damage paths.

Notable in the Indiana damage survey are (1) damage in Monticello, including destruction of a railroad bridge, (2) damage in the Madison-Hanover area, (3) the Kennard path, and (4) damage to schools. Particularly thorough photographic documentation of the damage areas in Indiana, and of the Xenia-Cincinnati areas, are on file at Ball State University. More than 3000 photographs (both black and white and color), vertical aerial photographs, and extensive logs, interviews, and newspaper clippings are available.

Monticello and Rochester, Indiana

The tornado path through Monticello is illustrated in Figures 11 and 12. The storm crossed an open field as it approached the three schools located on the southwestern edge of the town. From the school complex it moved into a residential area, across an abandoned school, and into the central business district where the county courthouse was severely damaged (Figure 13). It then passed through another residential area to a bluff over the Tippecanoe River. Unusual events took place here: (1) the tornado followed the terrain closely by damaging houses and industrial buildings at the foot of the bluff (approximate elevation difference is 60 ft.) and (2) the winds pushed four spans of a Penn Central Transportation Company railroad bridge off their piers. The spans consisted of two 10 ft. deep plate girders 105 ft. in length carrying a single track. Damaged bridge piers are shown in Figure 14. Structural details of the bridge are available at Texas Tech University.

The damage path continues northeastward from Monticello to Rochester where it caused extensive damage to railroad equipment, industrial buildings and residences. Figure 15 illustrates overturned railroad cars and damaged industrial buildings. Figure 16 includes nine houses in Rochester which were destroyed. Note that in five of these eight residences, a small portion of the interior of the residence survived.

The Monticello and Rochester damage documentation is significant because of the variations in types of structures affected, the fact that engineered structures were damaged, and the unusual events associated with the traversing of the relatively narrow river valley on the eastern edge of town. Damage to three of the Monticello schools is discussed in a special section on Indiana schools, below.

Madison and Hanover, Indiana

Of significance in the Madison-Hanover area is damage caused by the tornado as it approached the Ohio River on the north bank. The storm affected an electric power plant, a state hospital, residential areas, schools, and Hanover College (Figure 17). Several types of structures were affected--a damaged nursing home is shown in Figures 18 and 19, a damaged apartment house is shown in Figure 20, damage to Hanover College is illustrated in Figure 21, and damage to residences in Hanover is shown in Figure 22.

Kennard Damage Path

The damage path through Grant City and Kennard is illustrated in Figure 23. Damage to a funeral home in Parker/Farmland area is shown in Figure 24. Mobile home damage in this area is illustrated in Figure 25. Damage along this path was to rural housing and buildings.

School Damage

An important, and sometimes highly emotional, problem which faces the designers and owners of schools concerns the providing of protection for school children from the effects of tornadoes. The Indiana Department of Public Instruction compiled data on 24 schools which sustained storm induced damage; a summary of this agency's report is contained in Table V-2. No school related deaths were reported in Indiana schools, or in schools that were affected by the storm in Ohio, Kentucky, and Alabama, principally because of the late afternoon and evening times of tornado occurrences. Nonetheless, the realization of the disaster which may have occurred has brought forth expressions of concern from school officials and recommendations for additional attention to occupant protection from architects and engineers. Several specific school damage incidents are presented in the following subparagraphs to emphasize the nature of the problem and to summarize the data that are available.

Meadowlawn, Twin Lakes, and Roosevelt Schools, Monticello

Three schools on the southwestern edge of Monticello experienced the effects of a tornado that passed across the town late in the afternoon of

April 3. Meadowlawn Elementary School caught the full effects of the tornado. Twin Lakes High School felt severe, but not direct, effects next. Roosevelt Junior High School was located on the left edge of the advancing tornado and was less severely damaged.

The Meadowlawn school should provide investigators with a classic tornado-structure interaction event for study. This school has a principal main hallway oriented east-west, with classrooms on either side. The tornado slammed directly into the school from across an open field. Classrooms on the south side of the hallway were extensively damaged--window walls demolished and open web steel roof joists and roof were uplifted. Classrooms on the north side of the hallway were virtually undamaged. The principal hallway was undamaged except for the west glass doors which were broken. The hallway would have been a safe haven for school children.

The Twin Lakes High School is oriented such that the southwesternmost corner of the complex is a gymnasium (Ref. Figures 12 and 26). This corner of the complex is approximately 1000 ft. north and east of the Meadowlawn school. Damage to the Twin Lakes school was concentrated in the gymnasium area (the gym proper and adjacent one-story dressing rooms) and in classrooms on the west side of the complex. Unreinforced, nonloadbearing masonry walls (12 in. concrete block with brick facing), which formed the south and west external walls of the gymnasium (extending from the roof of the first floor dressing rooms to the roof level of the gym) toppled outward. Although atmospheric pressure change inducing outward acting pressures may have been a factor in these wall failures, there is evidence of lateral movement of the gymnasium structural frame (steel trusses on beams which frame to pipe columns; column height approximately 30 ft.) within the masonry "shell". The evidence (vertically cracked interior masonry walls at the locations of pipe columns) suggests that wind loads induced a lateral translation of the structural frame to the northeast and, upon rebounding, the frame pushed the south and west unreinforced masonry walls outward.

A significant missile incident at the Twin Lakes school involves a steel wide-flange beam which formed the roof support along the western edge of a second story classroom (Ref. Figure 26). This beam was lifted over the school building as the second story roof failed upward, and fell on the opposite (east) side of the building in the school yard. (Near white automobile on east side of school, Figure 26). Additional study of this incident using data available at PASC-Detroit is indicated.

As in the Meadowlawn school, hallways would have proved to be safe havens for school children in the Twin Lakes school. The school tornado plan called for building occupants to move to first floor hallways away from outside doors; this plan would have assured protection of building occupants, if warning times would have permitted planned movements of people.

The Roosevelt Junior High School, located to the north and west of the Twin Lakes school sustained less damage than the other two Monticello schools. The significant documentation item from this school is a barograph recording taken on a lower floor in the north central portion of the building. The barograph trace is reproduced in part in Figure 27.

Monroe Central School (Kennard Damage Path, Parker/Farmland)

The Monroe Central School was extensively damaged, but examination of the structure reveals that the principal failure mechanism was related to loadbearing masonry walls. Figure 28 illustrates damage to the gymnasium area (near wing) and to classrooms (far wings). Loadbearing masonry walls at the ends of the gymnasium failed (Ref. Figure 29). Although this failure compromised the structural integrity of the building the structural frame remained intact (Ref. Figure 30). Failures of masonry walls and failures of precast concrete roof units are also evident. Interior hallways, away from areas with roofs supported on exterior walls and away from entrances, would have been safe havens in this school.

Kennard, Elementary School

An old three-story elementary school at Kennard was heavily damaged (Ref. Figure 31). Although occupied by more than 100 persons at the time the tornado struck, no one was injured. Failures of loadbearing masonry walls provided the basic collapse mechanism (Ref. Figure 32). First floor interior hallways were havens of refuge in this structure.

Recommended Additional Work in Indiana

Extensive data assembled at Ball State University and data which can be assembled from other sources could be used to significantly advance understandings of the impact of tornadoes on structures and people. The following activities should be undertaken using Indiana events and data to add to the general knowledge of tornadoes and extreme winds and their effects:

(1) An extensive investigation of "Wind-Structure-Occupant Interaction" in slab on grade residences should be undertaken (1) to identify inherent tornado shelters, (2) to make design improvements to increase safety, and (3) to explore operational aspects of warning techniques. The ultimate goal of the study is a possible publication--with easily understandable recommendations for home owners, designers, and civil defense planners.

(2) In view of the extensive damage to the Monticello central business district, development of alternative urban design concepts for Monticello as well as conceptual studies for selected architectural projects could be undertaken.

(3) Various building types should be studied to determine characteristic modes of failure and to attempt a measurement of the risk of survival at recommended places of refuge within buildings. The main purpose of the study would be to examine the scope of alternatives available to the design profession.

(4) An effort is warranted to continue the data bank compilation, to analyze structural damage (aided by a series of aerial photo reconnaissance maps taken April 6 and 16), and to make a detailed personal injury survey. The latter task will be particularly valuable. There is a dearth of data that specifically relates personal injury to precise details of structural damage in tornado disasters--the indicated work to significantly add to the literature in this regard.

(5) Specific studies of Indiana schools--accomplished in conjunction with similar studies of schools in Ohio, Kentucky, and Alabama--should provide a very complete picture of the responses of various types of structural systems to the effects of extreme winds. Furthermore, such studies should provide valuable information for school officials on (1) where school children should be located in existing schools when tornadoes threaten and (2) how to design tornado protection into new schools.

(6) Studies of the unusual events associated with the crossing of the lake in Monticello by the terrain following tornado--including studies of the damaged railroad bridge--should be undertaken.

TABLE V-1

SUMMARY OF INDIANA TORNADOES - APRIL 3, 1974

MAJOR DAMAGE PATH NUMBER	TORNADO LOCATION	NUMBER OF TORNADOES	DEATHS	INJURIES (Hospitalized)	PROPERTY DAMAGE ($ Million)
1.	Monticello/ Rochester	3-4	24	432	50+
2.	Kennard/ Farmland	3	2	54	10+
3.	Hamburg	3	5	40	10+
4.	Hanover/ Madison	3-4	17	370	50+
5.	Opposite Brandenburg, Kentucky	1	0	0	1
6.	Swayzee	2	0	12	5-10
7.	N. Manchester	1	0	0	0.2

TABLE V-2

SCHOOL DAMAGE REPORT - INDIANA*

COUNTY	SCHOOL AND CORPORATION	DAMAGE ESTIMATE
Harrison	NORTH HARRISON SCHOOLS Morgan Twp. Elementary (1-5) Enrollment - (258)	Roof deck damage. Estimated Loss - $20,000
Jefferson	MADISON CONSOLIDATED SCHOOLS E. O. Muncie Elem. School (K-6) Enrollment - (779)	Roof/Windows. Estimated Loss - $500,000 Covered by insurance.
	Michigan Rd. School (K-6) Enrollment - (239)	Estimated Loss - $500,000 Future uncertain. Covered by insurance.
	SOUTHWESTERN JEFFERSON SCHS. Southwestern High School (9-12) Enrollment - (464)	Estimated Loss - $300,000 Gymnasium - $100,000 (repairable)
	Southwestern El.-Jr. H. S. (K-8) Enrollment - (1266)	Estimated Loss - $1,500,000 Will be rebuilt.
Decatur	DECATUR CO. COMM. SCHOOLS South Decatur High School (7-12) Enrollment - (739)	60% of gym roof damaged. Water damage to gym floor. Water damage to lobby area. Water damage to music area. Cafeteria wall caved-in. Estimated Loss - $100,000
Henry	CHARLES A. BEARD SCHOOLS Kennard Elem. School (K-6) Enrollment - (176)	Total loss. Estimated Loss - $720,000 Insurance covers 90% of the cost.

* Data from Indiana Board of Education.

TABLE V-2

SCHOOL DAMAGE REPORT - INDIANA (Cont'd.)

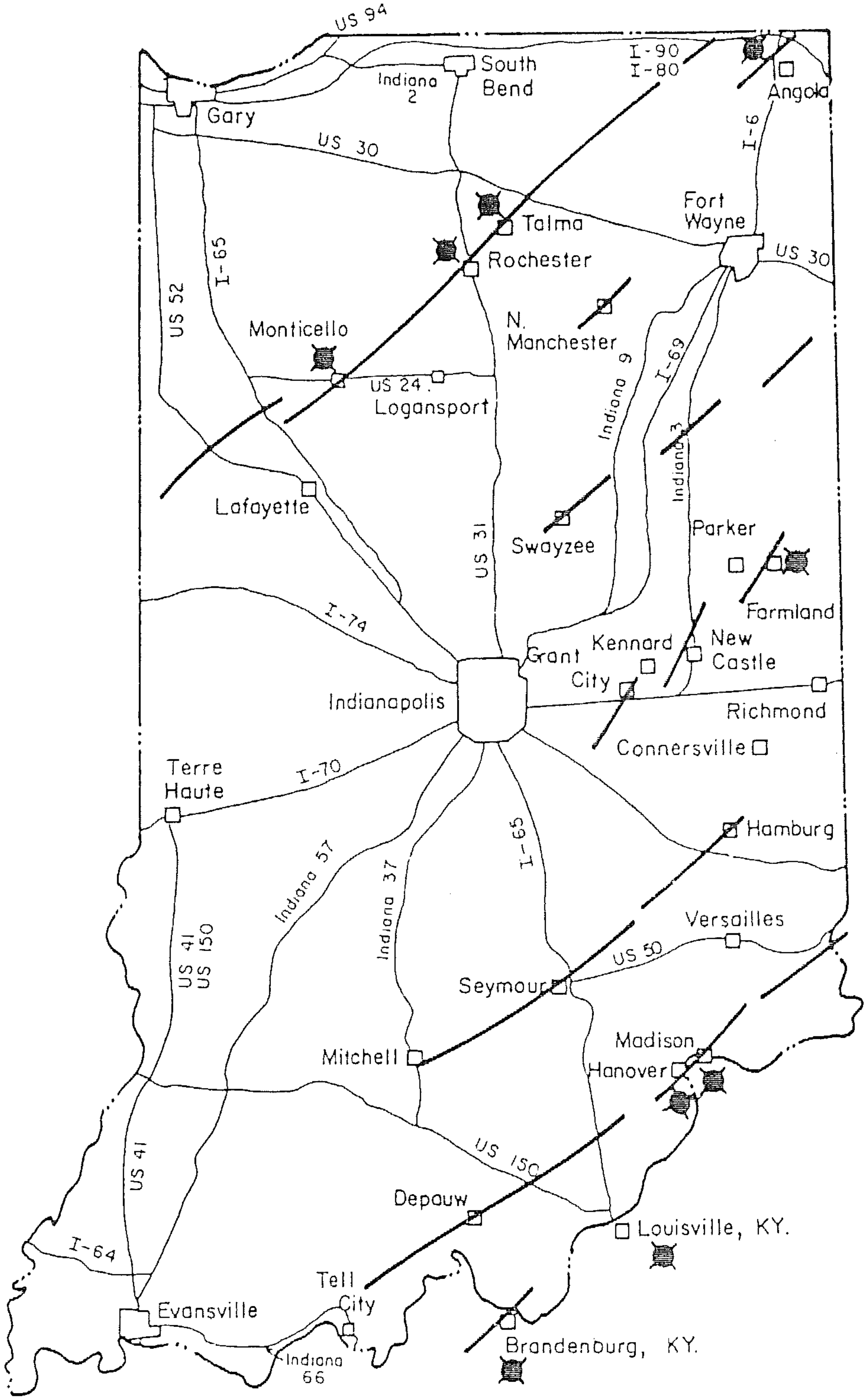
COUNTY	SCHOOL AND CORPORATION	DAMAGE ESTIMATE
	BLUE RIVER VALLEY SCH. CORP. Blue River High School (7-12) Enrollment - (582)	Roof damage, glass damage, and water damage. Roof of gym damaged. Estimated Cost - < $20,000 Fully covered by insurance.
Randolph	MONROE CENTRAL SCHOOL CORP. Monroe Central H. S. (7-12) Enrollment - (565)	Estimated Loss - $1,900,000 Insurance available $1,500,000. Some equipment salvageable.
Kosciusko	WARSAW COMMUNITY SCHOOLS Atwood Elem. School (K-6) Enrollment - (179)	Roof/Windows. Estimated Loss - $11,000
	Leesburg Elem. School (K-6) Enrollment - (410)	Roof on gym and top of school. Estimated Loss - $14,000
Miami-Grant Counties	OAK HILL UNITED SCHOOL CORP. Swayzee Elem. School (K-6) Enrollment - (393)	Gym roof damage. Estimated Loss - $30,000
Fulton	ROCHESTER COMMUNITY SCHOOLS Riddle Elem. School (K-5) Enrollment - (559)	60-65% of building damaged. Roof, wall and 3/4 of glass. Estimated Loss - $300,000
Kosciusko-Fulton Counties	TIPPECANOE VALLEY SCH. CORP. Talma Middle School (6-8) Enrollment - (279)	Total Loss - No Estimate.
Adams	NORTH ADAMS COMM. SCHS. Bellmont High School (9-12) Enrollment - (1082)	Auditorium roof moved--with water damage. Roof on high school damaged; also, window and water damage. Estimated Loss - $50,000

TABLE V-2

SCHOOL DAMAGE REPORT - INDIANA (Cont'd.)

COUNTY	SCHOOL AND CORPORATION	DAMAGE ESTIMATE
	Bellmont Jr. High School (5-8) Enrollment - (422)	Steeple of church next door fell through roof and floor. Estimated Loss - $100,000
Washington	EAST WASHINGTON SCH. CORP. Eastern High School (7-12) Enrollment - (572)	Nominal roof damage. Estimate Unavailable.
	Polk Elementary School (1-6) Enrollment - (146)	Roof damage. Estimated Loss - $5,000
Noble	WEST NOBLE SCH. CORPORATION Perry Central Elem. Sch. (K-6) Enrollment - (404)	Roof of auditorium blown off. Gym cannot be rebuilt, class-room damage. Estimated Loss - $1,000,000+
Hancock	EASTERN HANCOCK SCH. CORP. Wilkinson Elem. School (1-6) Enrollment - (350)	Gym roof damage Estimated Loss - $10,000
	Charlottesville Elem. Sch.	Estimated Loss - $3,000
White	TWIN LAKES SCH. CORPORATION Twin Lakes High School (10-12) Enrollment - (669)	Total Loss. Estimated Loss - $3,300,000
	Roosevelt Jr. High School (7-9) Enrollment - (713)	Building can be utilized with repairs. Estimated Loss - $1,900,000
	Meadowlawn Elem. School (K-6) Enrollment - (508)	Total Loss. Will be rebuilt. Estimated Loss - $1,000,000

Total students involved. All schools reporting	11,754
Total estimated cost. All schools reporting	$13,283,000+
Total students moved and/or changed facilities	6,000
Number of school corporations reporting damage	25
Number of counties reporting damage	16



Ground observations, documentation available

FIGURE 10. TORNADO DAMAGE PATHS IN INDIANA. Tracks as determined by Fujita.

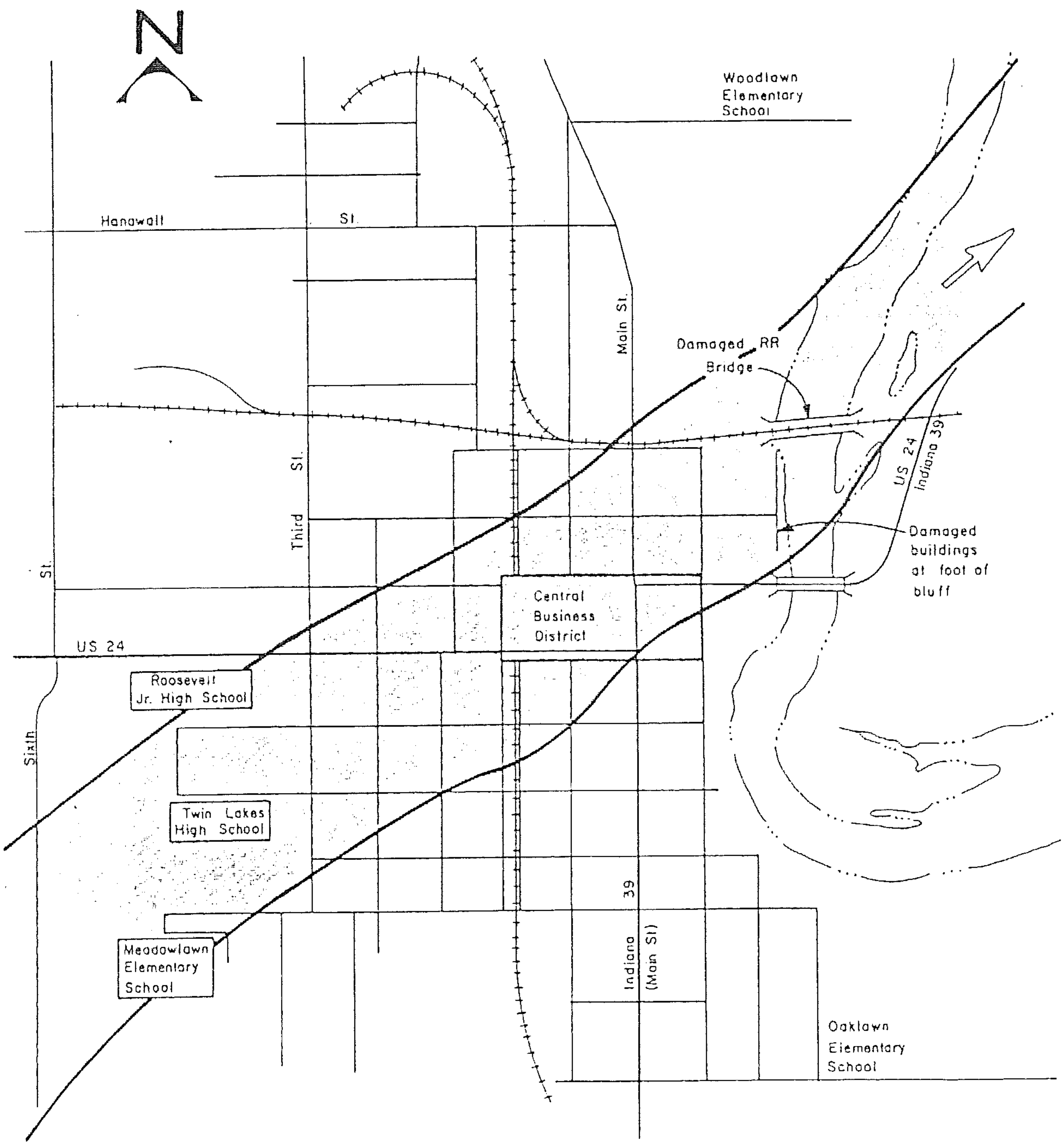


FIGURE 11. TRAJECTORY OF THE TORNADO THROUGH MONTICELLO.

FIGURE 12. AERIAL VIEW OF DAMAGE PATH THROUGH MONTICELLO. View is toward northeast; Twin Lakes High School is in foreground and damaged railroad bridge is in background. (photograph courtesy U. F. Koehler, Ball State University)

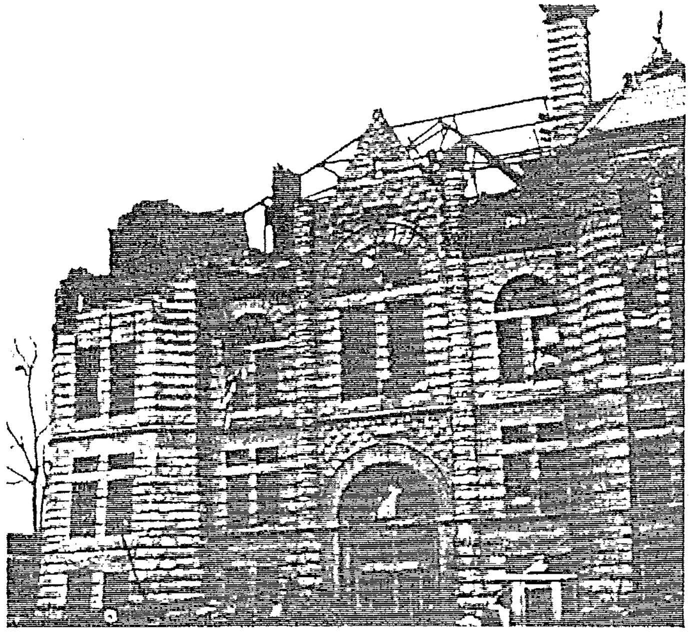


FIGURE 13. COUNTY COURTHOUSE, MONTICELLO, INDIANA. (photograph courtesy J. J. Abernethy, University of Detroit-PASC)

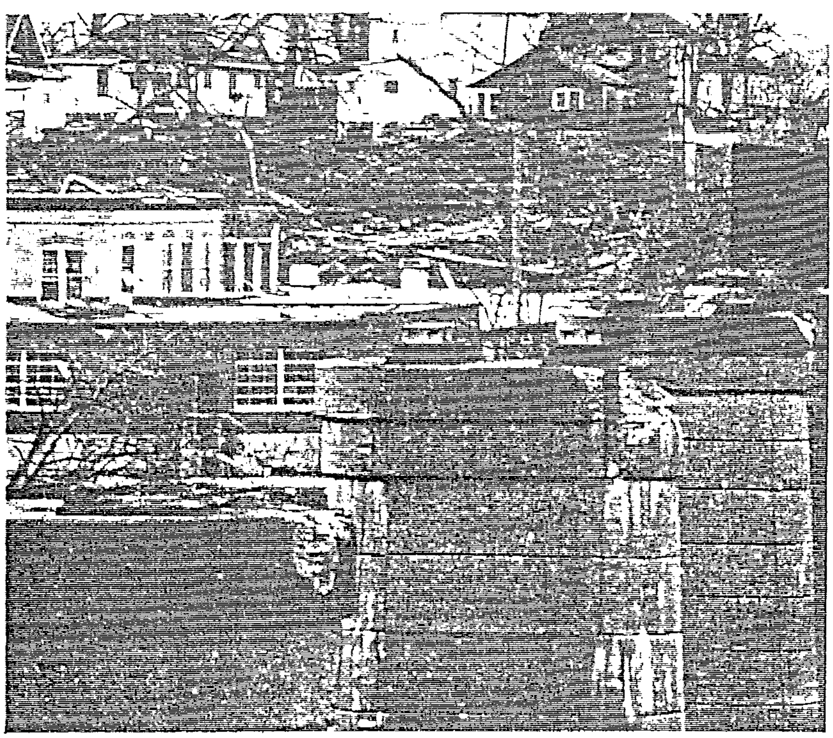


FIGURE 14. DAMAGED RAILROAD BRIDGE, MONTICELLO, INDIANA. Four spans, each with two 10 ft deep by 110 ft long girders, toppled into the river. (photograph courtesy J. J. Abernethy, University of Detroit-PASC)

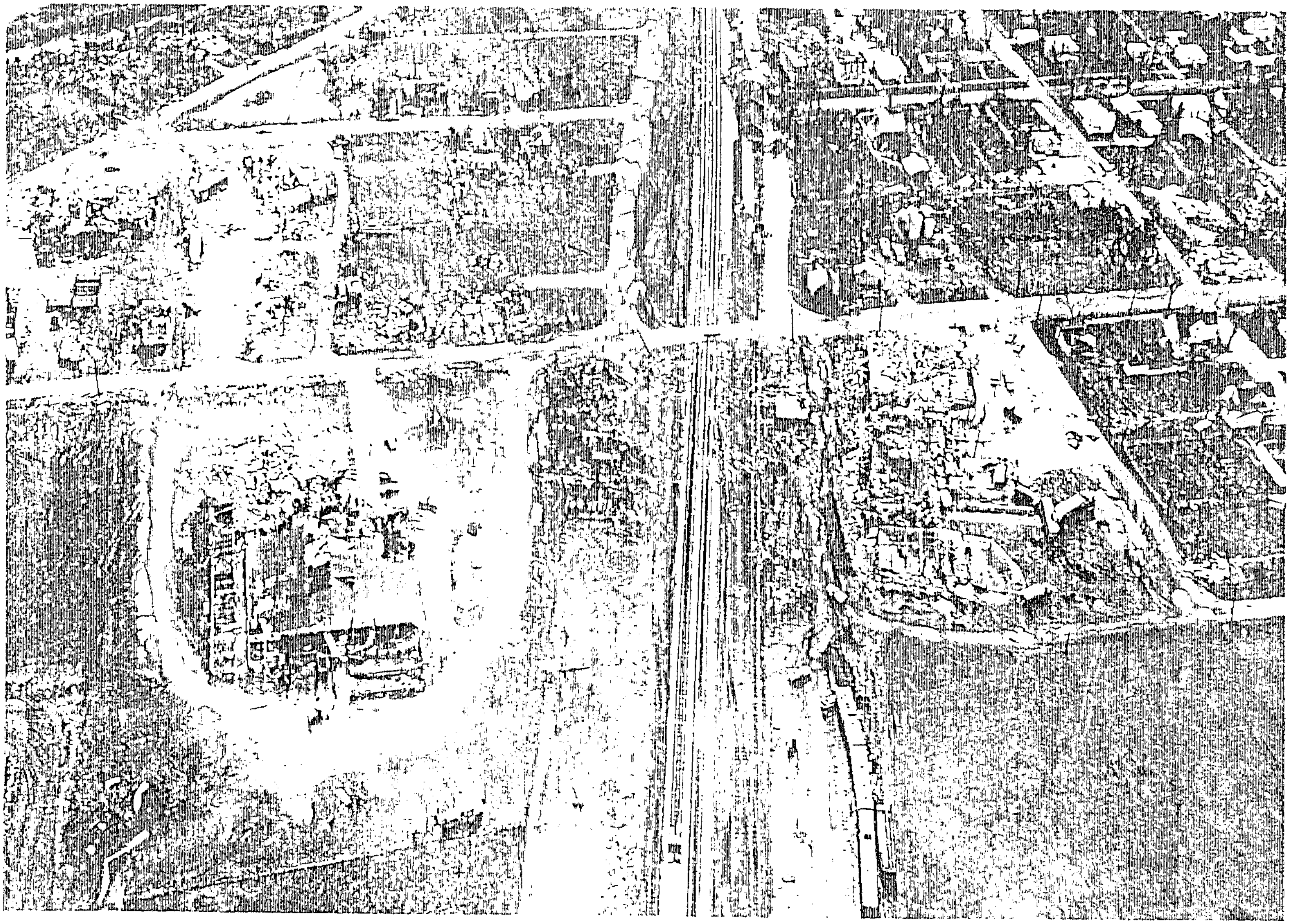


FIGURE 15. DAMAGE NEAR ROCHESTER, INDIANA. North portion of city at Erie Lackawana RR and US Highway 31; view to the east. (photograph courtesy South Bend Tribune)

FIGURE 16. DAMAGED RESIDENCES IN ROCHESTER, INDIANA. Note remaining interior portions of some residences. (photograph courtesy U. F. Koehler, Ball State University)

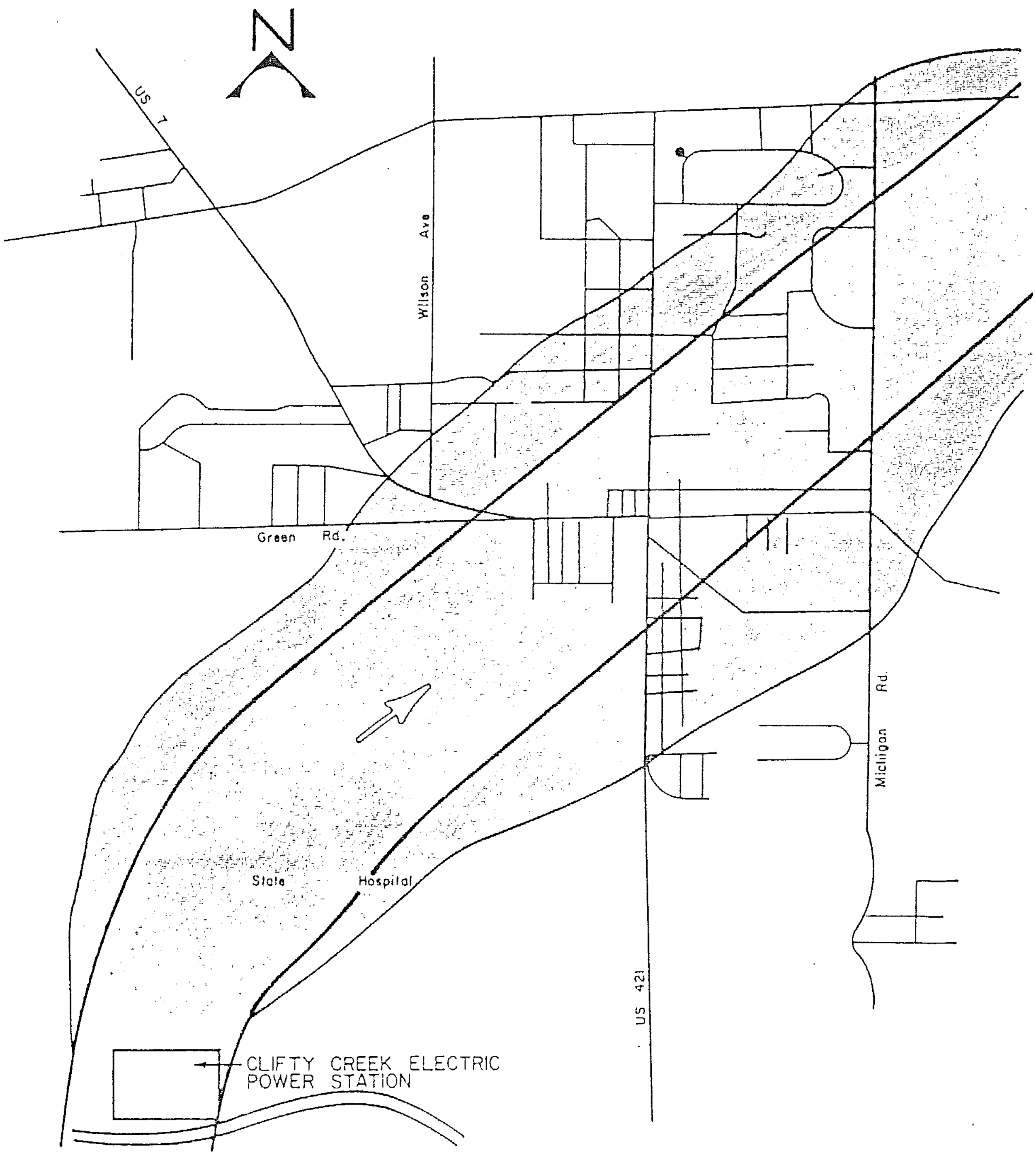


FIGURE 17. TRAJECTORY OF THE TORNADO THROUGH MADISON, INDIANA.

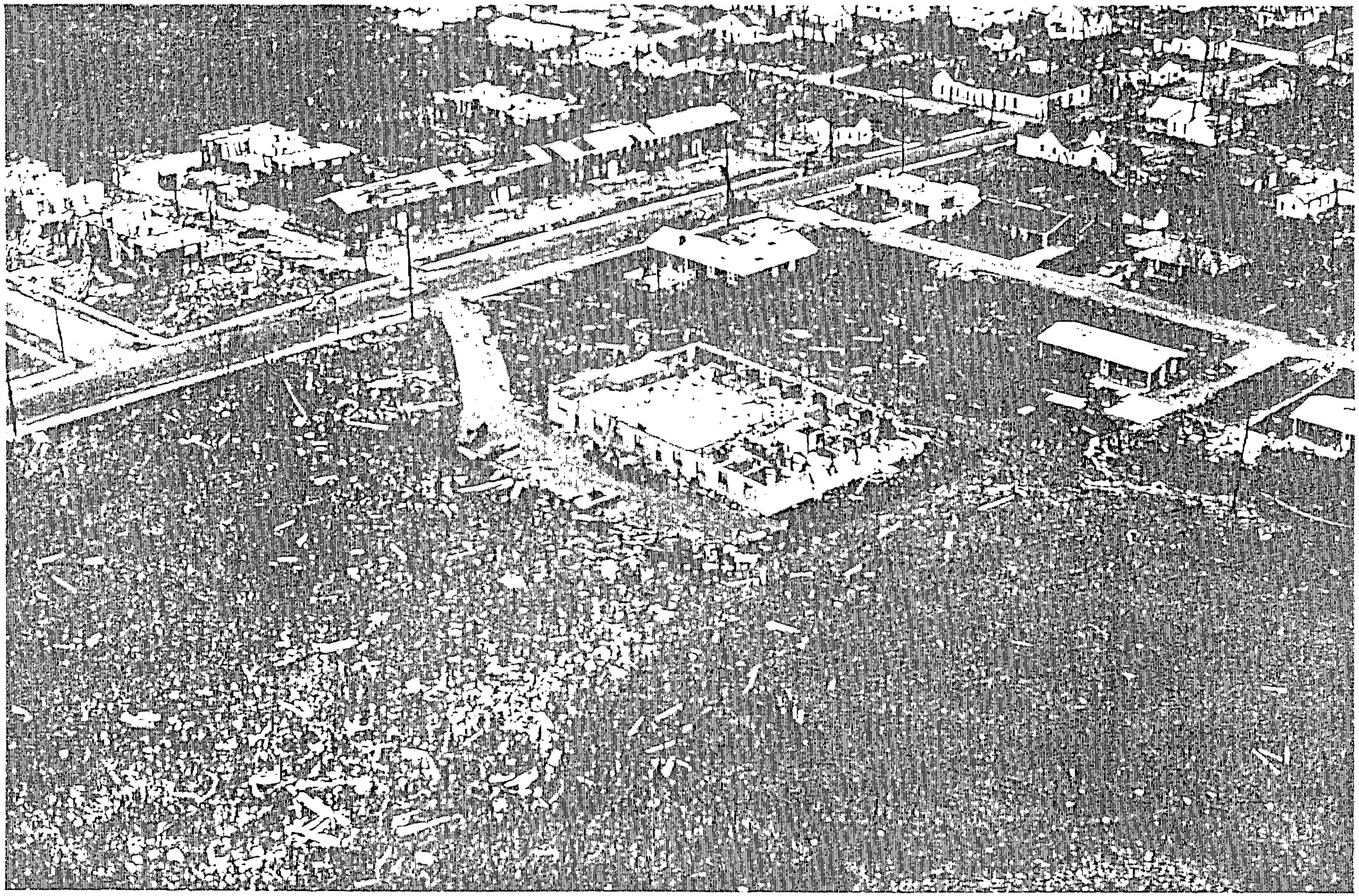


FIGURE 18. DAMAGED NURSING HOME IN MADISON, INDIANA. (photograph courtesy U. F. Koehler, Ball State University)

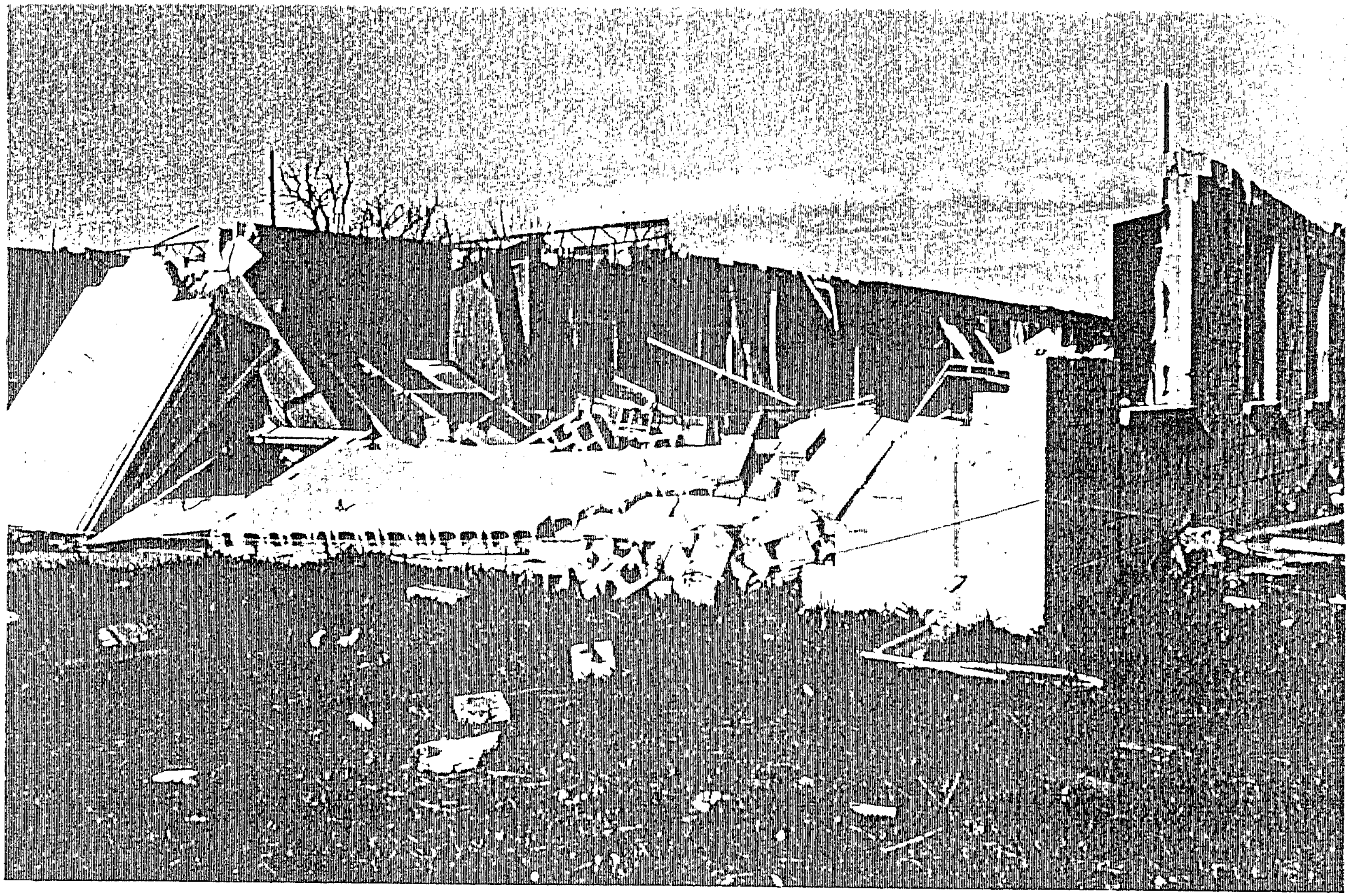


FIGURE 19. CONCRETE BLOCK WALL FAILURE IN NURSING HOME, MADISON, INDIANA. Note absence of vertical reinforcing steel and wall-foundation anchorage. (photograph courtesy U. F. Koehler, Ball State University)

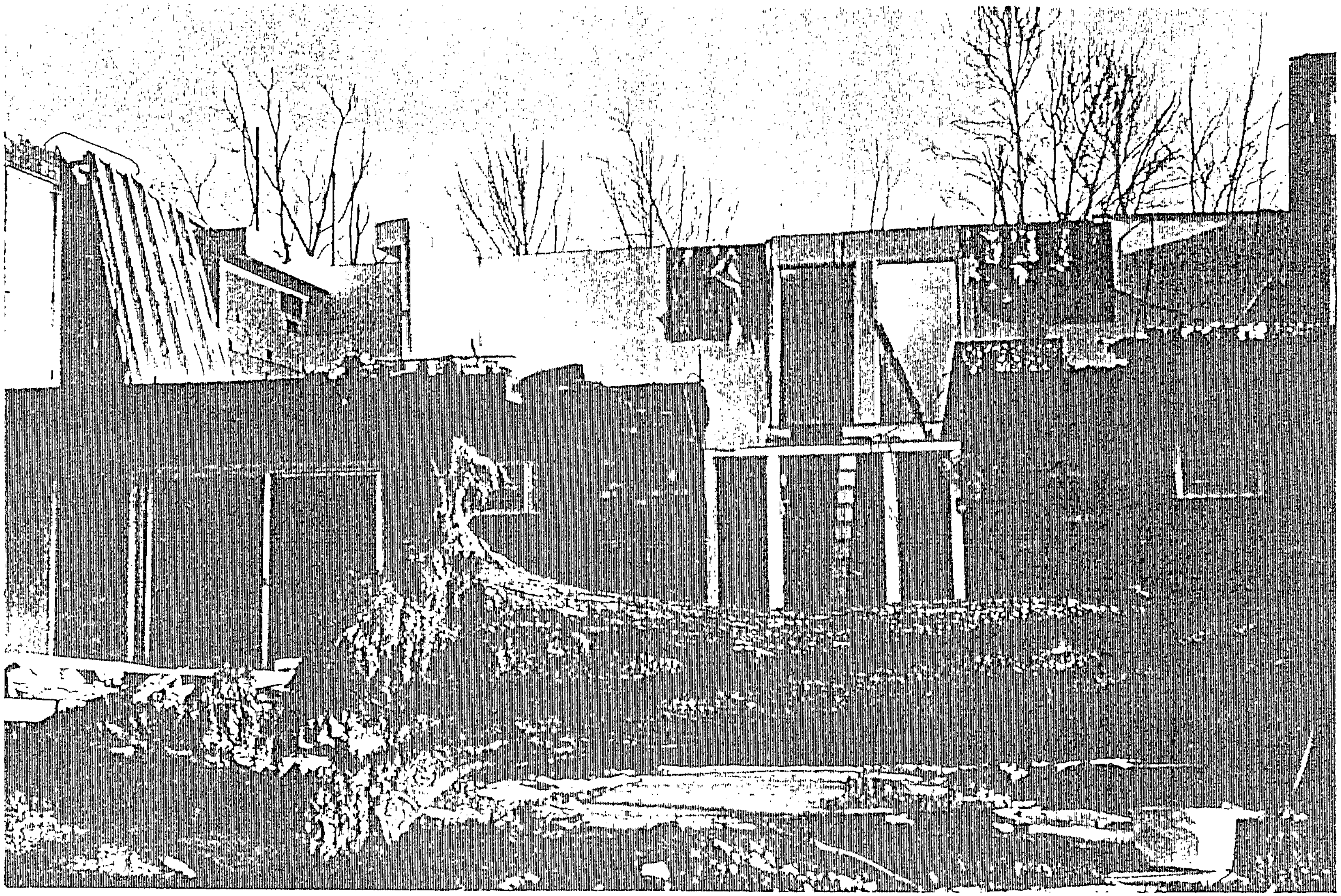


FIGURE 20. DAMAGE TO APARTMENT HOUSE IN MADISON, INDIANA. (photograph courtesy U. F. Koehler, Ball State University)

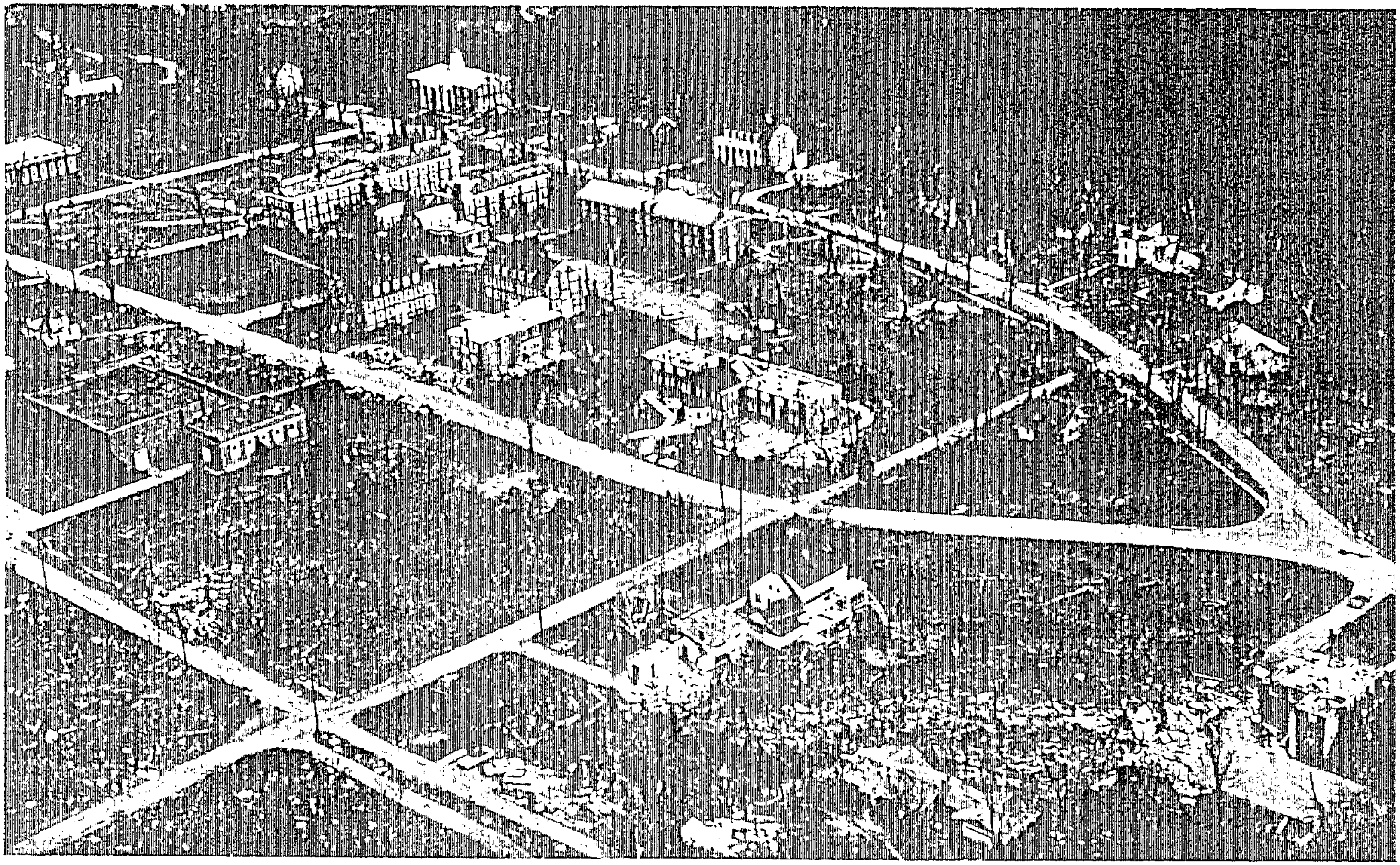


FIGURE 21. DAMAGE TO HANOVER COLLEGE, HANOVER, INDIANA. (photograph courtesy U. F. Koehler, Ball State University)

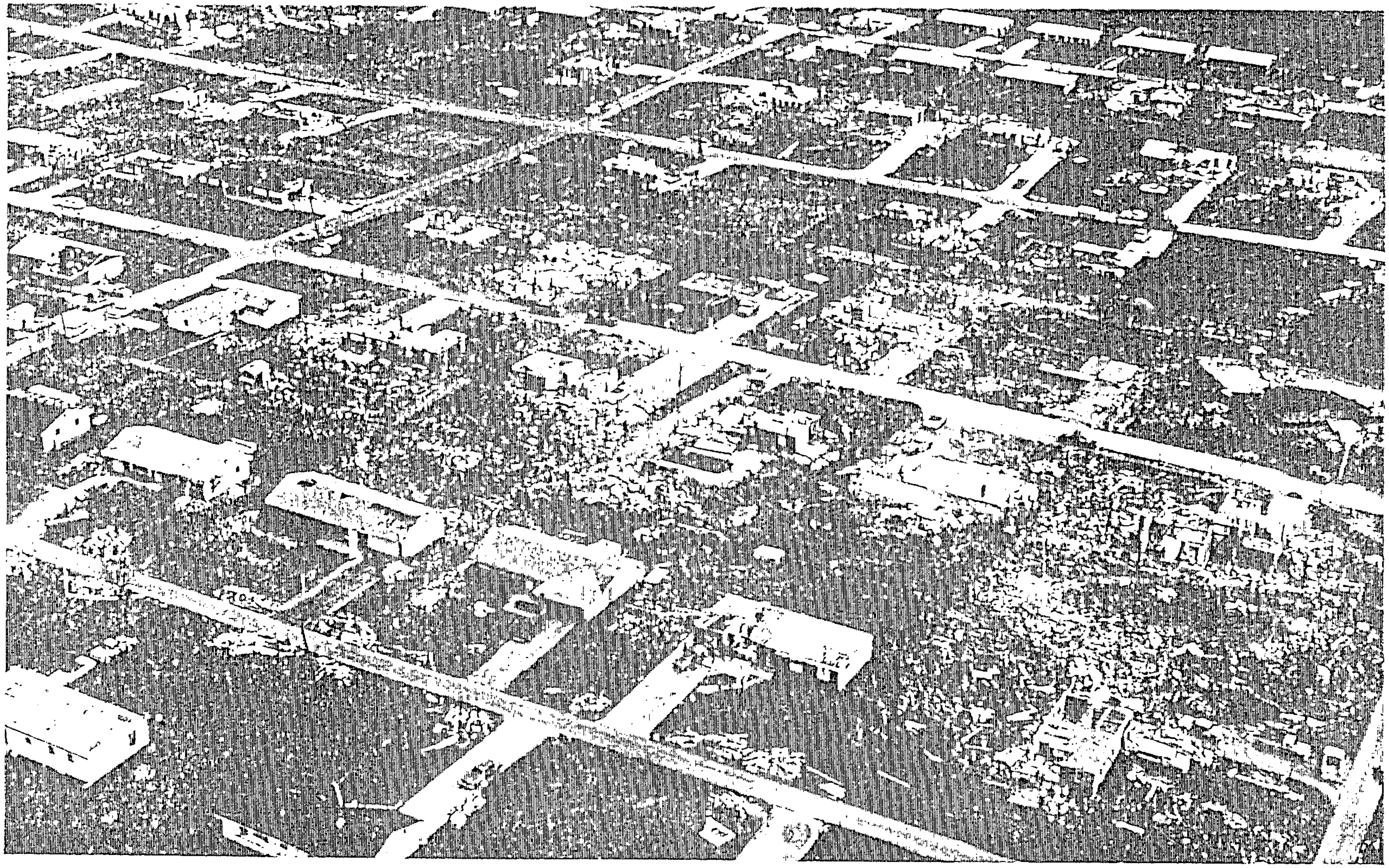


FIGURE 22. DAMAGE TO RESIDENCES IN HANOVER, INDIANA. Note interior portions of some houses which remained standing. (photograph courtesy U. F. Koehler, Ball State University)

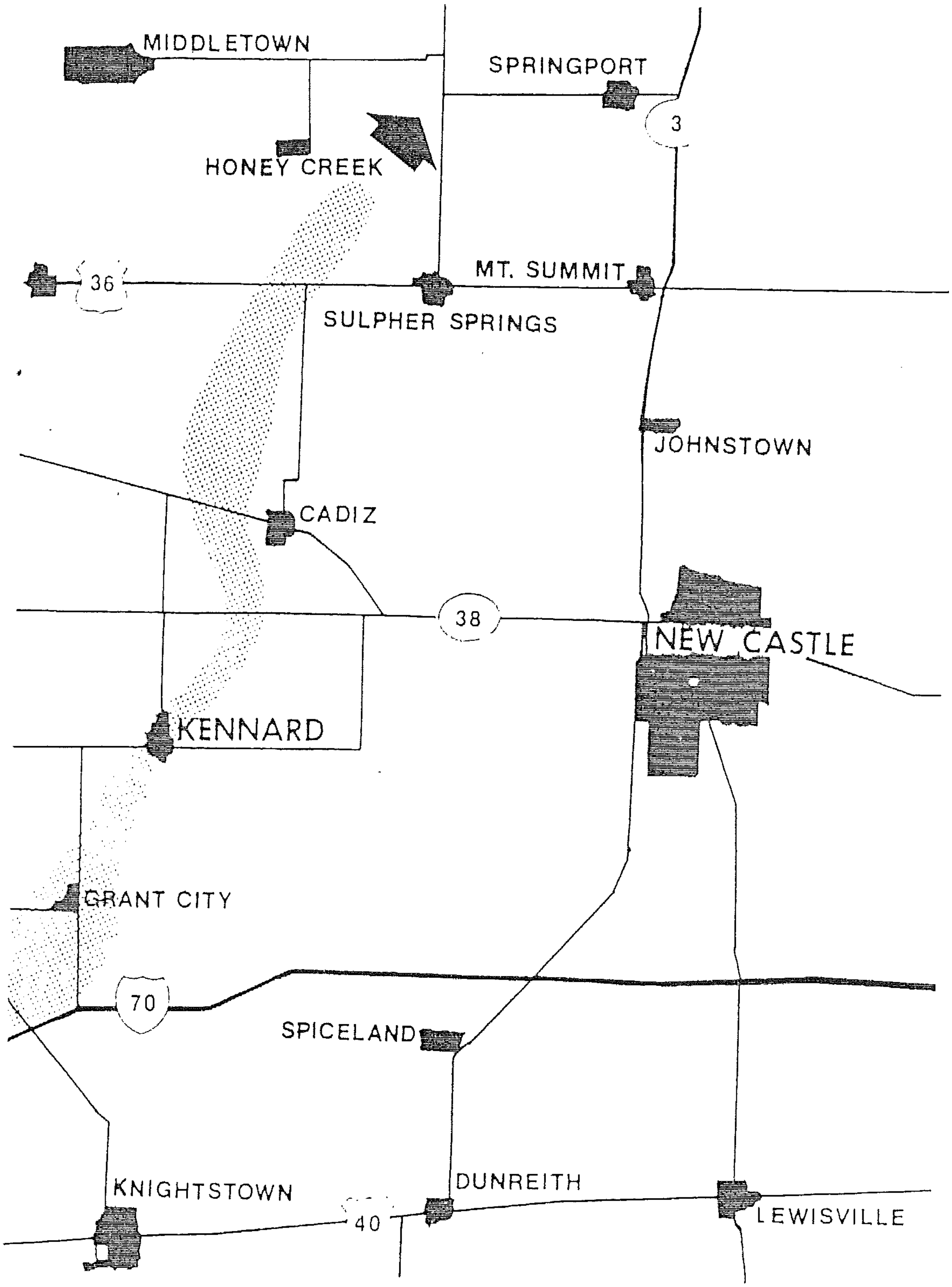


FIGURE 23. DAMAGE PATH THROUGH GRANT CITY, KENNARD AREA. (drawing courtesy U. F. Koehler, Ball State University)

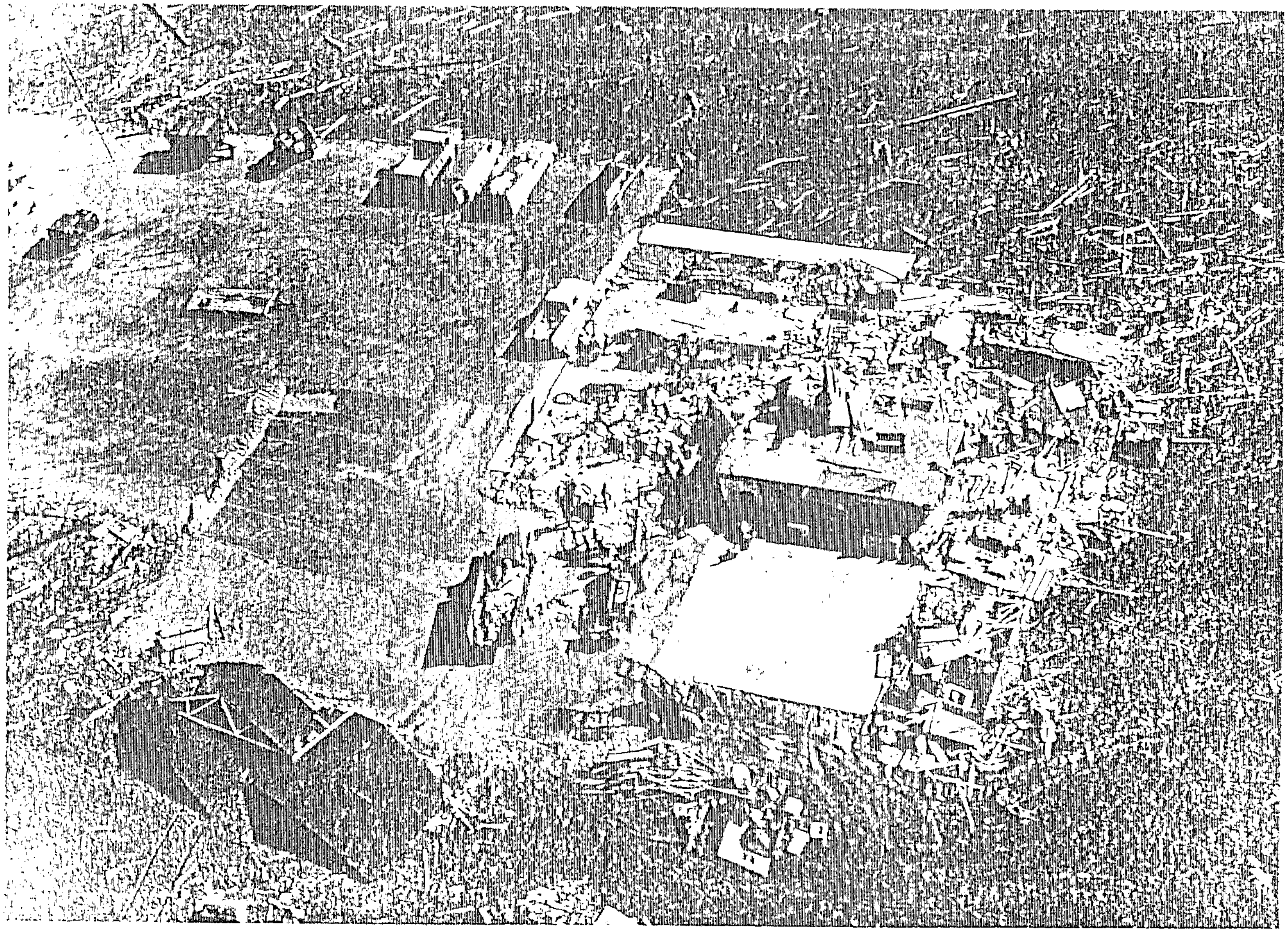


FIGURE 24. FUNERAL HOME DAMAGE, PARKER/FARMLAND, INDIANA. (photograph courtesy U. F. Koehler, Ball State University)

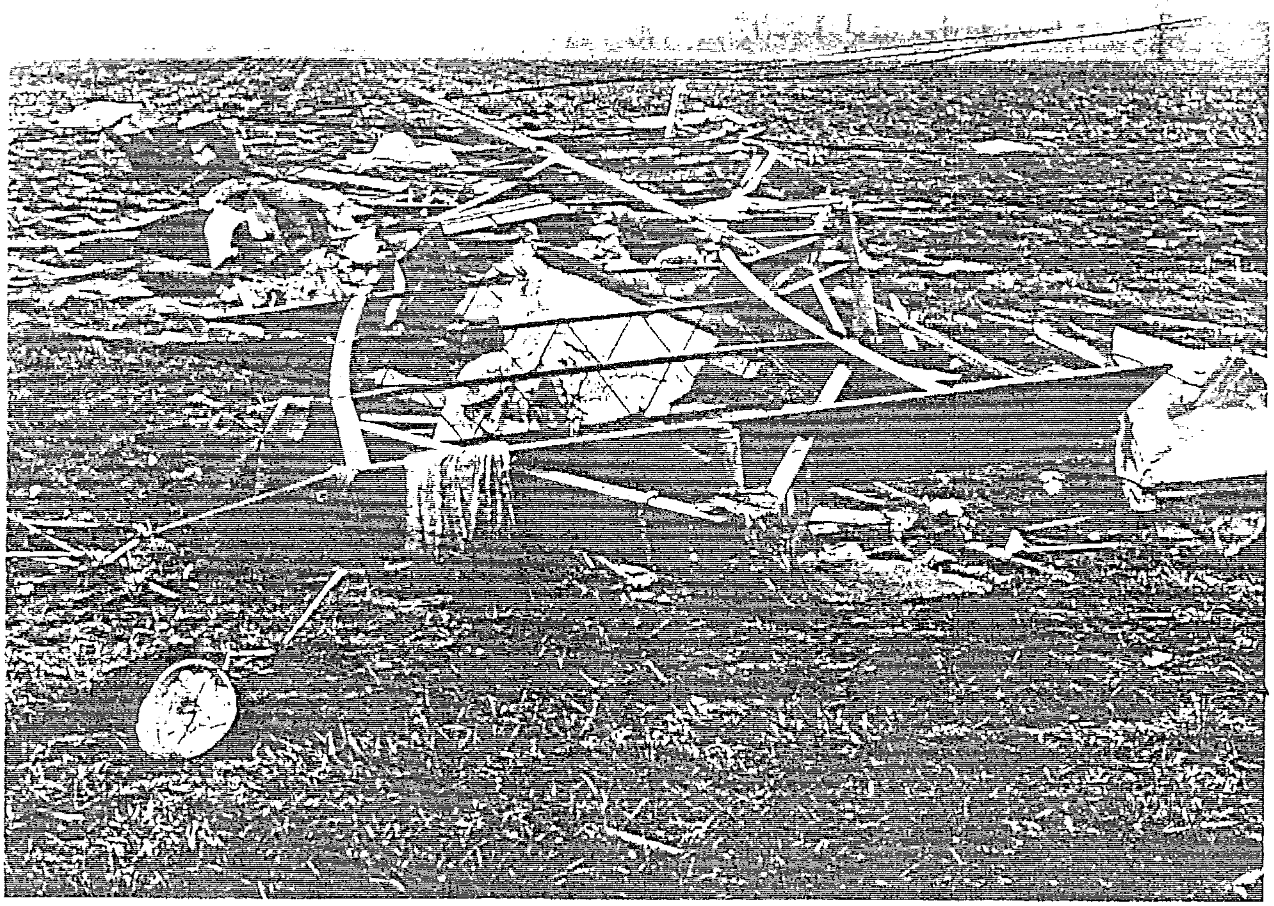


FIGURE 25. MOBILE HOME DAMAGE IN KENNARD DAMAGE PATH. (photograph courtesy U. F. Koehler, Ball State University)

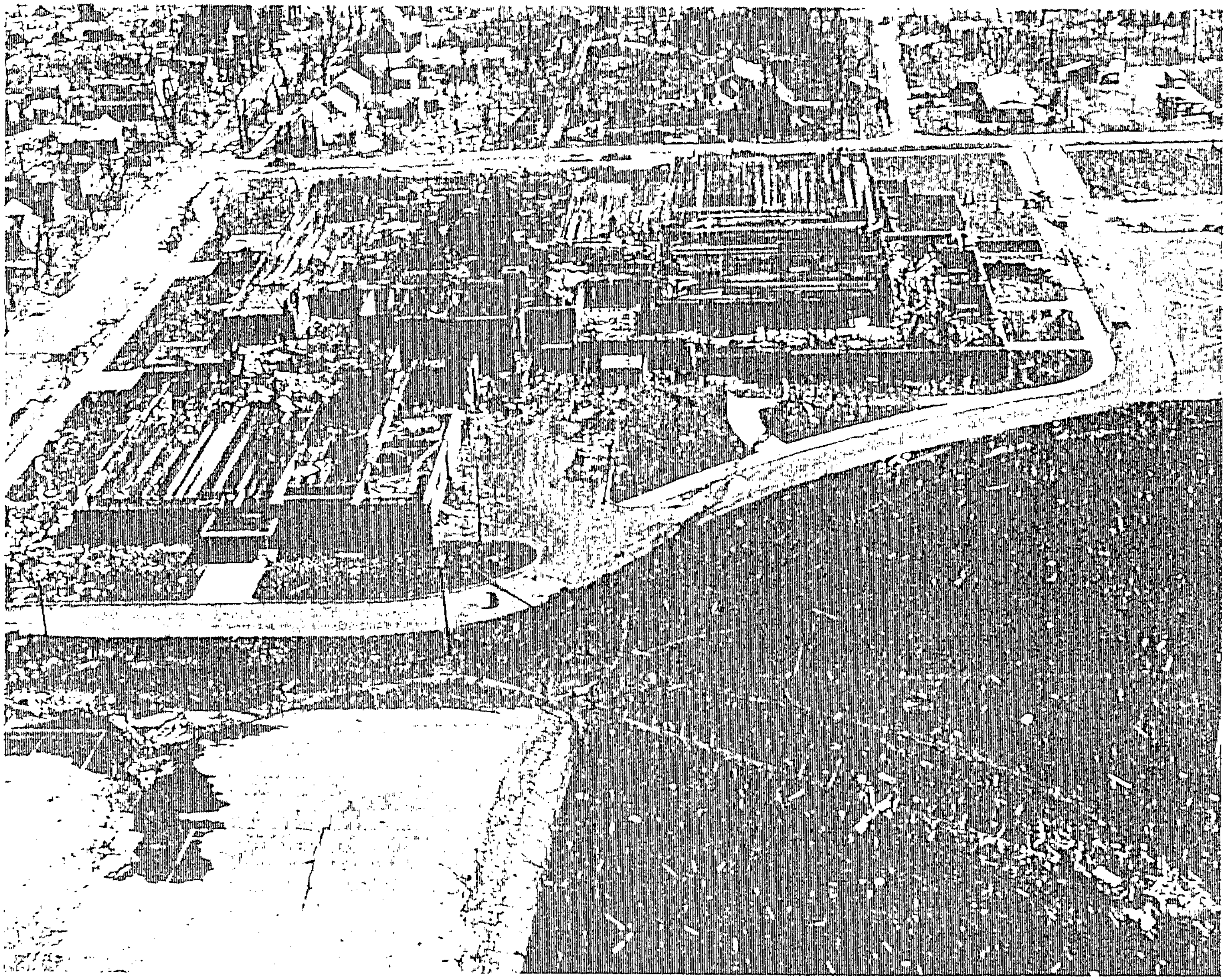
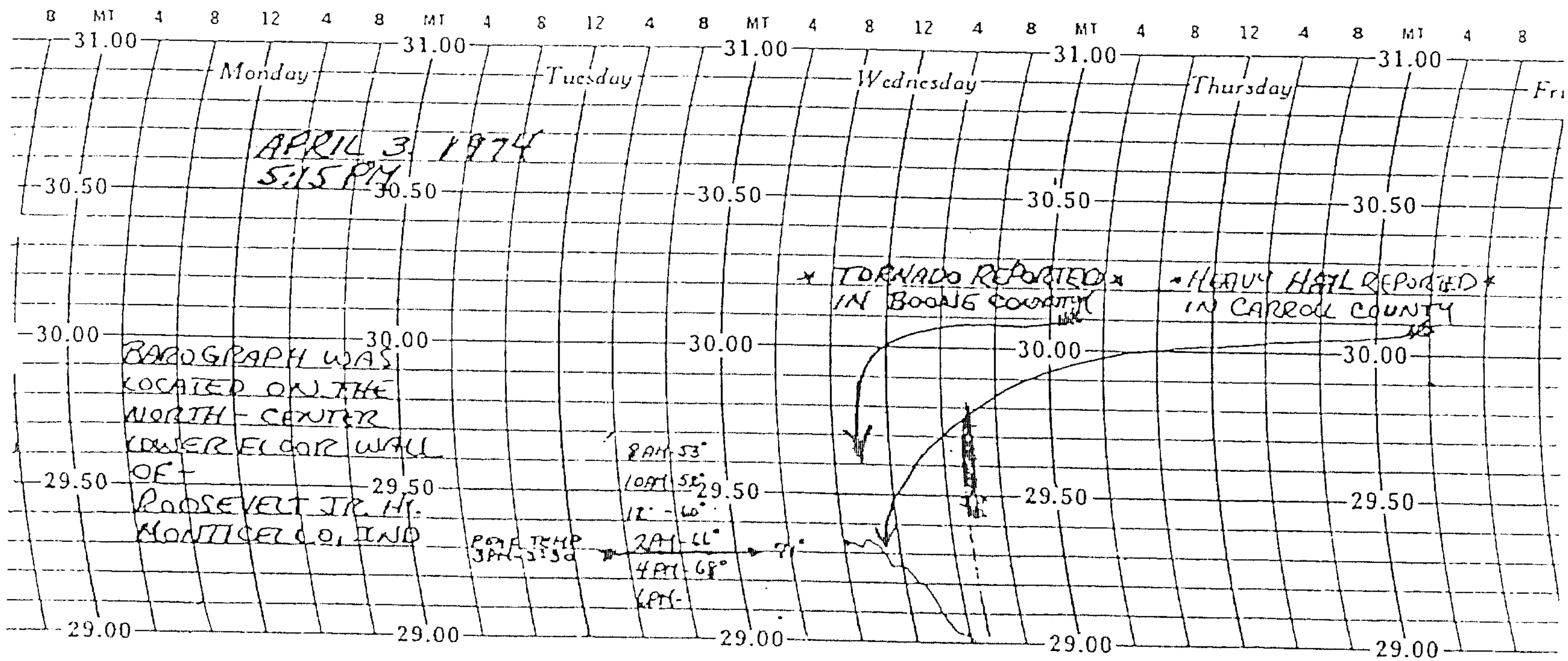


FIGURE 26. DAMAGE TO TWIN LAKES SENIOR HIGH SCHOOL, MONTICELLO, INDIANA. View is to east; gymnasium is right, center; beam which traveled over school was located originally atop exterior wall of classroom immediately left of gymnasium wall. (photograph courtesy U. F. Koehler, Ball State University)



Barograph Record from April 3, 1974 by Mr. J. Storm, Science Teacher, Roosevelt Junior High School, Monticello, Indiana. Electricity was interrupted at school when storm struck.

FIGURE 27. BAROGRAPH TRACE FROM RECORDS TAKEN AT ROOSEVELT JUNIOR HIGH SCHOOL, MONTICELLO, INDIANA, ON APRIL 3, 1974.

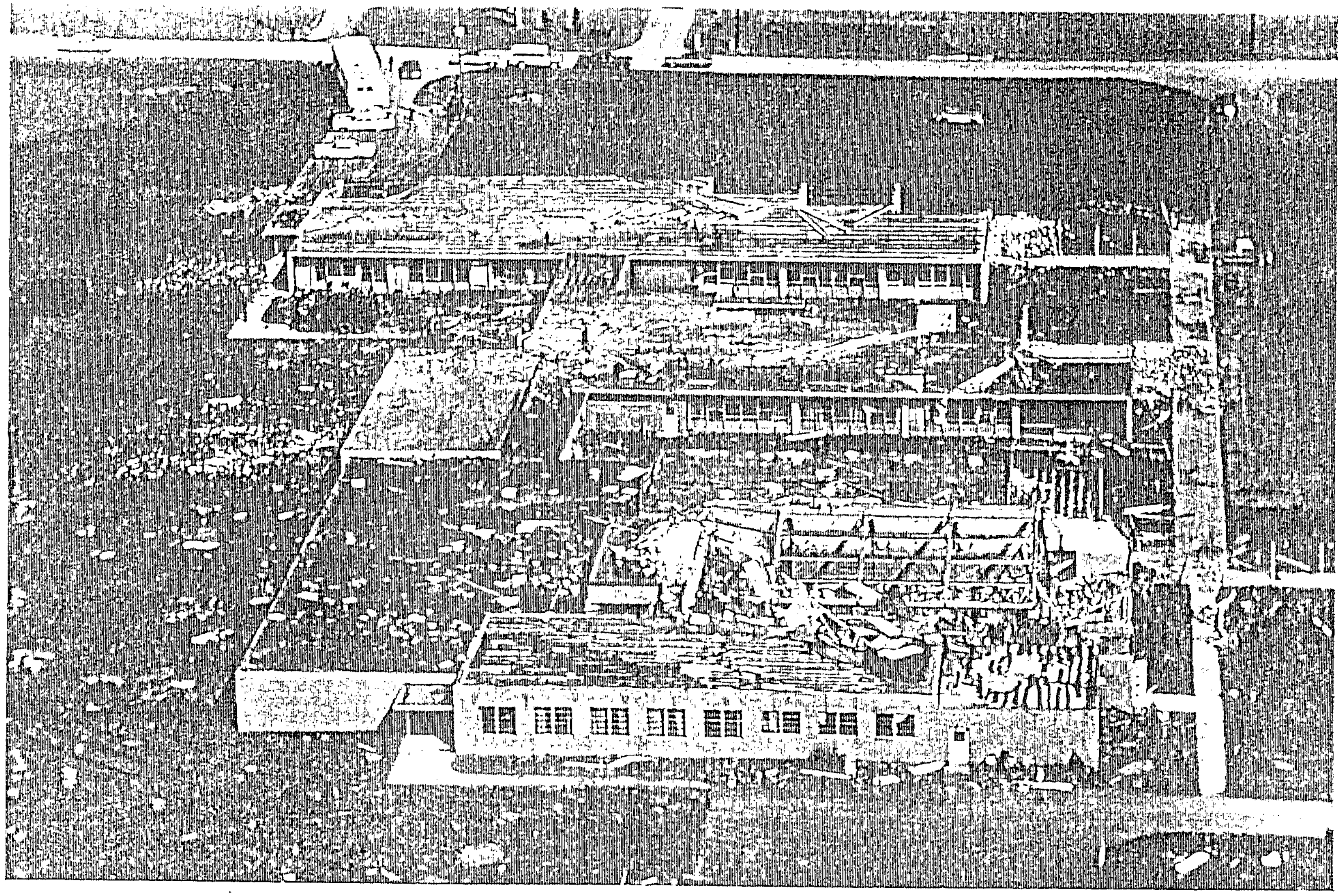


FIGURE 28. MONROE CENTRAL SCHOOL, PARKER/FARMLAND. Note intact structural frame of gymnasium and masonry wall failures. View is to east. Note precast roof planks missing and on roof on extreme east wing of building. (photograph courtesy U. F. Koehler, Ball State University)

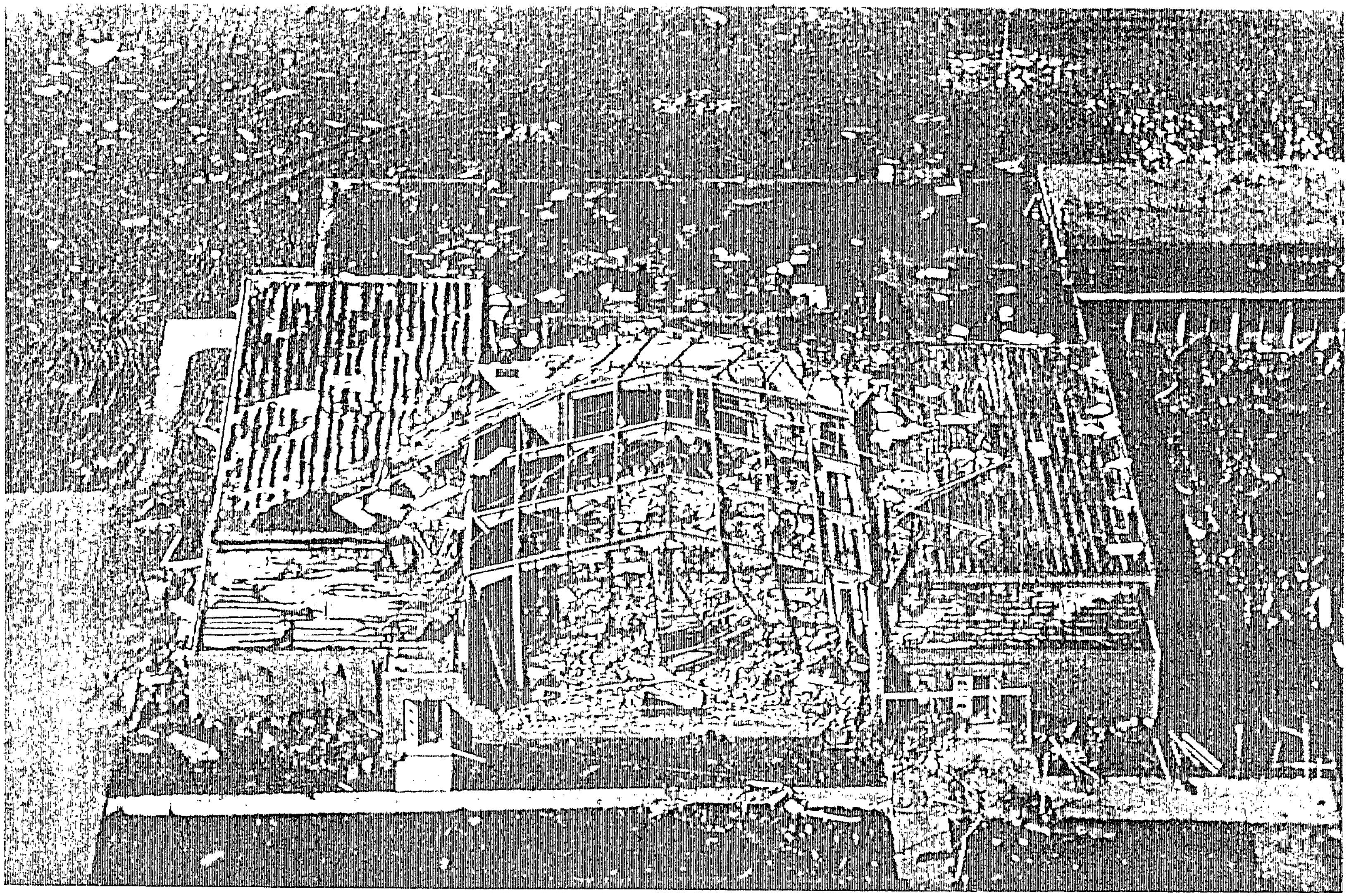


FIGURE 29. MONROE CENTRAL SCHOOL, PARKER/FARMLAND. Failures of gymnasium near wall (inward) and gabled portion of far wall (outward) was the basis for damage to this part of the structure. View is to north. (photograph courtesy U. F. Koehler, Ball State University)

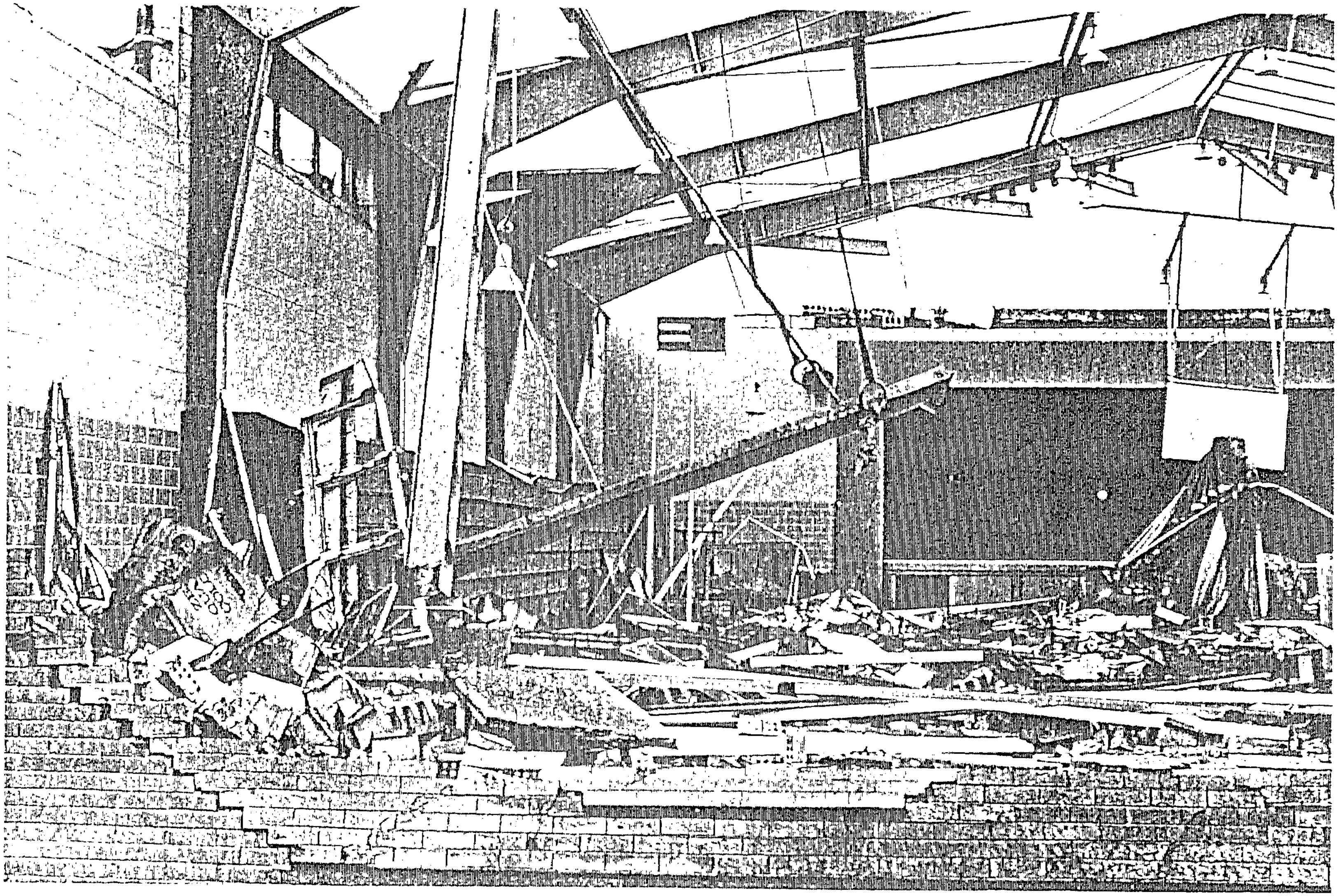


FIGURE 30. INTERIOR OF GYMNASIUM, MONROE CENTRAL SCHOOL. Note lack of damage to structural frame. View is to north. (photograph courtesy U. F. Koehler, Ball State University)

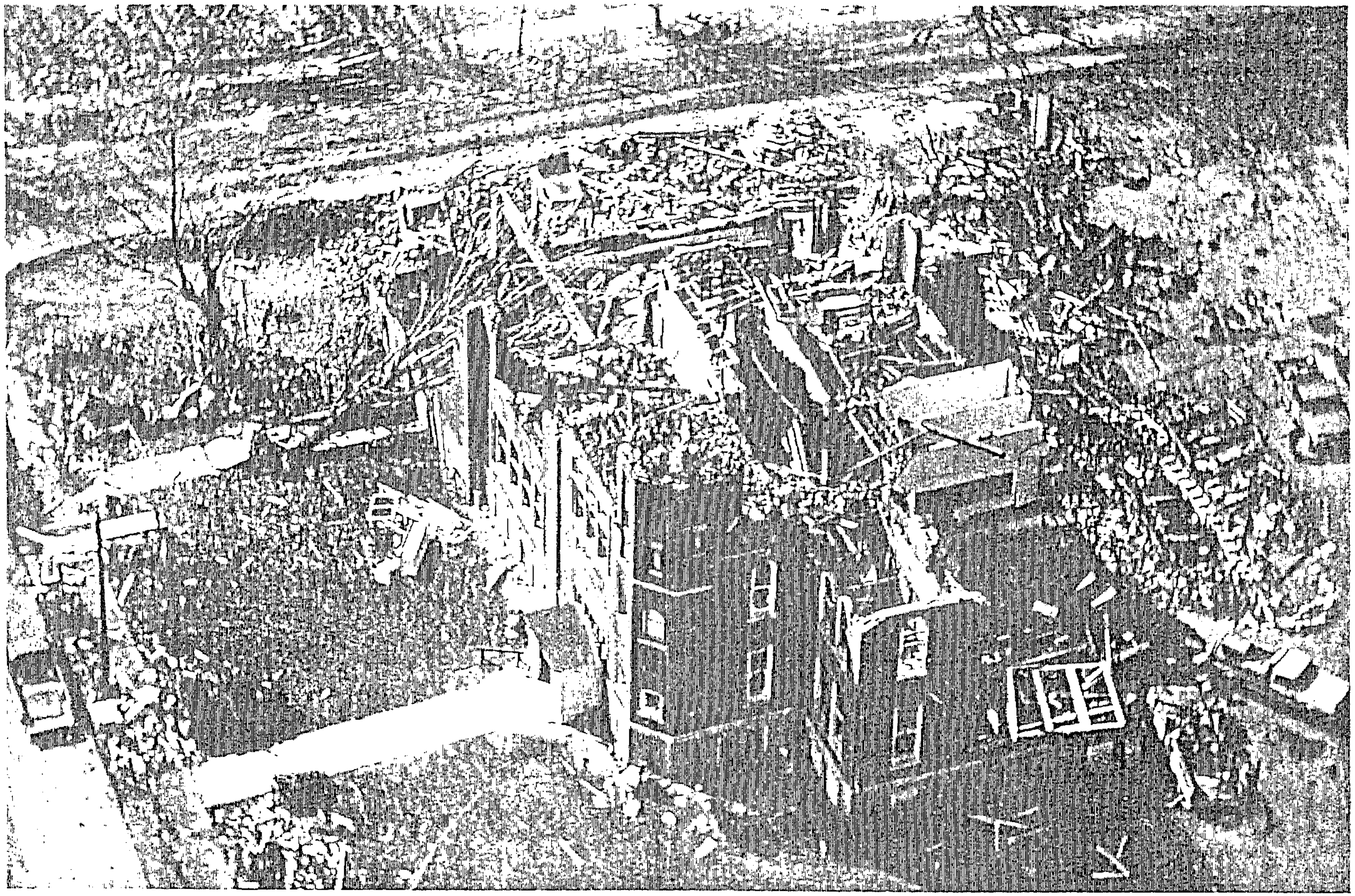


FIGURE 31. KENNARD ELEMENTARY SCHOOL. One hundred people in the building were uninjured. (photograph courtesy U. F. Koehler, Ball State University)

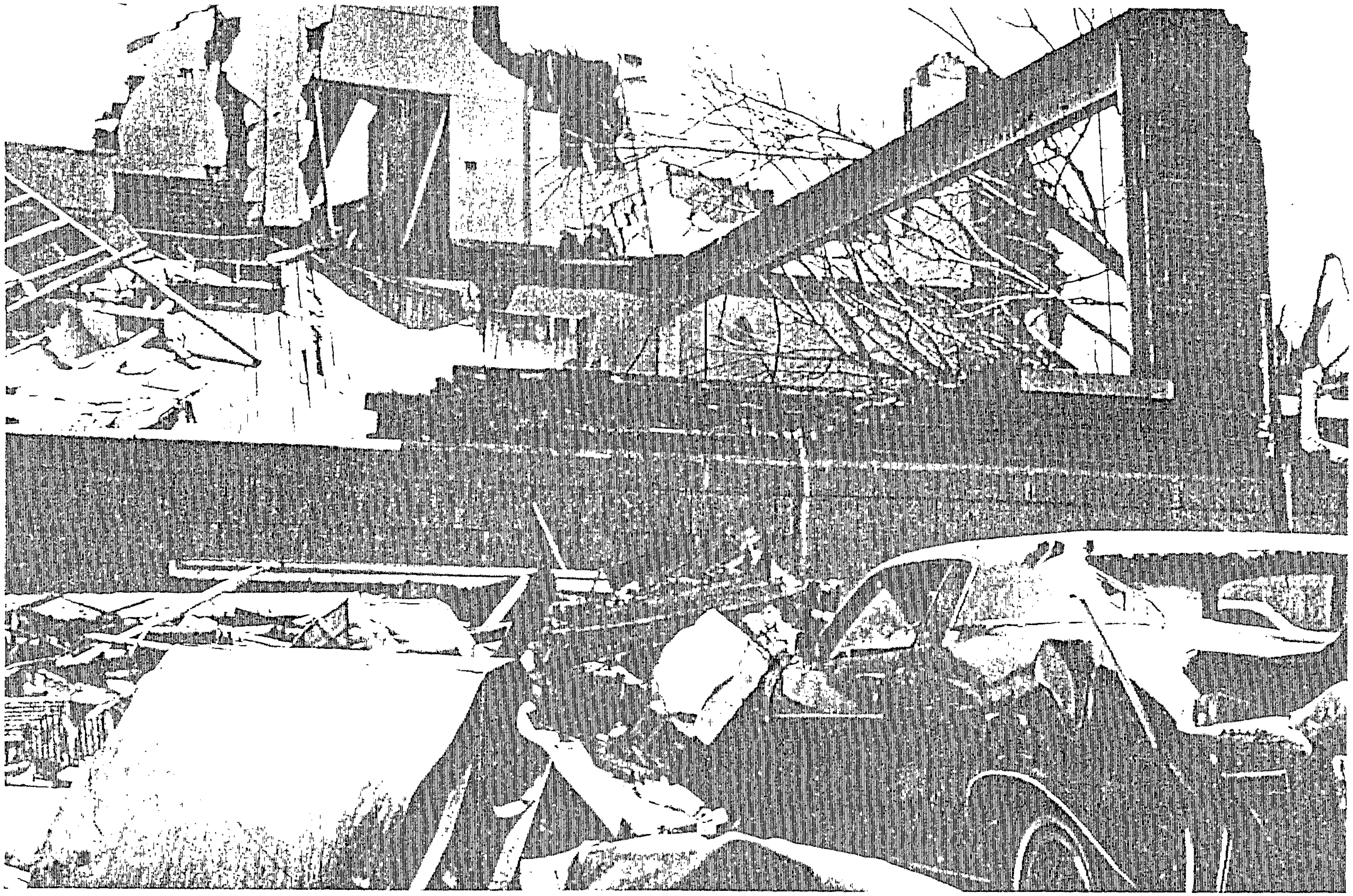


FIGURE 32. KENNARD ELEMENTARY SCHOOL, WEST FACADE. (photograph courtesy U. F. Koehler, Ball State University)

VI. OHIO

The tornadoes in Ohio occurred in the late afternoon of April 3, 1974. Dr. Fujita has indicated that there were nine separate tornado tracks; these tracks are shown in Figure 33. Three of these tornadoes produced extensive damage: two in the suburbs of Cincinnati and one through the city of Xenia. Xenia, a city of 25,000, experienced the most intense damage of all the locations which were affected by the Storms of April 3 and 4, 1974. The damage in Xenia was extensive and severe enough to warrant a thorough ground level documentation. A team of investigators from Texas Tech University documented damage in Xenia during a period of four days. Aerial surveys were also made by a Ball State University investigator. Total damage in the State is estimated to be more than $100,000,000. Forty persons lost their lives in Ohio; thirty of these deaths occurred in Xenia.

Xenia, Ohio

This town of 25,000 people sustained damage in residential as well as in commercial areas. The tornado was in contact with the ground when it entered the city from the southwest. It stayed on the ground through the city and damaged residential areas in the southwest, commercial areas in the center of the city, and residential areas in the northeast part of the city. Figure 34 indicates the path of the storm and identifies the damaged areas. The total number of buildings which sustained major damage is estimated to be 1750 (including residences). Approximately 1200 additional buildings sustained minor damage. The damage path varied from 2000 to 3000 ft. in width through the city, as shown in Figure 34. There was scattered damage extending up to 500 ft. on each side of the damage path. This scattered damage was restricted to window glass breakage, loss of roof shingles, breaking of tree branches, and other minor damage.

One type of engineered structure which sustained considerable damage is schools. Five of ten schools in the city were in the direct path of the tornado; these schools are identified in Figure 35. Two schools, Shawnee Elementary and Cox Elementary, were just outside the damage path and they sustained only superficial damage. The five damaged schools (two elementary schools, two junior high schools, and one high school) sustained very heavy damage to exterior classrooms, to gymnasiums, to cafeterias, and to upper stories. Interior hallways sustained negligible damage and would have provided safe shelter for the children had the schools been in session. (Since the tornado struck after school hours at about 4:40 P.M., there were no children in the schools.)

Preliminary maximum windspeed estimates based on damage observations are in the range of 170 to 210 mph.

Schools

Arrowood Elementary School is a modern, engineered one-story structure, 170 x 170 ft. in plan. The structural system is concrete and steel framing with a bar joist roof. Damage to the structural frame was limited to roof corners and roof ridges. Flying debris created heavy damage in exterior classrooms. Interior hallways sustained virtually no damage and they were free of debris. Figures 36 through 39 illustrate damage to this school.

West Junior High School sustained damage at corners of roof and in the gymnasium area. The roof of the two-story building was made of precast reinforced concrete double-tee beams. In a corner of the building two of the double-tee beams had collapsed onto the floor below, but did not break the floor slab (Ref. Figure 40). The gymnasium roof consisted of three-hinged arches, with timber beams seated on saddles between the arches. Almost half of the roof was lost and one of the end arches had collapsed (Ref. Figure 41). The non-reinforced concrete masonry walls at the ends of the gymnasium had collapsed, one inward and the other one outward. There was very little damage to the rest of the school structure. The interior hallways on the first floor were structurally sound and totally free of debris.

Simon Kenton Elementary School is a one-story structure with classrooms on the exterior and an interior hallway along the length of the school. The roof system consists of steel bar joists, bulb tees, and lightweight concrete roofing. The roof and the exterior walls of some classrooms were totally gone (Ref. Figures 42 and 43). Large amounts of debris had entered the classrooms through windows or through the uplifted roof (Ref. Figure 44). The interior hallway contained large amounts of debris (Ref. Figure 45) which apparently entered through the uplifted roof.

Central Junior High School was built in the early 1930's. It is a three-story structure. The structural system is brick masonry loadbearing walls with reinforced concrete floor and roof slab. Damage to the structure was caused by flying debris. The debris varied from roof gravel to a portion of roof from a residence across the street (Ref. Figures 46 through 50). The only structural damage to this building was collapse of a portion of a reinforced concrete (pan joist system) roof slab (15 x 15 ft. in area), probably because of the collapse of a parapet and coping material on the roof (Ref. Figures 48 and 49). The floor slab of the second floor was able to sustain the load of debris from the parapet and the collapsed roof. Interior hallways on each floor were clean of debris (Ref. Figure 51), although classrooms on every floor contained considerable amounts of debris (Ref. Figure 50).

The complex of Xenia High School buildings contains various structural systems: loadbearing masonry walls with open web steel joist roof, loadbearing masonry walls with precast reinforced concrete beam roof, lightweight steel framing with open web steel joist roof, precast concrete framing with precast beam roof, and loadbearing walls with hollow core roof slabs (Ref. Figures 52 through 57). The school sustained severe damage in the gymnasium and cafeteria areas (Ref. Figures 53 and 55). The loadbearing masonry walls of the gymnasium and cafeteria areas collapsed and the open web steel joist and precast concrete beam roofs collapsed downward. The second story roof which was made of open web steel joists was uplifted and totally disintegrated (Ref. Figure 54). The precast concrete framing survived the tornado but the wall panels were lost (Ref. Figure 55). Hollow core roof slabs at the edges and in the corner were uplifted (Ref. Figure 57). The interior hallways on the first floor of the buildings did not sustain damage and were free of debris (Ref. Figure 56).

Commercial District

The downtown area of the city sustained damage which was confined primarily to roofs, to upper stories of buildings, and to window glass. The furniture manufacturing plant shown in Figure 59 experienced partial collapse of the second story and heavy damage to the roof (locations of this building and of items shown in subsequent figures are shown in Figure 58). A five-story building in the center of the town sustained damage to the roof and to window glass (Ref. Figure 60). This type of damage to roofs and window glass was very typical to engineered commercial buildings.

Residences

Single family residences which were in the path of the tornado sustained very heavy damage. Most of these can be considered to be total losses. However, even in the residences which can be considered totally destroyed, there was generally a central part of the residence which was still standing (Ref. Figures 61 through 64). The few walls which remained standing could provide a safe place of shelter in case the residence did not have a basement. The experiences in Xenia add to the credibility of having an inresidence shelter in the central part of the residence which would be economical and safe.

Missiles and Debris

The tornado generated large amounts of debris when roofs and walls of residences were disintegrated. Most of the debris consisted of small pieces of lumber, roofing material, and other small items (Ref. Figure 65). There were four items of debris which were large enough to be considered major missiles. These items were as follows:

(1) A utility pole approximately 20 ft. in length. The pole snapped 2 ft. above ground, and traveled 160 ft. This pole is seen in the foreground in Figure 37. All other utility poles in the

tornado path which had snapped were found within 10 to 15 ft. of their original locations.

(2) Three empty truck trailers, 8 x 40 ft. in plan and 8-1/2 ft. high (Ref. Figure 66).

(3) A timber beam 3 x 13 in. in section and 20 ft. long (Ref. Figure 67).

(4) An open web steel joist shown in Figure 68.

Cincinnati, Ohio

The Cincinnati area experienced two tornadoes: one on the western edge of the city which damaged the Sayler Park area, and the other on the northern edge of the city in the Blue Ash and Sharonville areas (Ref. Figure 33). The second tornado track went through the towns of West Chester, Pisgah, Mason, and northward to Lebanon. Total aggregate damage in the greater Cincinnati area is estimated at $20,000,000. Five persons lost their lives in these tornadoes and at least 200 persons received hospital treatment for injuries.

The hardest hit area was the Sayler Park District where 70 residences were totally destroyed and additional 450 homes were damaged. There were no engineered structures in the path of the tornado in this area. The damage path was approximately three blocks wide. There were no deaths reported in the Sayler Park area.

Blue Ash, Elmwood Place, and Sharonville areas sustained damage to business districts and to engineered structures. However, the damage can be considered moderate, i.e., the type of damage that can be repaired without evacuating the building or closing the business. This tornado also damaged businesses along U.S. Highway 42 and in the towns of Mason and Lebanon. These towns sustained considerable damage to their business districts. A significant amount of damage and a number of injuries were the result of falling trees in residential areas.

Indicated Additional Work in Ohio

The tornado which affected Xenia was one of the most intense tornadoes that has passed through a populated area. Since the tornado damaged a wide variety of engineered structures it would be profitable to determine, accurately, windspeeds in this tornado and to assess the behavior of these structures to tornadic loading. In addition, specific items listed below warrant further investigation in order to advance general knowledge regarding the response of structures to extreme winds:

(1) Evaluation of the behavior of five severely damaged schools to ascertain survivability rates for building occupants who could have been in interior hallways.

(2) Evaluation of behavior of Xenia High School building complex to tornadic loading since the school contains a variety of structural systems, including precast concrete.

(3) Analysis of possible flight and deposition of truck trailers on roof of the bowling alley.

(4) Analysis of the flight of 3 x 13 in., and 20 ft. long timber beam and snapped utility pole to ascertain speed of missiles.

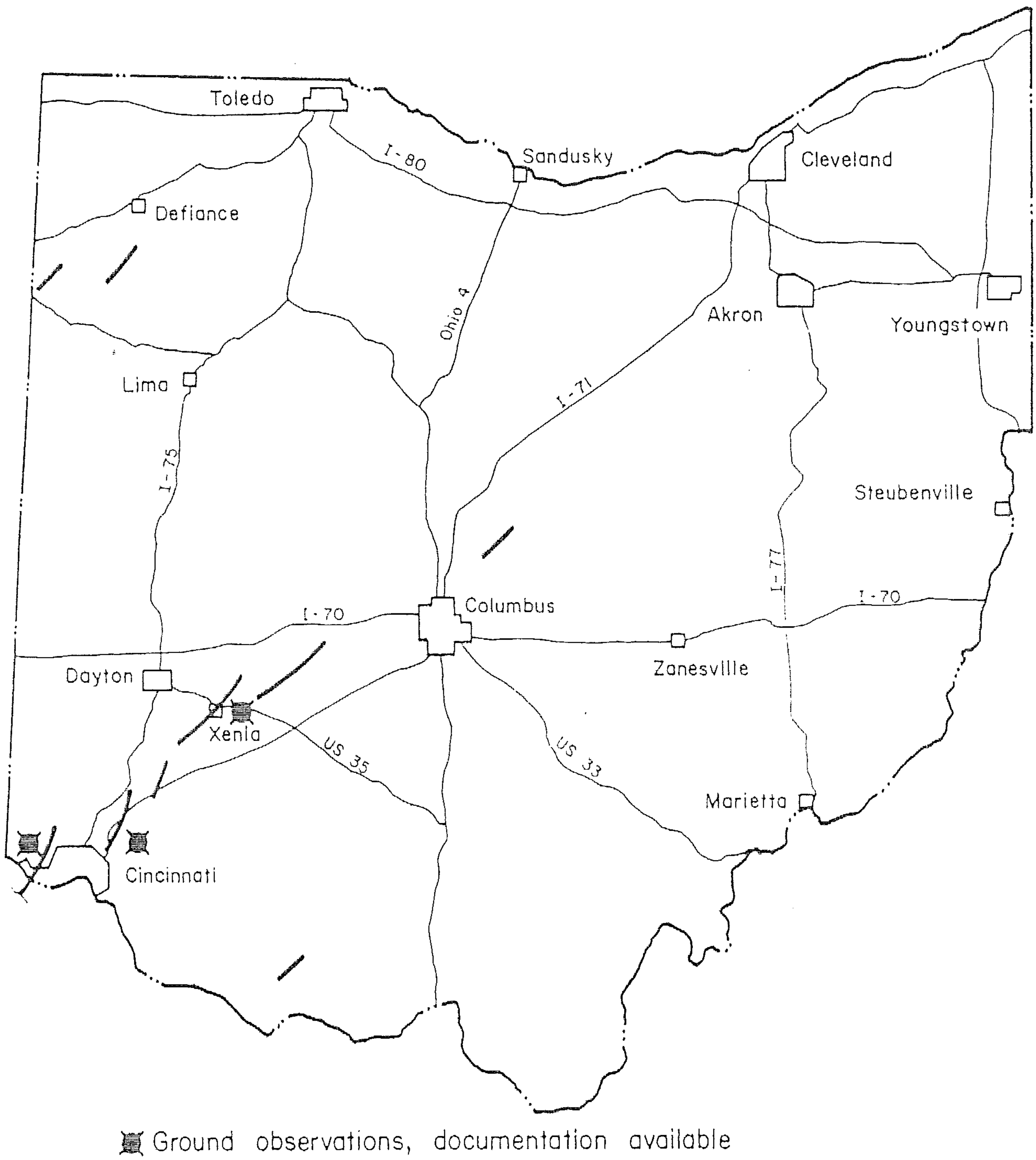


FIGURE 33. TORNADO TRACKS IN OHIO. Tracks determined by Fujita.

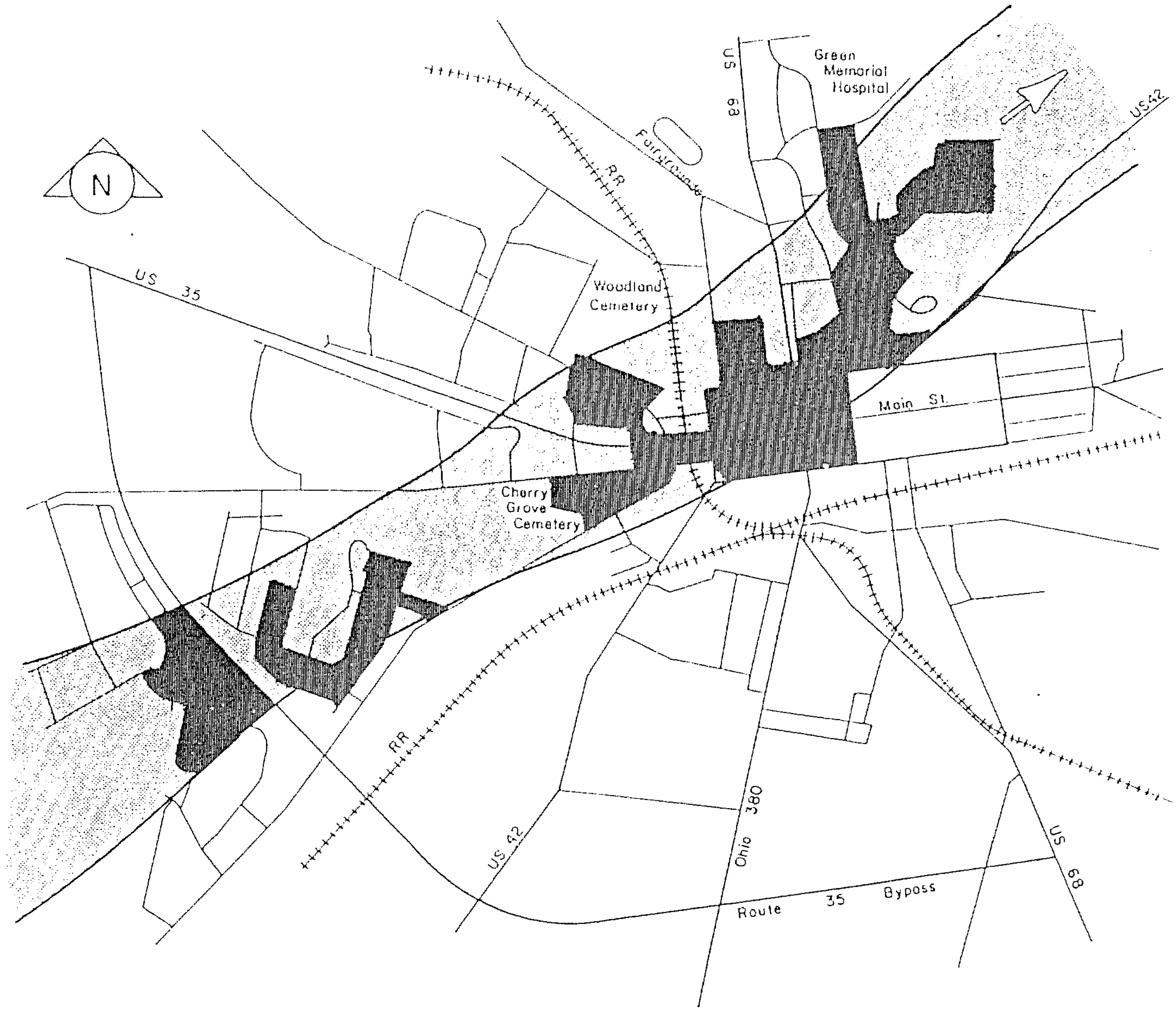


FIGURE 34. MAP OF XENIA. Dark areas show severely damaged residential, commercial, and downtown areas.

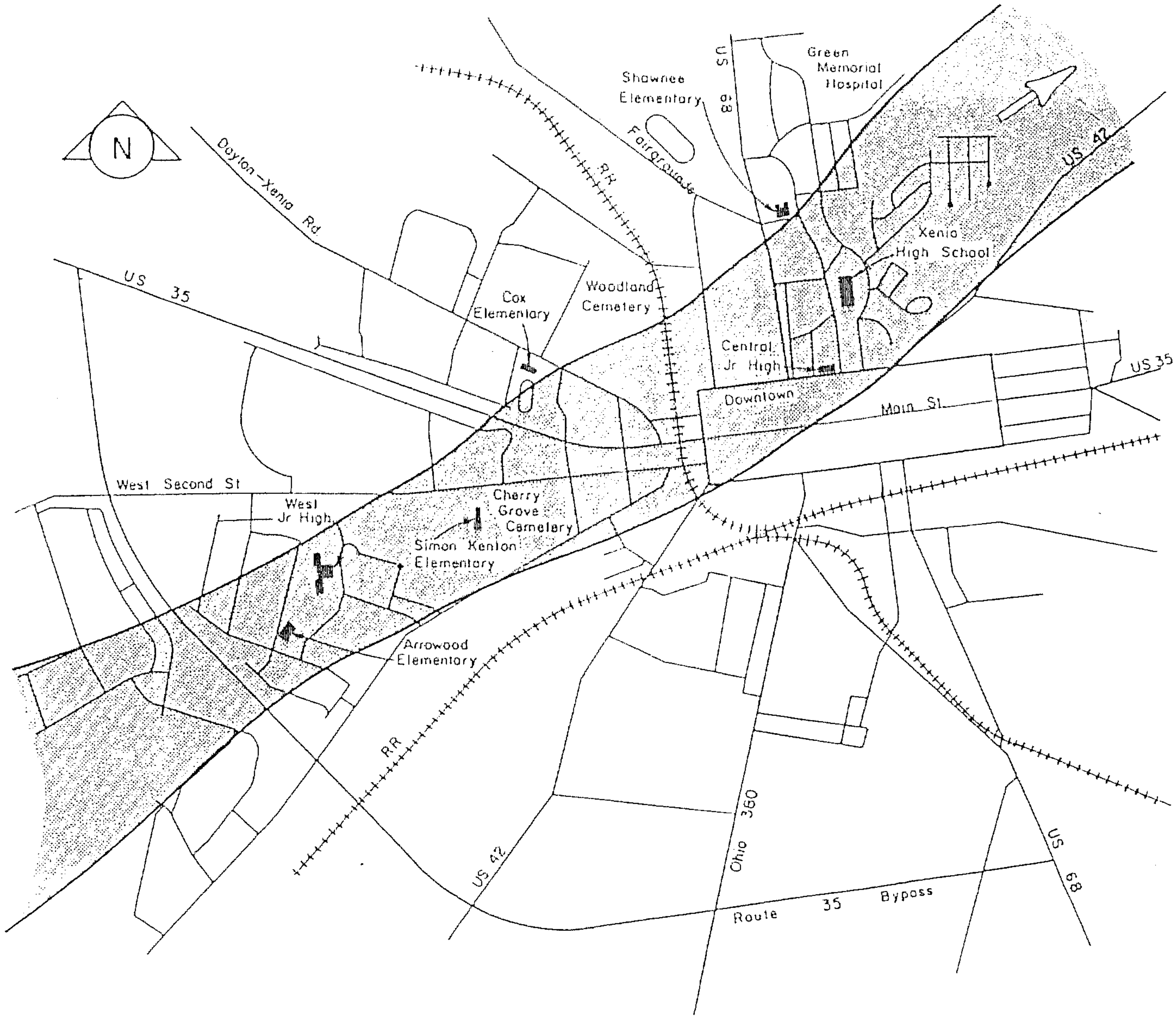


FIGURE 35. LOCATIONS OF XENIA SCHOOLS. Schools are shown in relation to the damage path.

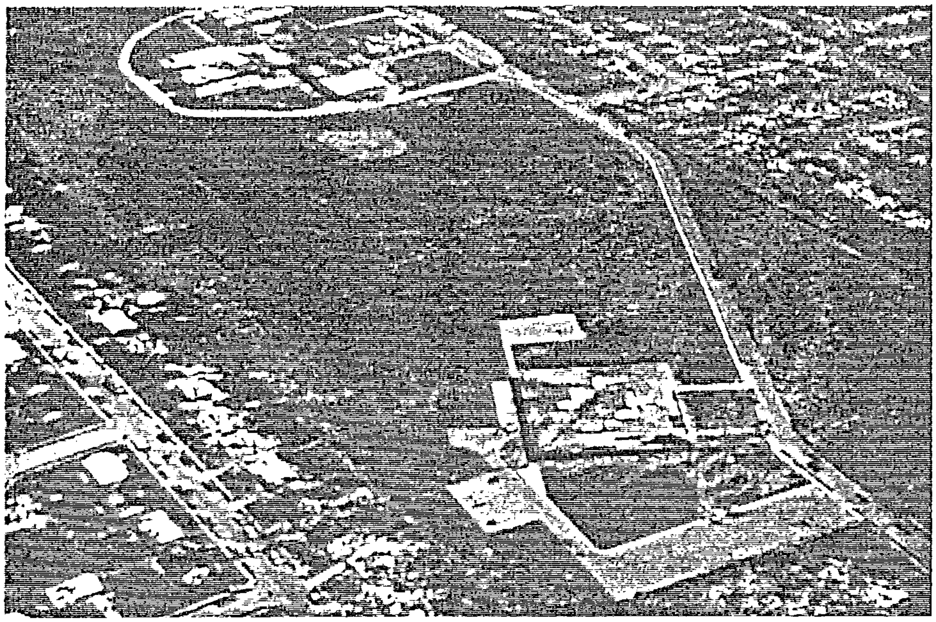


FIGURE 36. ARROWOOD ELEMENTARY SCHOOL. This school (foreground) sustained some damage to roof corners and roof ridges. Residences surrounding the school sustained very severe damage with many of them being totally destroyed.

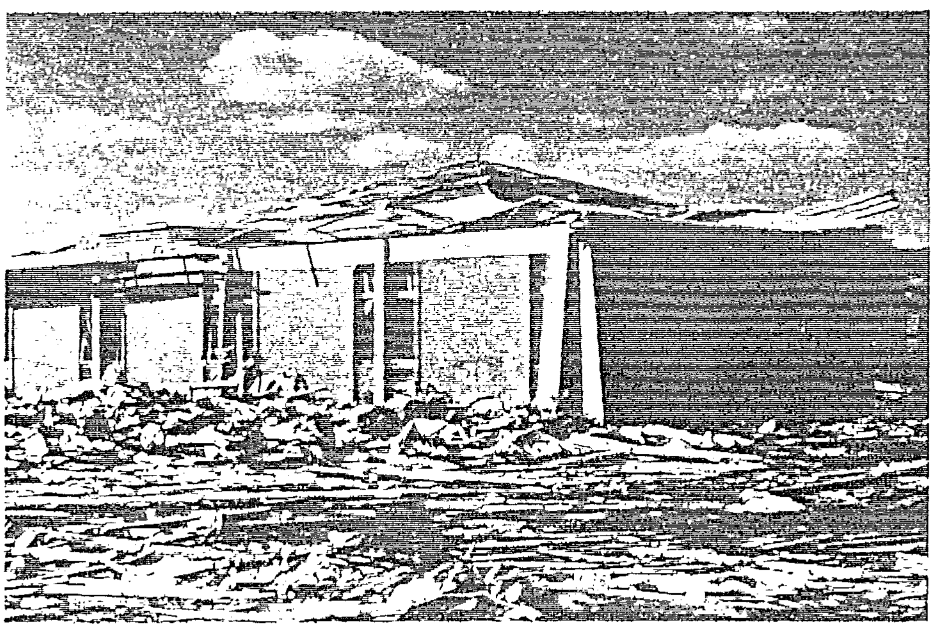


FIGURE 37. ARROWOOD ELEMENTARY SCHOOL, SOUTHEAST CORNER. The roof corner is uplifted and the windows to the classroom are broken. There was no damage to structural frame. Note the amount of debris that has collected outside of school.

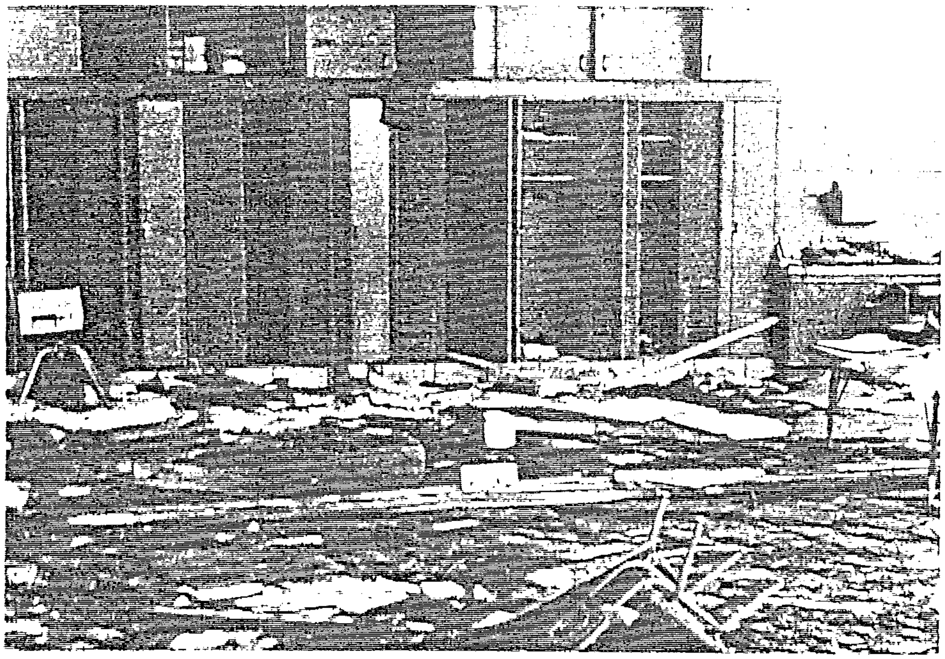


FIGURE 38. ARROWOOD ELEMENTARY SCHOOL, EXTERIOR CLASSROOM. A 2 x 8 in., 14 ft long piece of wood and an automobile tire had entered through windows.

FIGURE 39. ARROWOOD ELEMENTARY SCHOOL, INTERIOR HALLWAY. The hallway sustained no damage and is free of flying debris. Pieces on the floor are acoustic panels of the hallway ceiling which became loose.

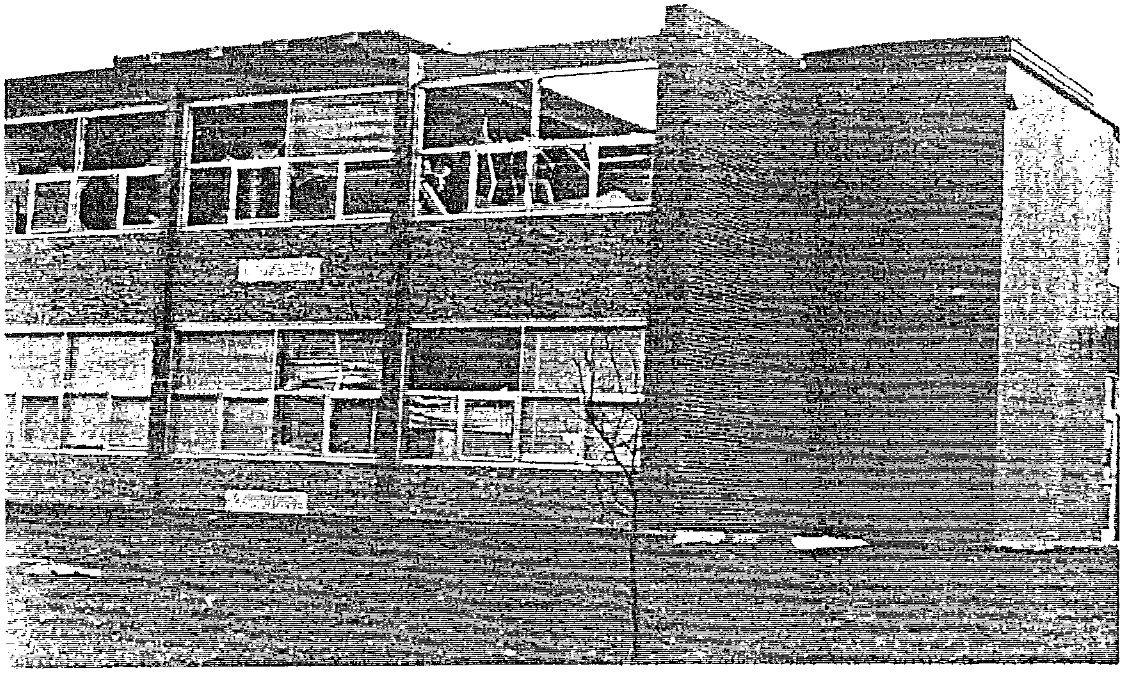


FIGURE 40. WEST JUNIOR HIGH SCHOOL, ROOF CORNER. Precast double-tee beams were uplifted. The two-story building did not sustain any other structural damage.

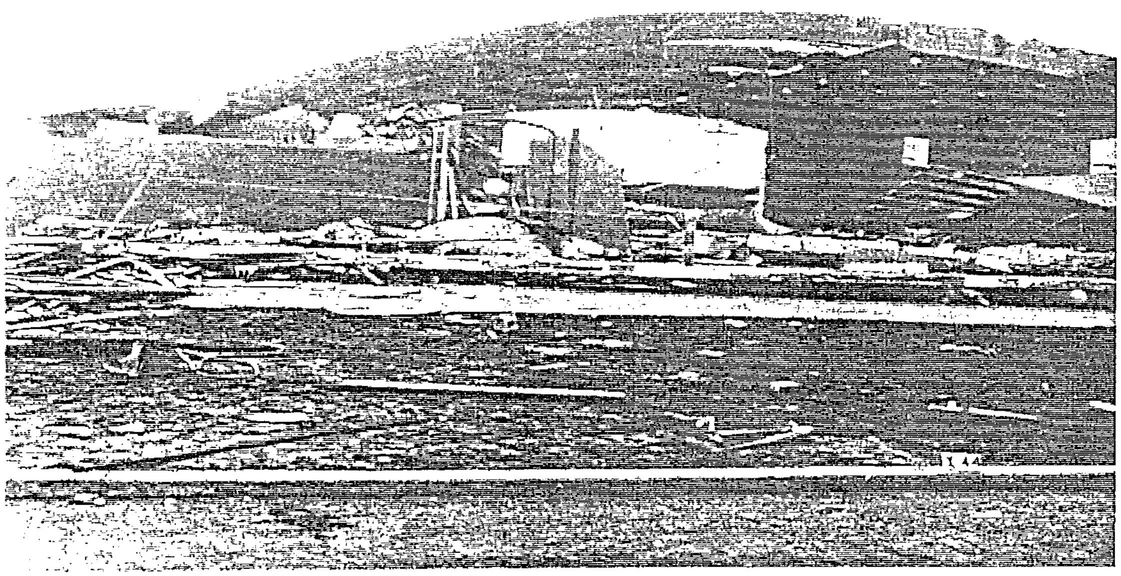


FIGURE 41. WEST JUNIOR HIGH SCHOOL, GYMNASIUM. The end walls collapsed and fifty percent of the roof was gone.

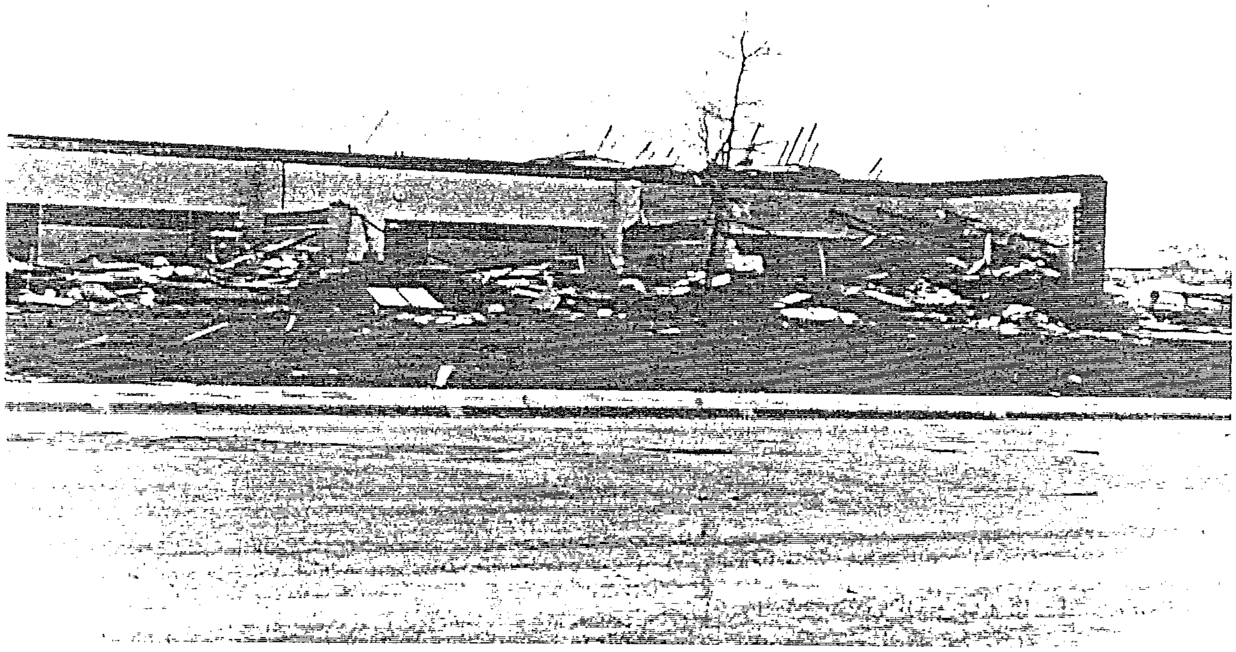


FIGURE 42. SIMON KENTON ELEMENTARY SCHOOL, CLASSROOMS. Exterior walls had collapsed and the roof was entirely uplifted.

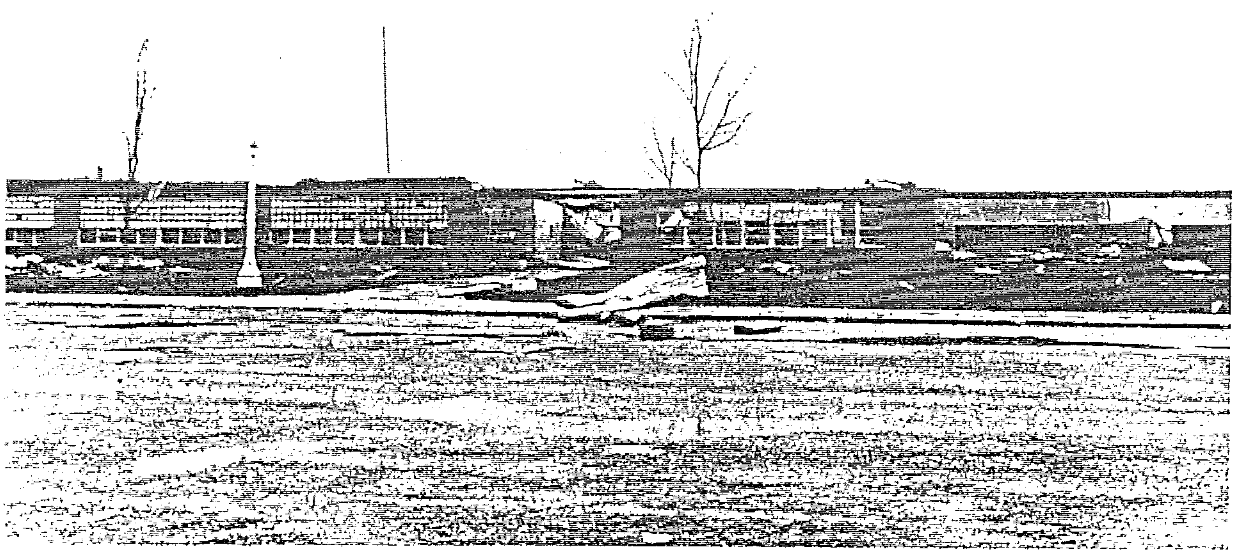


FIGURE 43. SIMON KENTON ELEMENTARY. Roofs over classroom and hallway were uplifted.

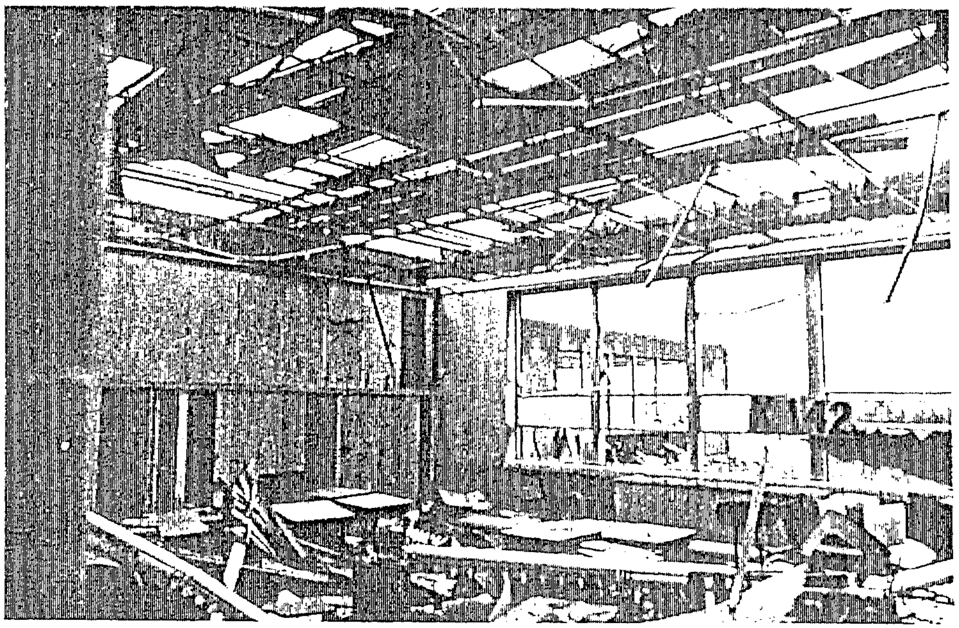


FIGURE 44. SIMON KENTON ELEMENTARY SCHOOL, CLASSROOM. Severe damage was due to wind and flying debris entering the classroom.

FIGURE 45. SIMON KENTON ELEMENTARY SCHOOL HALLWAY. Large amounts of debris entered through uplifted roof.

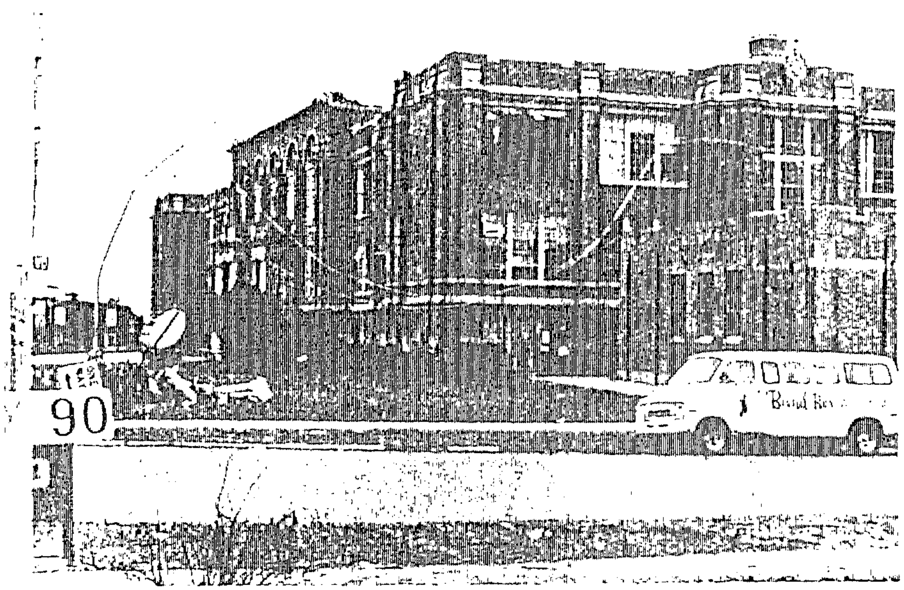


FIGURE 46. CENTRAL JUNIOR HIGH SCHOOL. Window frames on second floor were damaged by flying debris. The building sustained very little structural damage.

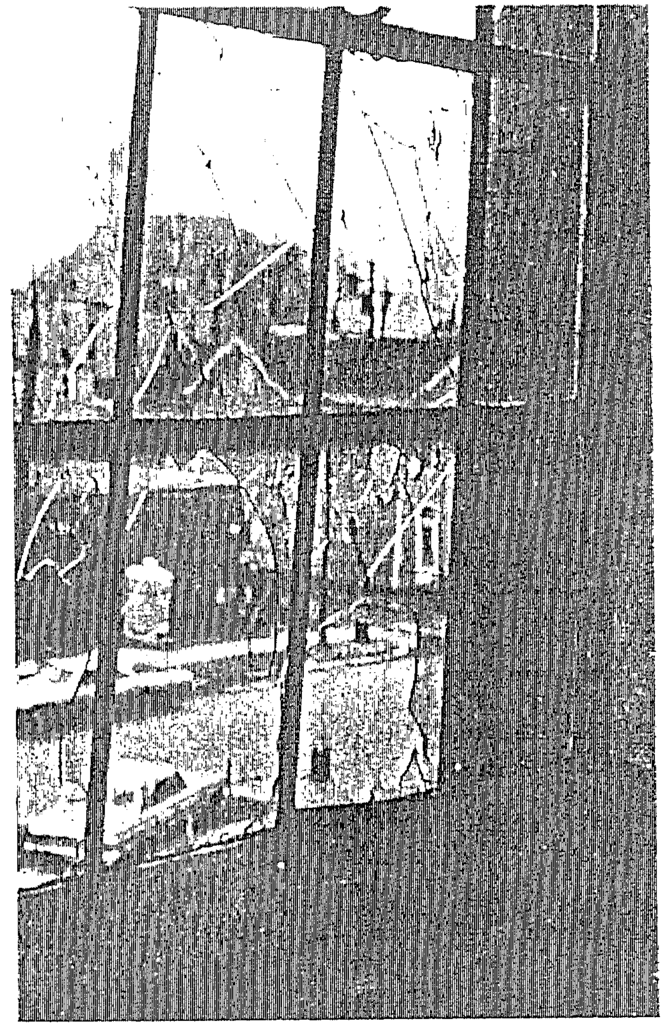


FIGURE 47. CENTRAL JUNIOR HIGH SCHOOL, WINDOWS. Windows were broken by roof gravel. The roof gravel came from one story building across the street.

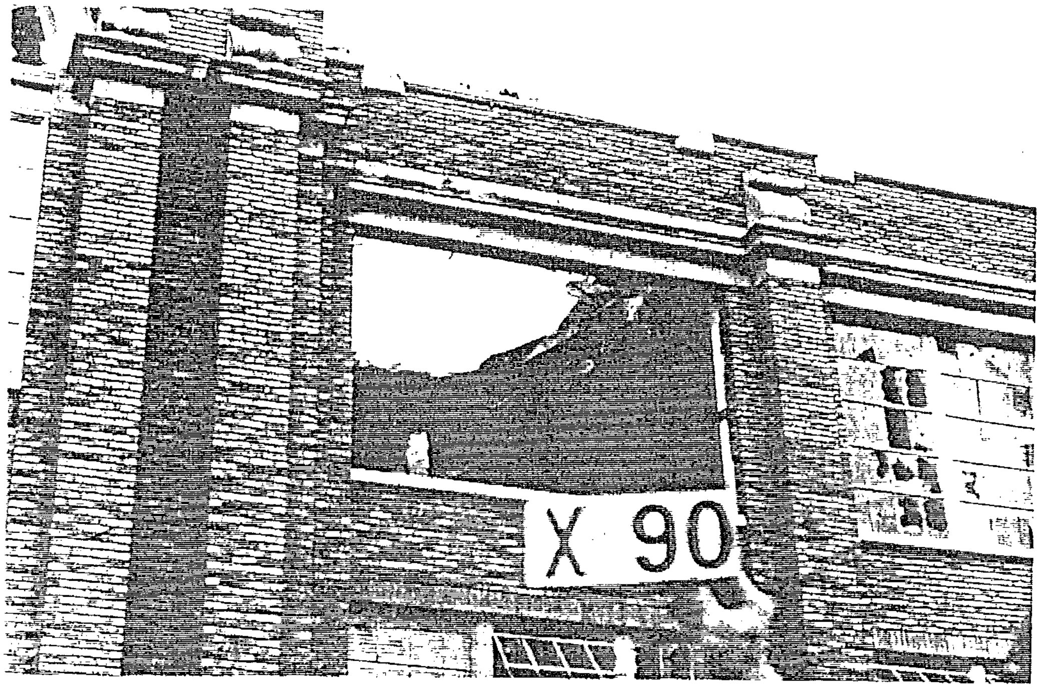


FIGURE 48. CENTRAL JUNIOR HIGH SCHOOL, ROOF SLAB. The slab collapsed under the weight of brick masonry parapet and cast stone coping material.

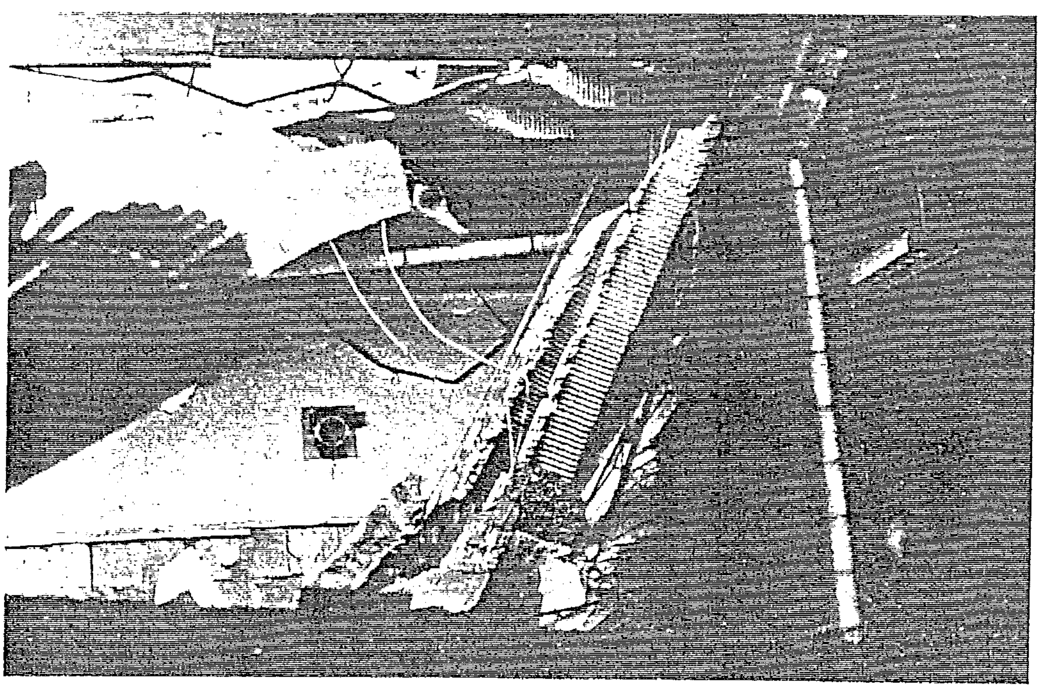


FIGURE 49. CENTRAL JUNIOR HIGH SCHOOL, ROOF SLAB. The reinforced concrete joists (pan joist system) with reinforcement are visible.

FIGURE 50. CENTRAL JUNIOR HIGH SCHOOL CLASSROOM. The second floor classroom contains a portion of a roof (approximately 40 sq ft in area) which flew in breaking the window frame. The roof and the window frame are visible.

FIGURE 51. CENTRAL JUNIOR HIGH SCHOOL, INTERIOR HALLWAY. The second floor hallway was free of debris. This lack of damage and lack of debris was typical on all three floors.

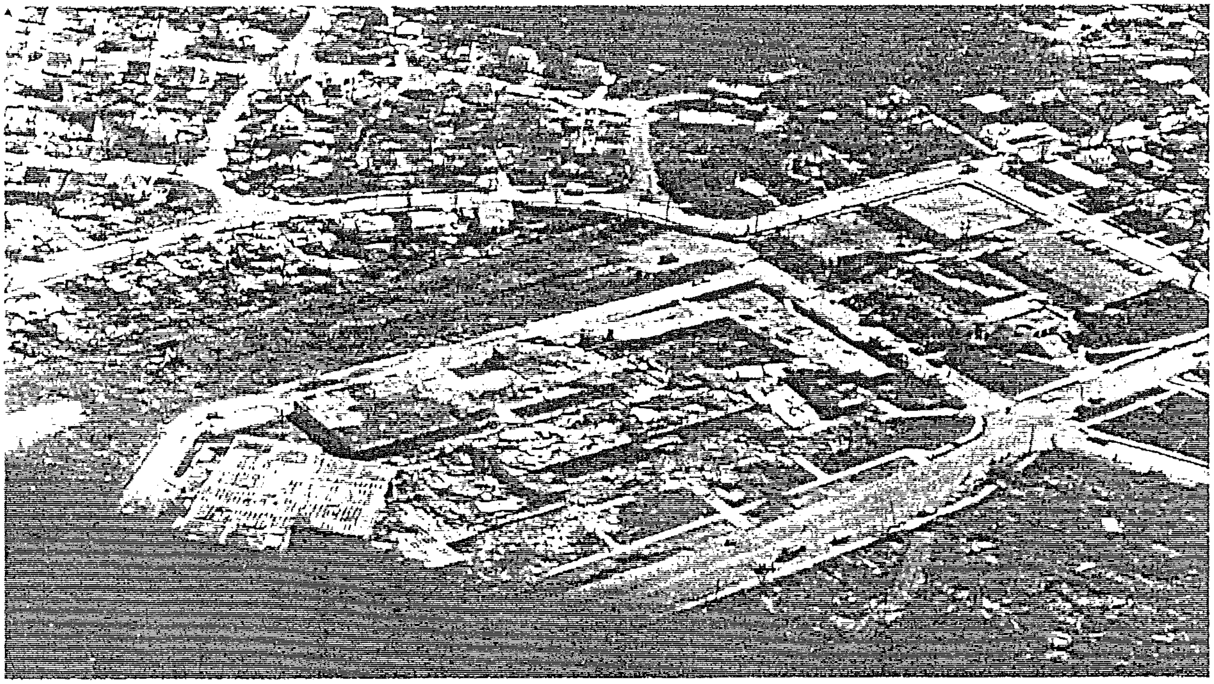


FIGURE 52. XENIA HIGH SCHOOL. Aerial view shows extensive damage to the school building and to the surrounding area. Tornado traveled from bottom right corner to top left corner of the photograph.

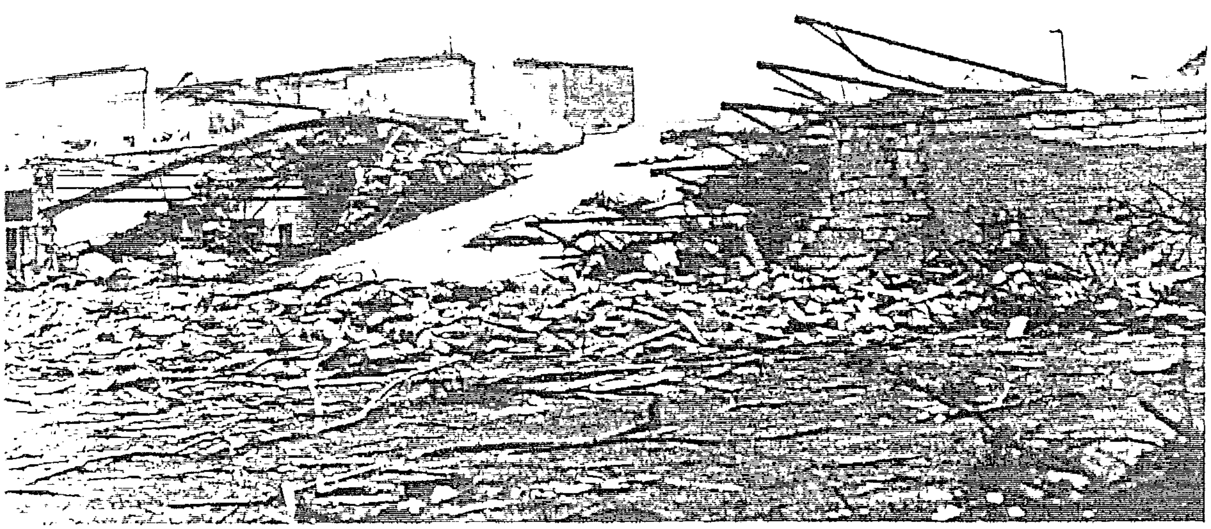


FIGURE 53. XENIA HIGH SCHOOL, CAFETERIA. Roof collapsed when loadbearing masonry walls failed.

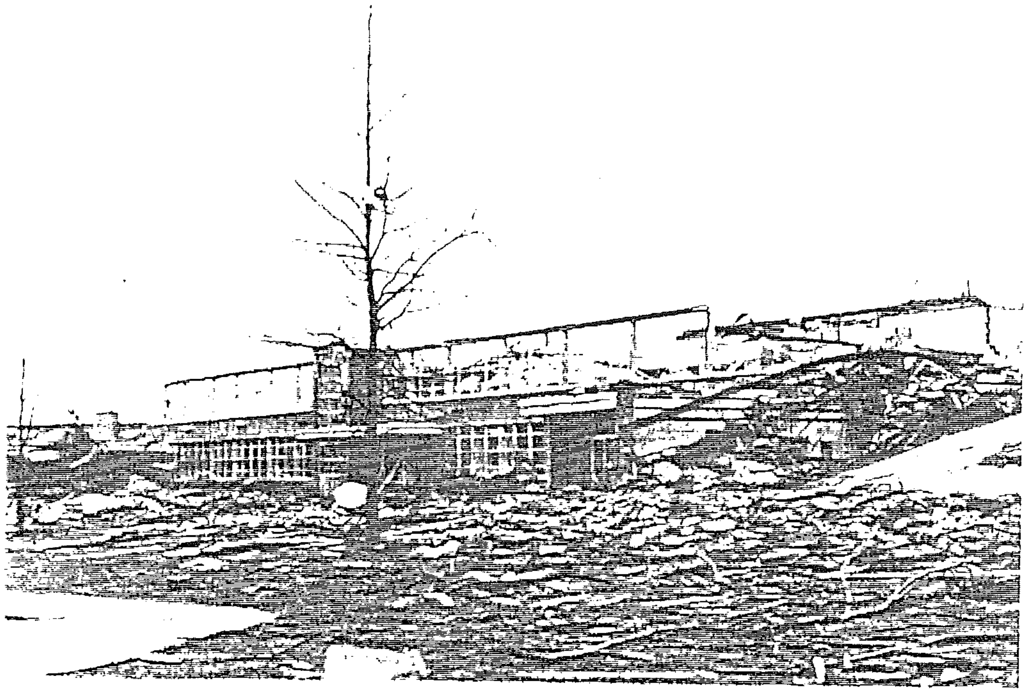


FIGURE 54. XENIA HIGH SCHOOL, TWO STORY BUILDING. The second story was totally gone. The roof system consisted of open web steel joists.

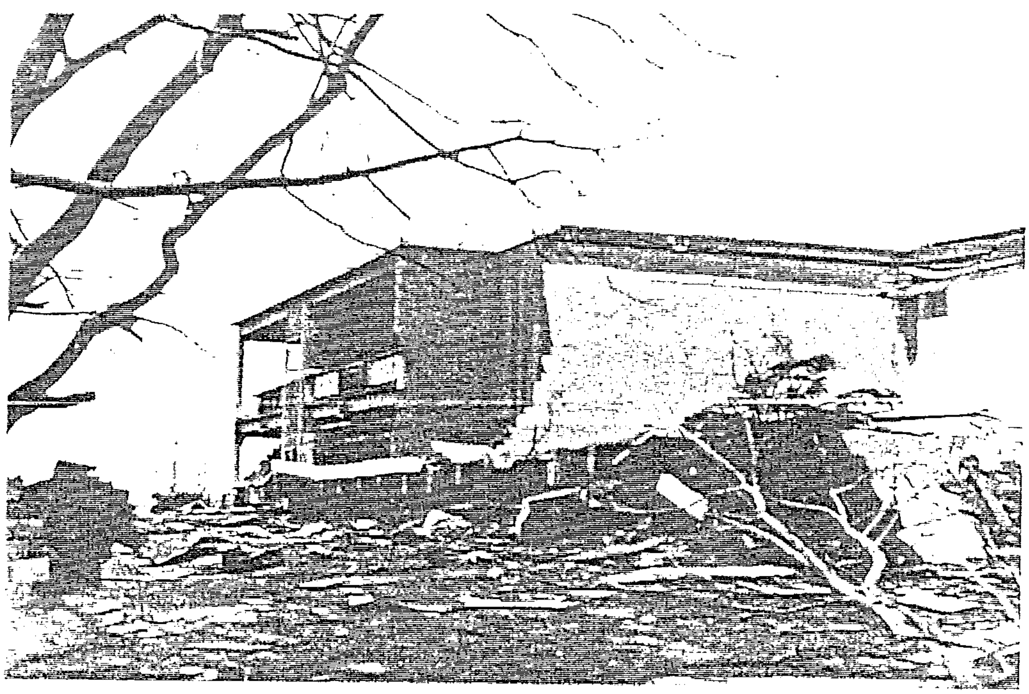


FIGURE 55. XENIA HIGH SCHOOL GYMNASIUM. The precast concrete roof of the gymnasium (foreground) collapsed when the loadbearing walls failed. In the background, precast concrete framing survived, but wall panels are gone.

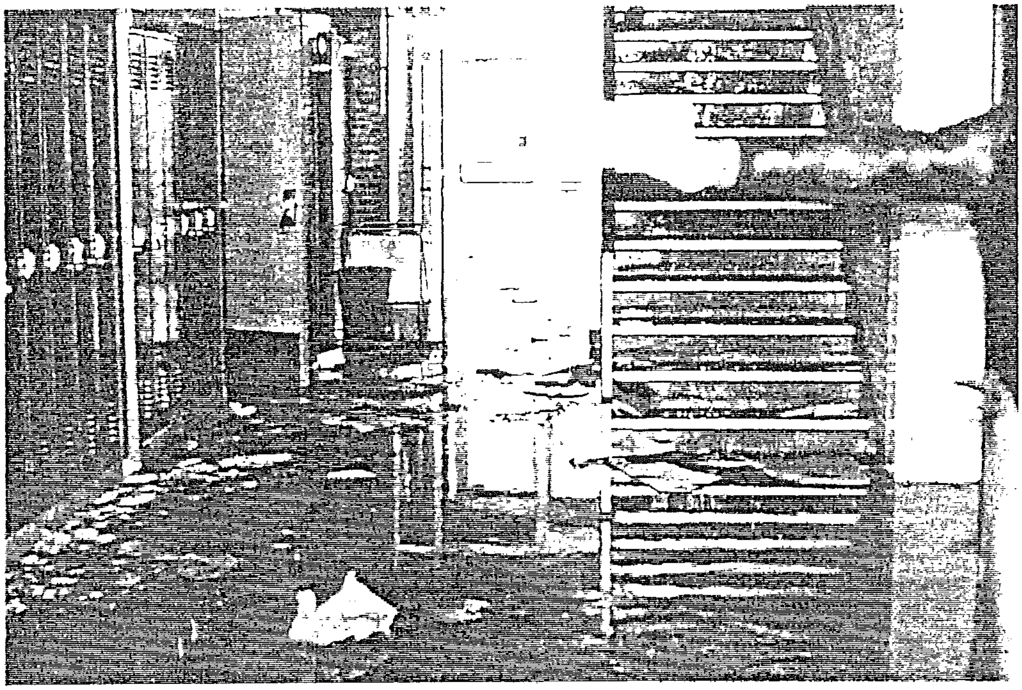


FIGURE 56. XENIA HIGH SCHOOL, INTERIOR HALLWAY. The first floor hallways were undamaged and were free of debris.

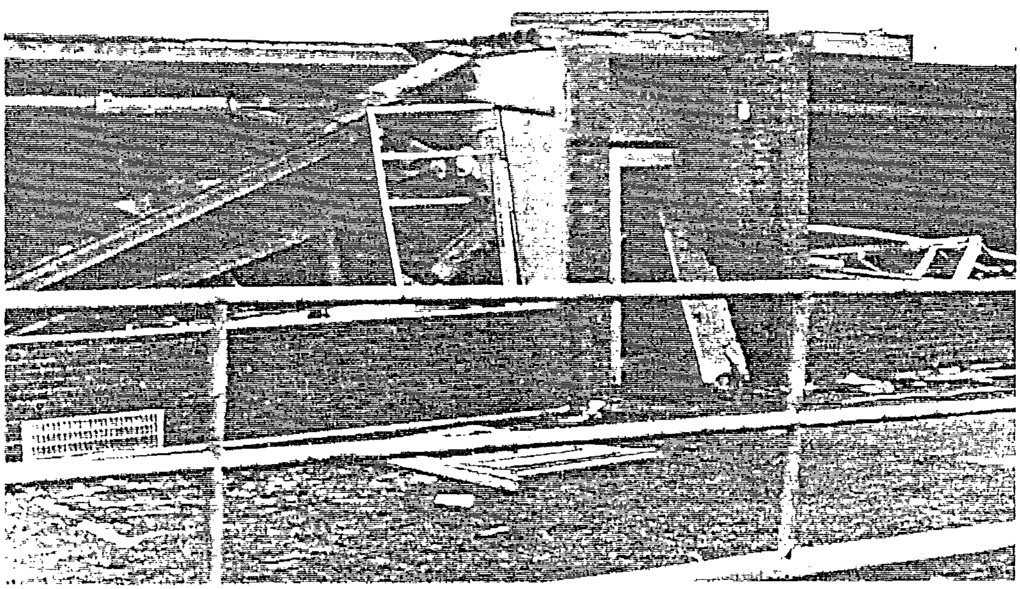


FIGURE 57. XENIA HIGH SCHOOL, ONE STORY CLASSROOM BUILDING. Hollow core roof slabs were uplifted.

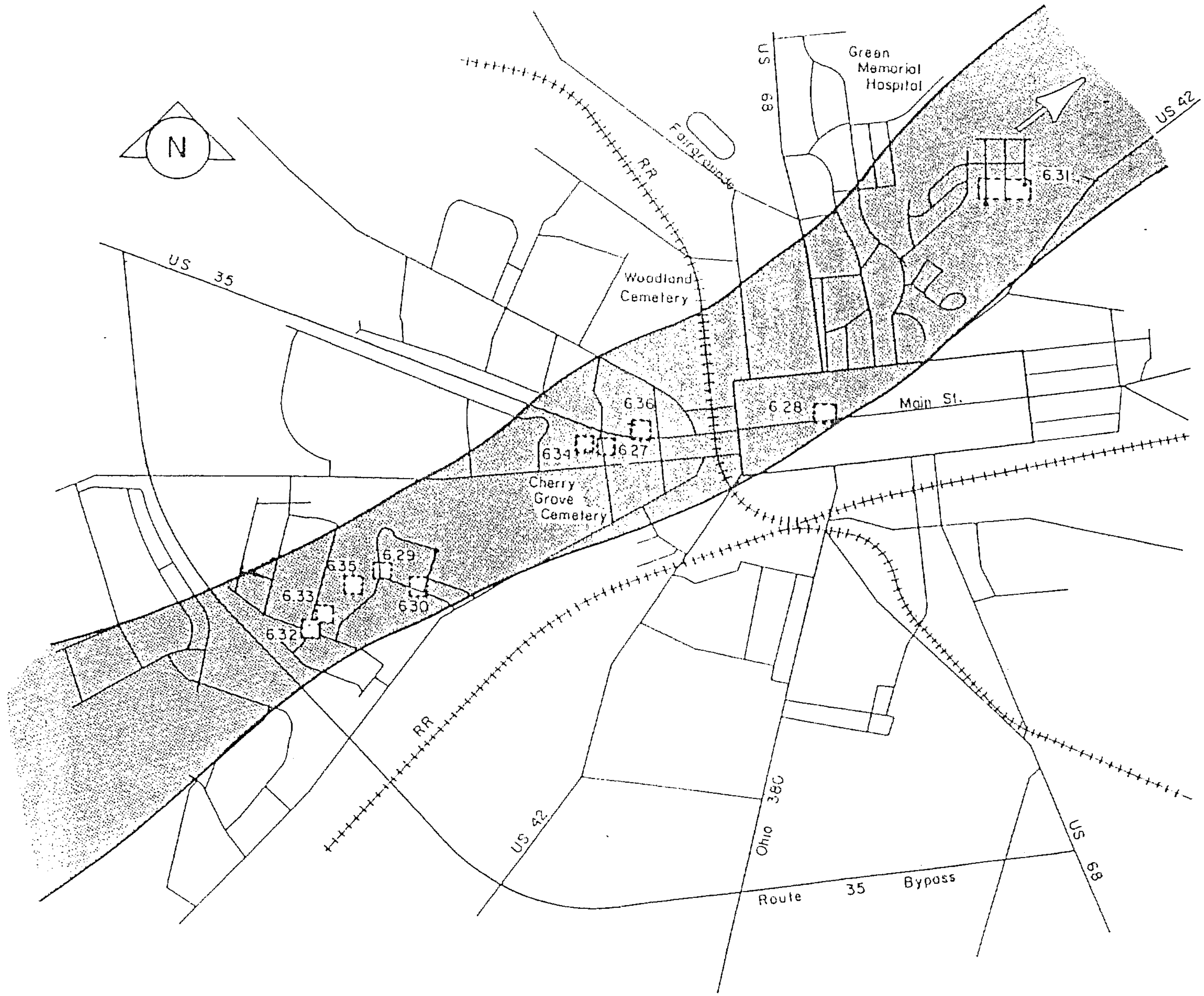


FIGURE 58. LOCATIONS OF BUILDINGS, RESIDENCES, AND MISSILES PRESENTED IN SUBSEQUENT FIGURES.

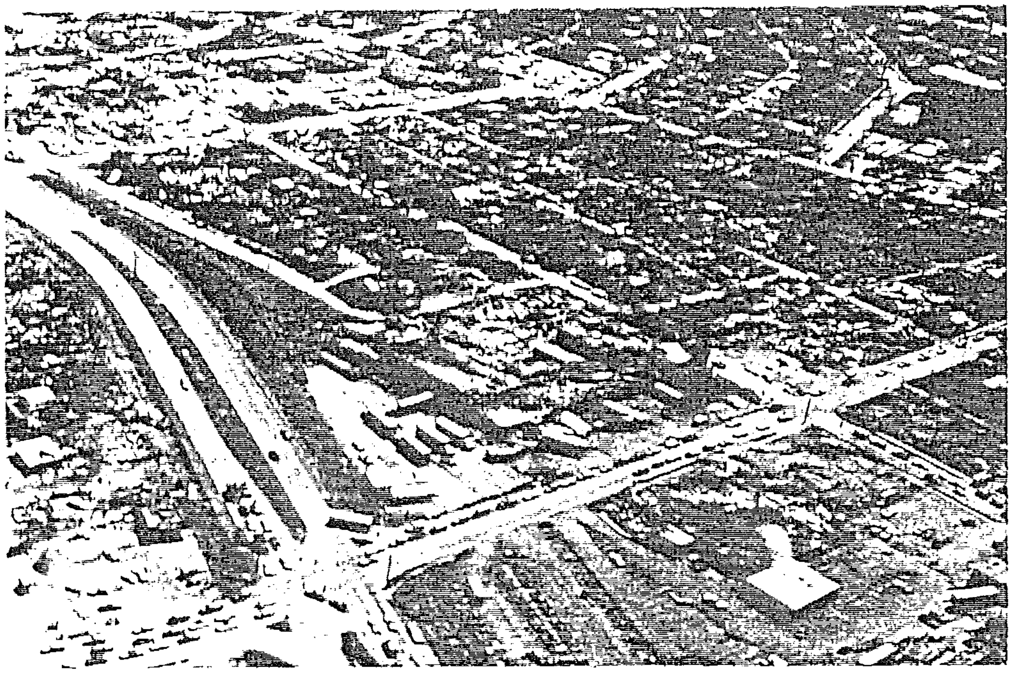


FIGURE 59. COMMERCIAL BUILDING: FURNITURE MANUFACTURING PLANT. Severe damage occurred to the roof and to the second story of the structure.

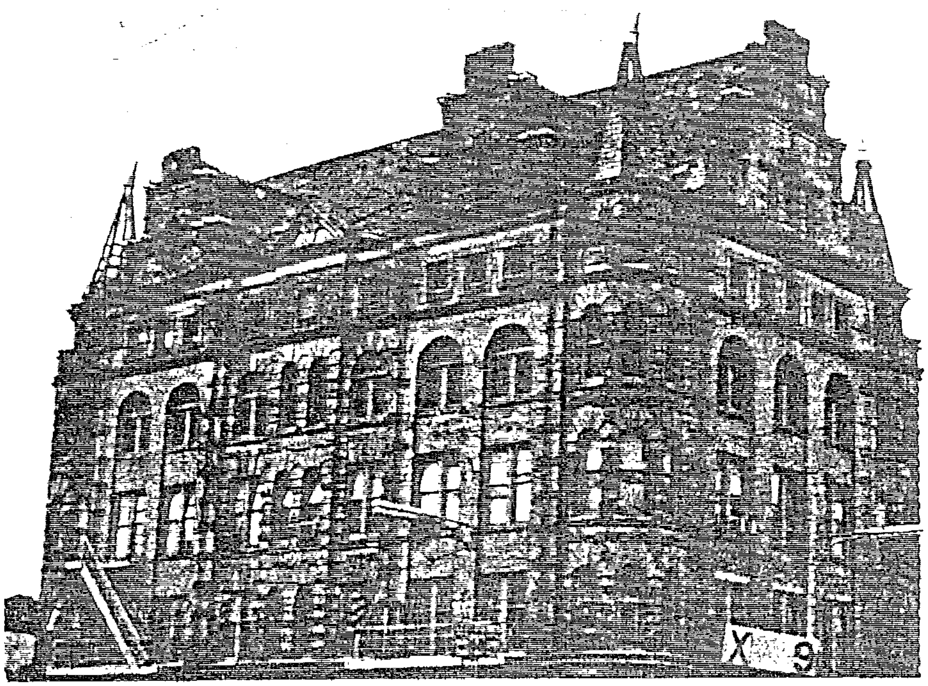


FIGURE 60. COMMERCIAL BUILDING: AN OLD FIVE STORY OFFICE BUILDING. Damage was restricted to the roof and to window glass.

FIGURE 61. RESIDENCE. Roof has been uplifted. The interior walls remained intact.

FIGURE 62. RESIDENCE. Exterior walls and the roof were blown away. The remaining room could have provided a shelter to the occupants.

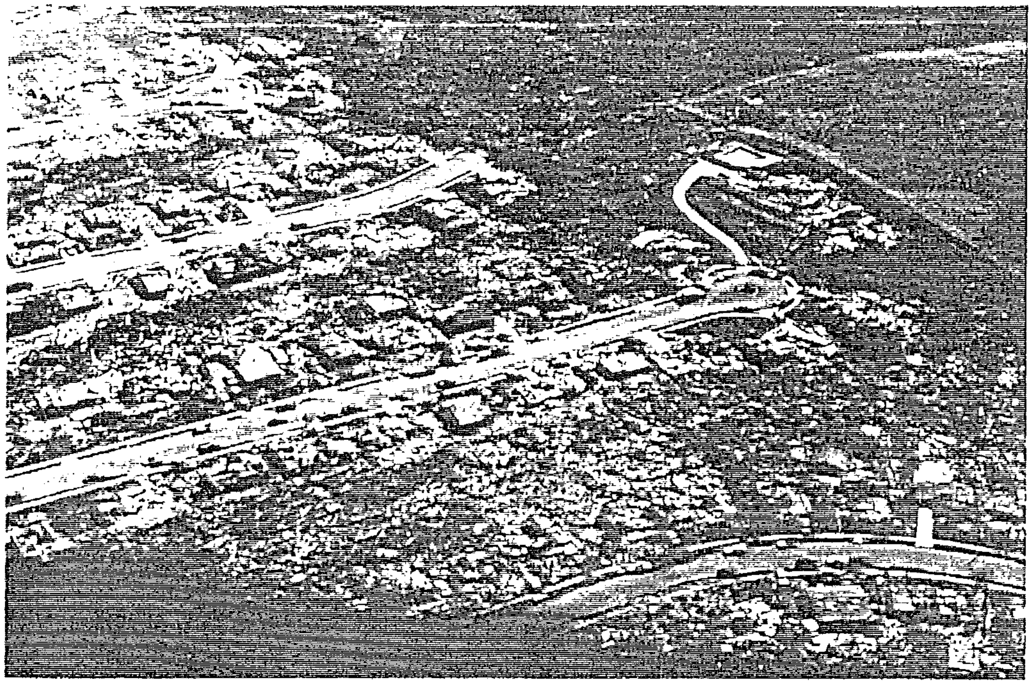


FIGURE 63. RESIDENCES IN NORTHEAST XENIA. The path of the tornado is from bottom right corner to the top left corner. Most of the homes were damaged beyond repair.

FIGURE 64. RESIDENCE IN SOUTHWEST XENIA. The residences were damaged beyond repair, although there remained some walls standing in most of them.

FIGURE 65. DEBRIS. Pieces of timber, roofing material, and other small items deposited at the corner of Arrowood Elementary School. This type of accumulation of debris was typical along the path of the tornado through residential areas.

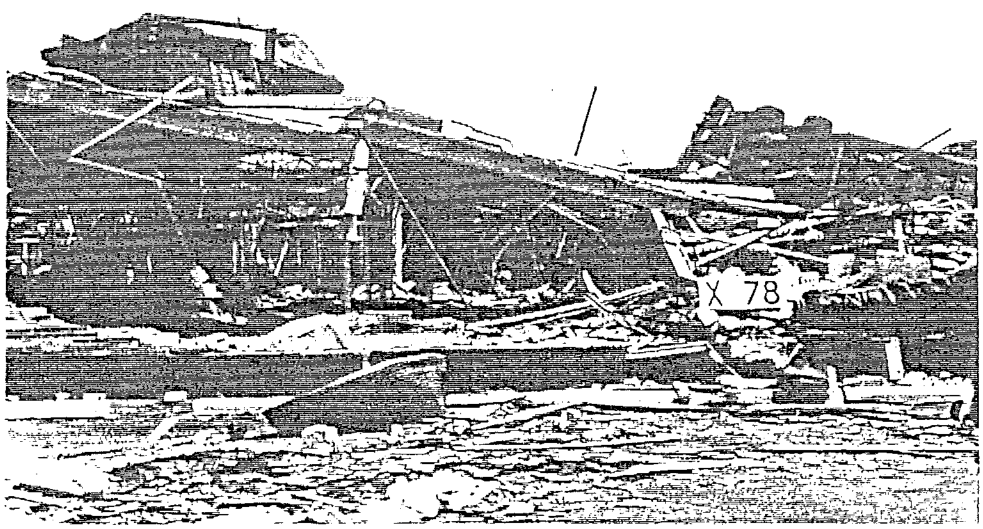


FIGURE 66. TRUCK TRAILERS. Two trailers, 8 x 40 ft in plan and 8 1/2 ft high were apparently uplifted from the furniture manufacturing plant (Ref. Fig. 59) and were deposited on the roof of a bowling alley structure. The trailers traveled about 150 ft.

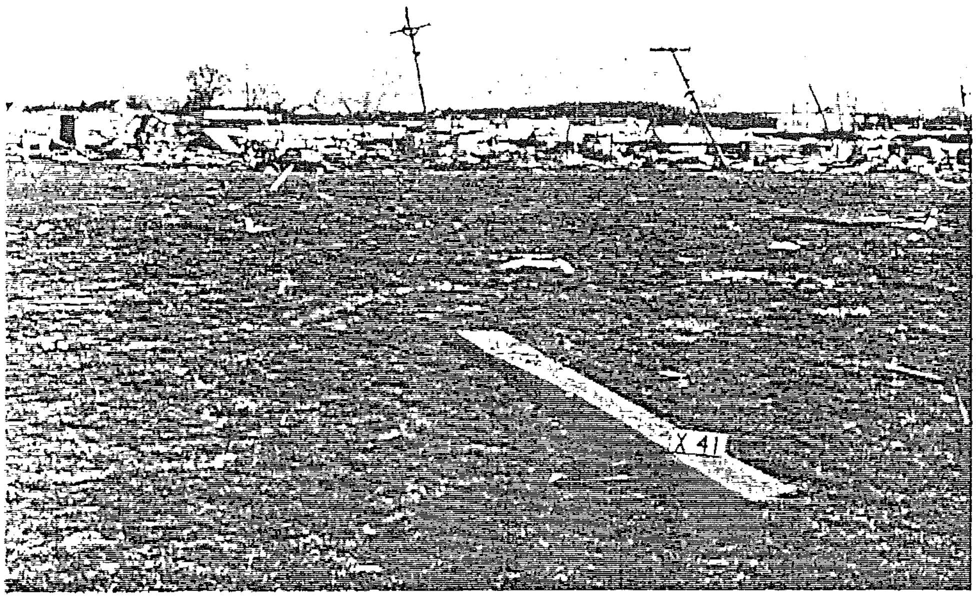


FIGURE 67. TIMBER BEAM. The beam, 3 x 13 in. in cross section and 20 ft long, was uplifted from the roof of the gymnasium of West Jr. High School (Ref. Fig. 41) and was deposited 450 ft from its original location.

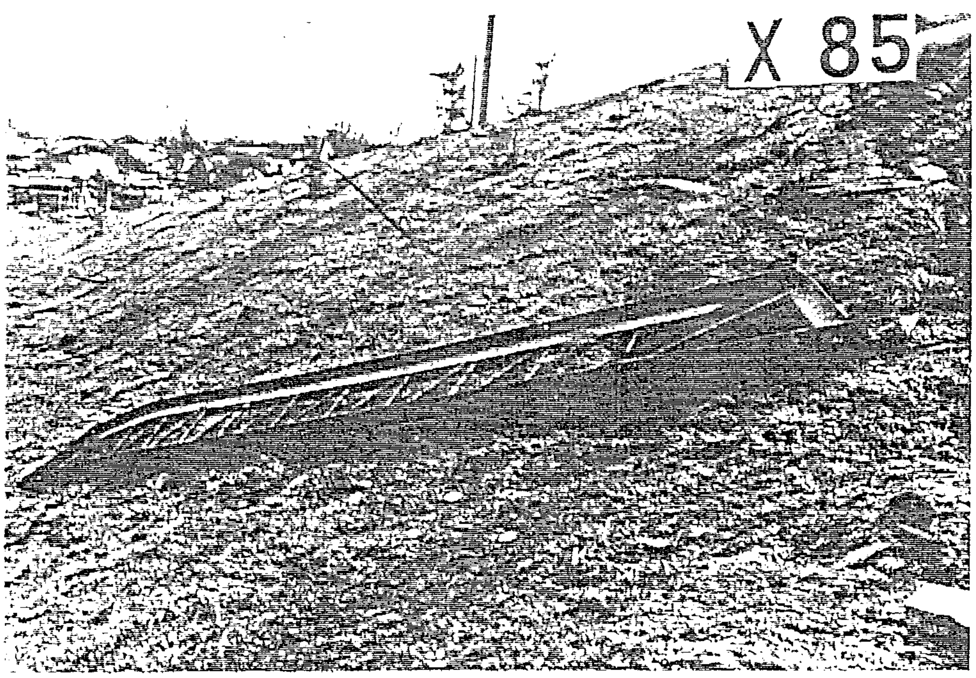


FIGURE 68. OPEN WEB STEEL JOIST. The joist, 20 ft long, was found at the location marked on Fig. 58. The original location of this joist was not found within a 300 ft radius area.

VII. KENTUCKY

Twenty-five individual tornado tracks shown in the map presented in Figure 69 have been identified in the State of Kentucky as a result of the April 3, 1974 storm system. Hardest hit were the cities of Brandenburg and Louisville. A total of 74 persons were killed and 1265 injured with damage, deaths and injuries reported in 13 counties.

A windstorm damage investigation team from Texas Tech University visited both Louisville and Brandenburg, arriving in Louisville on Thursday, April 4 and spending four days photographing and recording storm damage. Of particular interest to the investigation team were engineered structures, tornado generated missiles, schools and residences, which are discussed in more detail in the paragraphs below.

Louisville, Kentucky

At 4:37 P.M. on Tuesday, April 3, 1974 a tornado assaulted the city of Louisville causing a path of damage and destruction 10 miles long with a path width that averaged 660 ft. Damage occurred principally to residences and trees, although three elementary schools received extensive damage, as did the Kentucky Fair and Exposition Center.

The tornado that hit Brandenburg, Kentucky a few minutes earlier appeared to be heading toward Louisville, and although dissipating shortly after crossing the Ohio River, did serve to put the city of Louisville on alert. At 4:37 P.M. a tornado formed at Standiford Field in Louisville before the eyes of the National Weather Service Meteorologist-in-Charge, Mr. John Burke. The tornado then traveled through the city leaving a ten mile path of destruction. Because of the warning and because most residences in Louisville have basements, only two persons were killed, although 44 injured persons did require hospitalization.

The damage path through the city is shown in a map reproduced from the Louisville *Courier-Journal* (see Figure 70). The damage south and west of Interstate 64 was not as intense as that toward the upper end of the path. Based on the extent of damage to houses and trees, windspeeds along the first half of the path were estimated at 150 mph. Trees in the forest in Cherokee Park were leveled, while in the Indian Hills section, Northfield, and beyond, well-constructed frame houses had roofs and some walls torn off. From these and other observations the windspeeds were estimated to be 175-200 mph.

Kentucky Fair and Exposition Center

The most imposing structure to be hit by the Louisville tornado was the Kentucky Fair and Exposition Center, which consists of Freedom Hall, a basketball coliseum with seating capacity for 17,000 persons, and two exhibition wings extending to the east and west sides of Freedom Hall (see Figure 71). The west wing was out of the tornado path and received no damage. There was no structural damage to Freedom Hall but two large holes were ripped in the roof and caused postponement of the American Basketball Association playoffs underway at the time.

Schools

Three elementary schools received extensive damage from the tornado--Audubon, Chenoweth and Dunn Elementary Schools. The Audubon and Chenoweth schools were almost identical in floor plan and type of construction, having steel framing, loadbearing interior walls between classrooms, and suspended ceilings. Classrooms on the windward side of the building lost their roofing materials and suspended ceilings but roof joists, being well anchored to the walls and the steel framing, did not collapse. Interior hallways remained intact and would have provided excellent shelter for the occupants of both schools. An undesirable feature evident at both schools was that large, brick, incinerator chimneys extended eight feet or more above the roof. In each case the chimneys collapsed under the forces of the wind and struck the roof near loadbearing walls, causing the roof to collapse into the classroom (see Figure 73). It is extremely important for school officials to recognize the danger that a chimney poses in making up their emergency action plans for severe weather. Children in the immediate area of the collapse radius would have been killed or severely injured. Otherwise the hallways provided very adequate shelter in these two well-constructed buildings.

Dunn Elementary School, located just west of Interstate 71 near the Northfield Subdivision (see Figure 70), is a modern elementary school constructed at a cost of $1,400,000. Figure 72 is a schematic drawing of the building with the damaged areas shaded. The principal damage was due to collapse of exterior walls which were constructed of 8 in. concrete blocks and 4 in. face bricks and were unreinforced and unanchored at the roof level. Vertical control joints in the masonry had no horizontal reinforcement to tie the wall to the rest of the structure, leaving it a free standing wall, which would be susceptible to damage from winds of considerably less magnitude than observed (see Figure 74). Damage caused by this type of construction detail has been observed in other storms which should be called to the attention of industry.

Interior hallways again would have provided adequate protection to occupants of this building. The light fixtures in the building, installed in the suspended accoustical ceiling framework, were relatively large (36 x 18 in.). Air pressure between the ceiling and roof caused some to drop out of their supports and fall to the floor. A fixture of the size found in this building could cause injury to someone inside the building. A better anchoring system should be explored.

High Rise Buildings

Only two high rise buildings were located in the vicinity of the Louisville tornado. The Camodore Apartment building is a 14-story reinforced concrete and brick structure located near the entrance to Cherokee Park. The building suffered virtually no damage, neither superfical nor structural, although damage in the immediate vicinity was extensive. Screens on the windows on the windward side apparently shielded the glass from small debris flying in the wind. Almost none of the window panes was broken.

Glenview East Condominiums, a new 12-story precast concrete structure, was located well out of the path of the tornado. However, damage to the building was caused by missile impacts on the precast panels that form the exterior cladding of the building. The missiles were small; none of them perforated the walls. Nevertheless, extensive damage was done to the appearance of the exterior of the building. Many windows were broken on the windward side, but because the glass was double layered no damage to the interior from wind or water was observed.

Residences

Damage to residences was typical of the estimated wind velocities. More than 900 houses were damaged to the point that they were uninhabitable without repair, much of the damage being caused by falling trees. In the older sections of town where there were many beautiful trees 60 to 80 ft. in height, the houses were not as extensively damaged as those in newer areas where the trees were either nonexistent or were much smaller. The sheltering effect provided by trees was very noticeable.

Brandenburg, Kentucky

Brandenburg is a small rural town of approximately 1650 persons, located in Meade County on the banks of the Ohio River about 40 miles southwest of Louisville. The tornado that hit Brandenburg first touched down near Irvington in Breckenridge County about 10 miles southwest of Brandenburg at 3:45 P.M. Three persons were killed in Irvington. The tornado traveled in a generally northeast direction through open country between Irvington and Brandenburg, hitting the southwest edge of Brandenburg at 4:10 P.M.

The tornado created a damage path 600-800 ft. wide through the center of town (see Figure 75). The first major structure to be destroyed was the Mead County Rural Electric Cooperative Headquarters. It then traveled in a northeast direction causing damage to a lumber yard and a number of small residences, scattering tombstones as it crossed the cemetery, and heading toward the town's central business district. It passed just north of Central Elementary School where it caused very little damage. The school was later used as a morgue and as headquarters for rescue and relief operations. Other businesses that were destroyed included radio station WMMG, Phillips Memorial Baptist Church, Jenkins-Sturgeon Funeral Home, the Applegate and English Ford Agency, and the County Court House. In all, 20 businesses were damaged or destroyed and 65-100 residences destroyed or severely damaged. After passing through Brandenburg and crossing the Ohio River, the tornado soon dissipated. Only some scattered light damage was observed from the air on the other side of the river.

For a community so small, the death toll was high. Thirty persons were killed and more than 100 were injured with at least 48 requiring hospital care. Most of the injured were treated at Ireland Army Hospital at Fort Knox, Kentucky. Many bodies were so mutilated that identification was difficult. For use in the identification of bodies, the Army brought in two refrigerated semi-trailer trucks, one marked "IDN" meaning bodies identified, the other marked "UNK" meaning unknown. Relatives and friends had to pass through the second trailer in order to identify missing persons. The last victim was not found in the debris until Saturday, April 6--three days after the storm struck. Most of the victims were old people and young children. Several entire families were wiped out.

The damage created by this tornado was devastating. Maximum windspeeds were estimated by the investigating team to be 230-250 mph. Well-constructed frame houses were leveled, leaving piles of debris; structures with weak foundations were lifted, torn and carried great distances; trees were debarked by small flying debris. The tornado path length was longer than 10 miles and the average path width was 750 ft.

Residences

Figure 76 shows typical damage to a well-constructed residence in Brandenburg. The second floor is gone and all that remains are the strongest interior walls at the first floor level.

Tornado Generated Missiles

Probably the most significant observation made of the damage related to the potential missiles at the Rural Electric Cooperative Headquarters. Figure 77 shows an overall view of the storage yard located immediately behind the headquarters building. This yard was in the direct path of the tornado as shown by the damage to the headquarters building. Located on the storage dock were stacks of fence posts (5 in. diameter x 6 ft.), stacks of utility pole cross arms (4 in. x 5 in. x 8 ft.), assorted sizes of electric transformers, spools of electric conduit, and other miscellaneous timber and steel members. Careful examination of the area around the storage yard did not show evidence that any of these items became airborne. Utility poles (8 in. diameter x 20 ft.) were stacked on a rack oriented at right angles (most favorable position) to the storm path. None of these poles became airborne, although they were blown off the rack itself (see Figure 78). These poles were in an ideal position to become airborne, but did not fly. Some 40 gallon barrels of herbicide were moved a considerable distance by the winds, but there was no evidence that they were actually airborne.

Past the REC headquarters the tornado struck a lumber yard where lumber of various sizes was stored in a two level shed 14 ft. wide and 100 ft. long. It had an 8 ft. overhang on the roof, making the shed very susceptible to wind forces. Figure 78 shows that the entire shed and all of the lumber except that shown was blown away. The investigation team found 2 x 4's, 14 ft. long, 300 yards down the path from the shed location. The owner reported that some pieces of timber (identifiable by mill marks) had been observed more than one and one-half miles down the path. This could not be positively verified because the clean-up operation had destroyed the evidence before storm investigators arrived.

Other Tornadoes in Kentucky

Twenty-three other individual tornado tracks were identified in the State (see Figure 69). Most of these occurred in rural areas, but there were significant numbers of deaths and injuries.

Indicated Additional Work in Kentucky

Louisville was the largest city which sustained damage in the tornado outbreak of April 3, 1974. The damage at Brandenburg suggests that this tornado may have had the most intense windspeeds of the tornadoes which occurred on April 3, 1974. These two observations suggest that detailed analyses of damage in Kentucky is warranted. Specific items that should be evaluated further are as follows:

(1) A number of schools were severely damaged in Louisville. Although the interior hallways generally remained intact, brick chimneys collapsed upon roofs of the hallways. Subsequent failures of the roof deposited heavy debris on hallway floors. Evaluations of this type of progressive collapse are important because the interior hallways may be considered as shelter areas for children by school officials.

(2) Large numbers of potential missiles were available on the grounds of a rural electric cooperative headquarters in Brandenburg when an intense tornado passed through the area. Preliminary observations indicate that relatively heavy items such as utility poles, transformers, and 40 gallon barrels did not become airborne. This fact may have implications in studies of missiles in windstorms.

(3) Relatively large percentages of the exposed population (2 percent) in Brandenburg received fatal injuries. Further investigation of injuries and deaths in terms of location and circumstances will provide valuable data for the development of design criteria for occupant protection.

(4) Since the appearance of damage in Brandenburg is suggestive of extreme ground level windspeeds, examinations of damaged structures and missile incidents should be undertaken to define, as closely as possible, actual windspeeds.

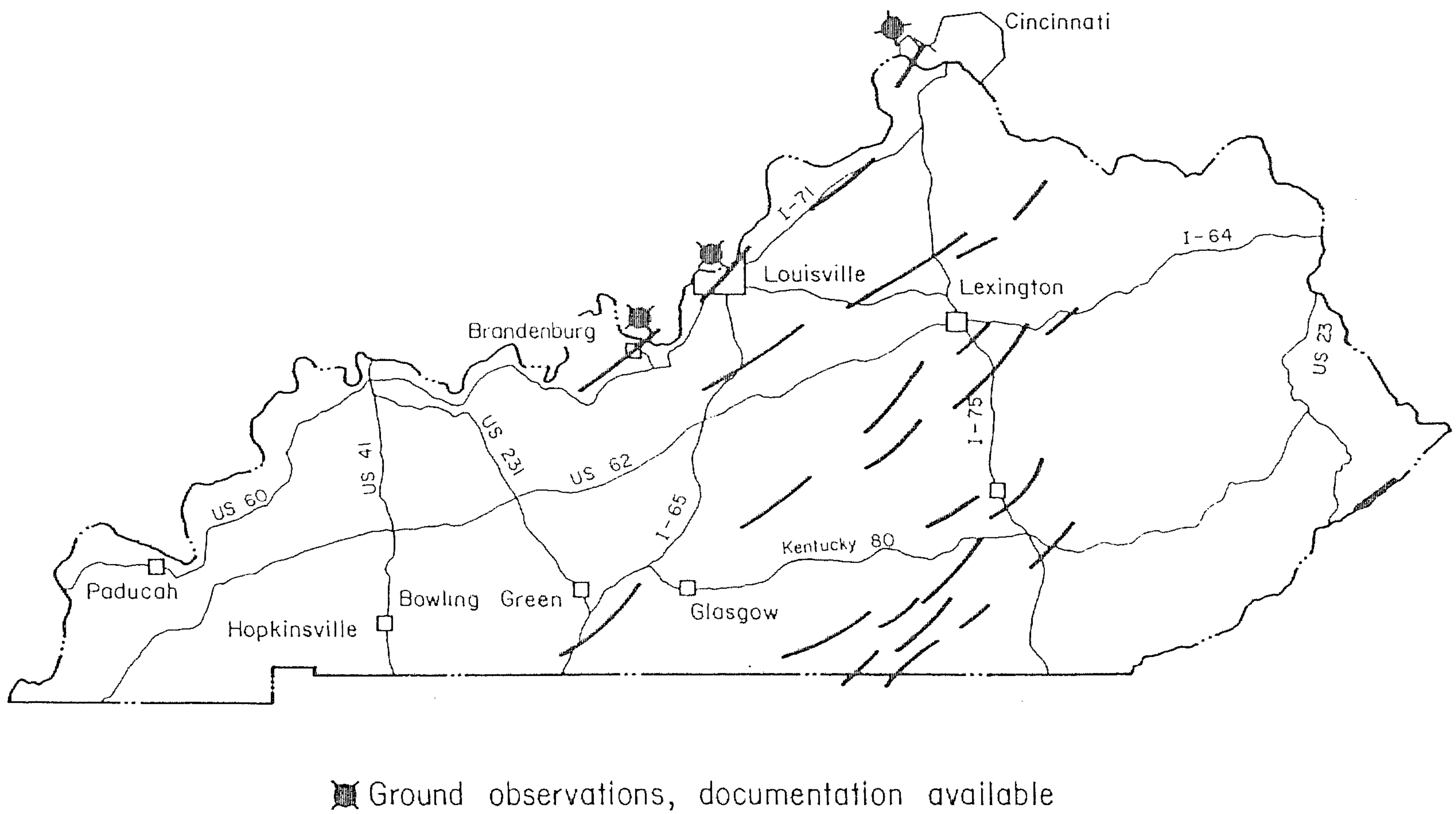


FIGURE 69. STATE OF KENTUCKY. Twenty-five individual tornado tracks are shown on the map. The most extensive damage was found at Louisville and Brandenburg. Tracks shown were established by Fujita.

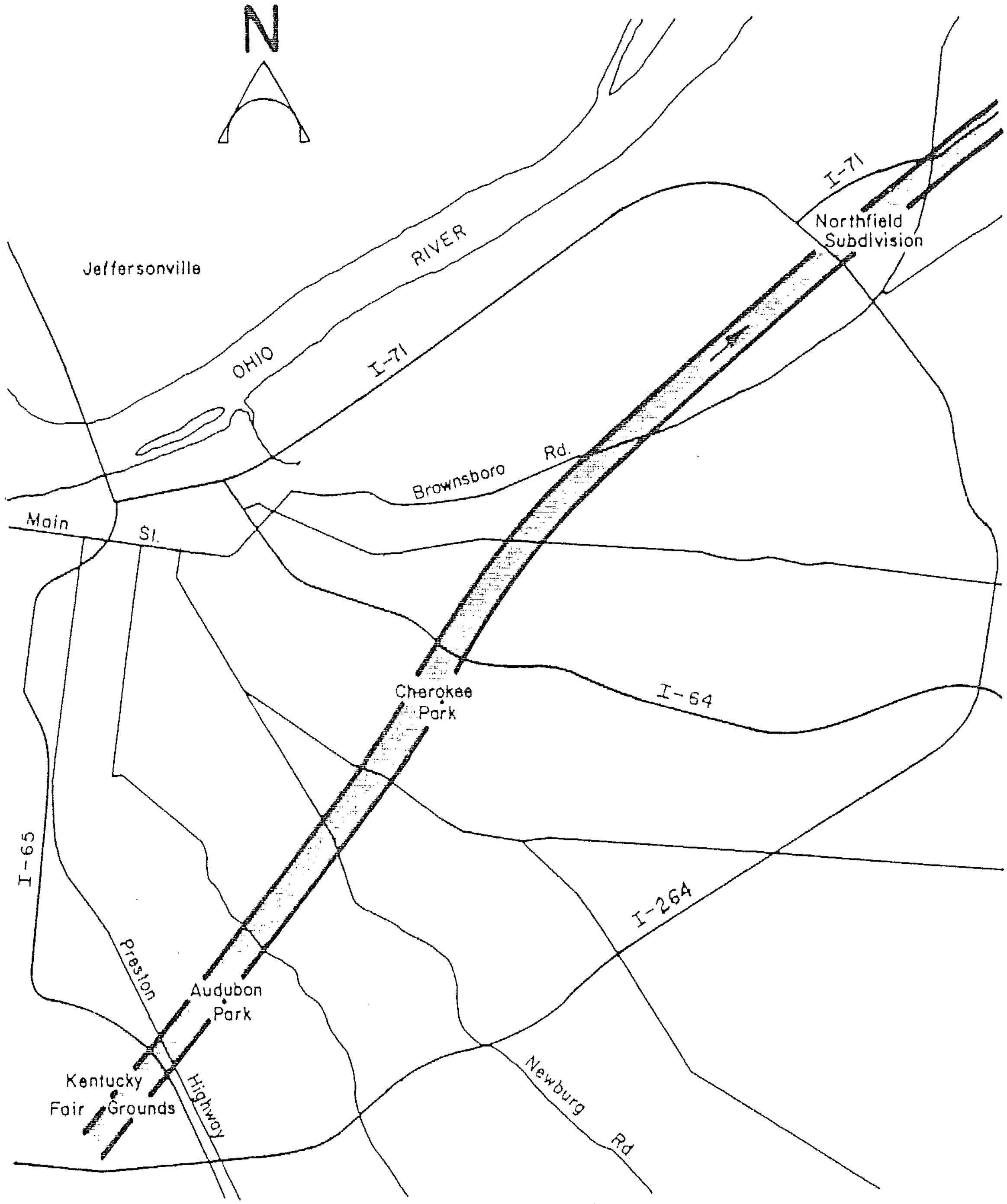


FIGURE 70. LOUISVILLE STORM PATH. The storm path averaged 660 ft wide and was 10 mi long. Most of the damage was to residences. (Copyright (C) 1974, The Louisville Courier-Journal)

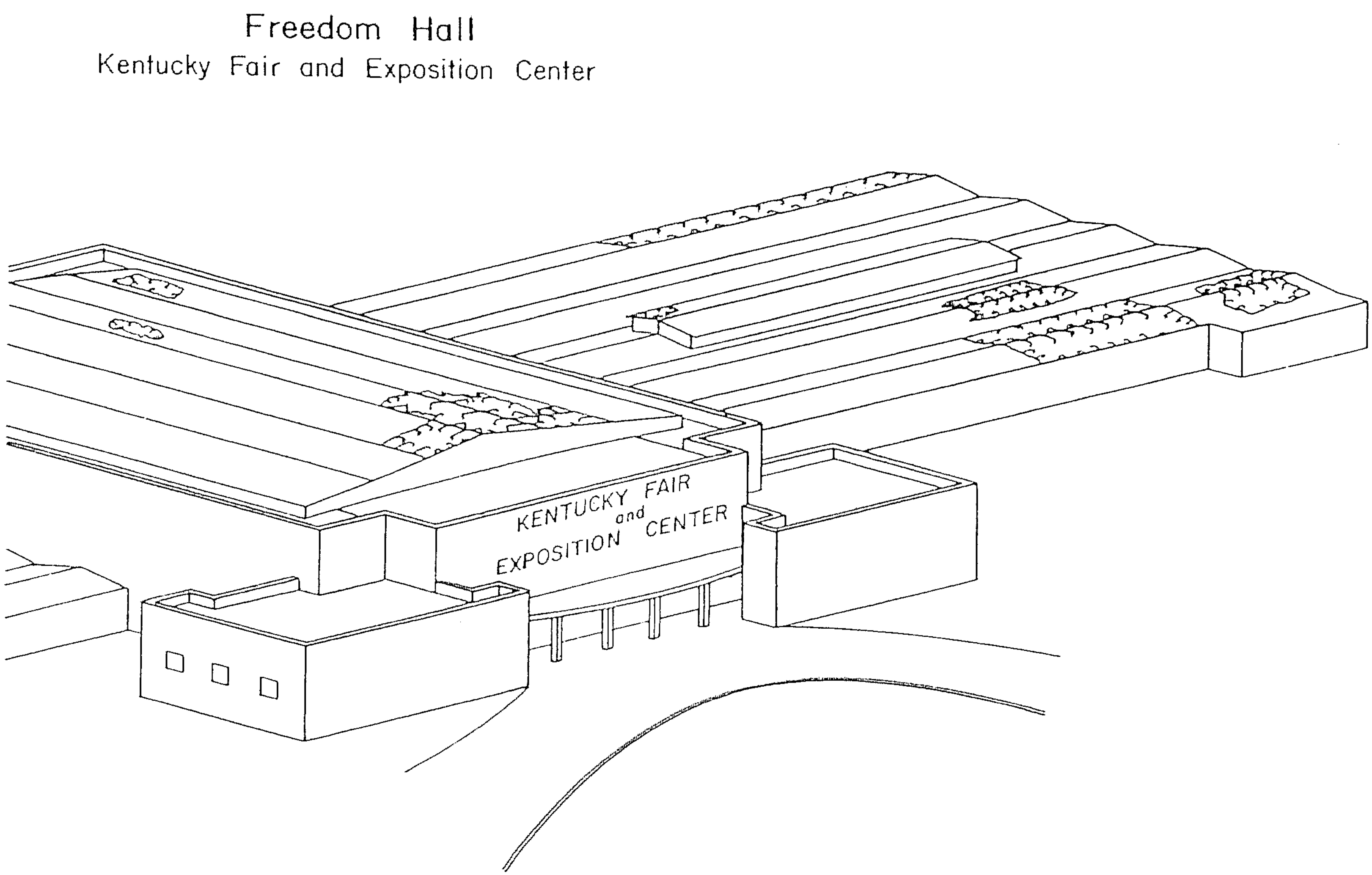


FIGURE 71. KENTUCKY FAIR AND EXPOSITION CENTER. The shaded areas show locations of roof damage to Freedom Hall and the East Wing.

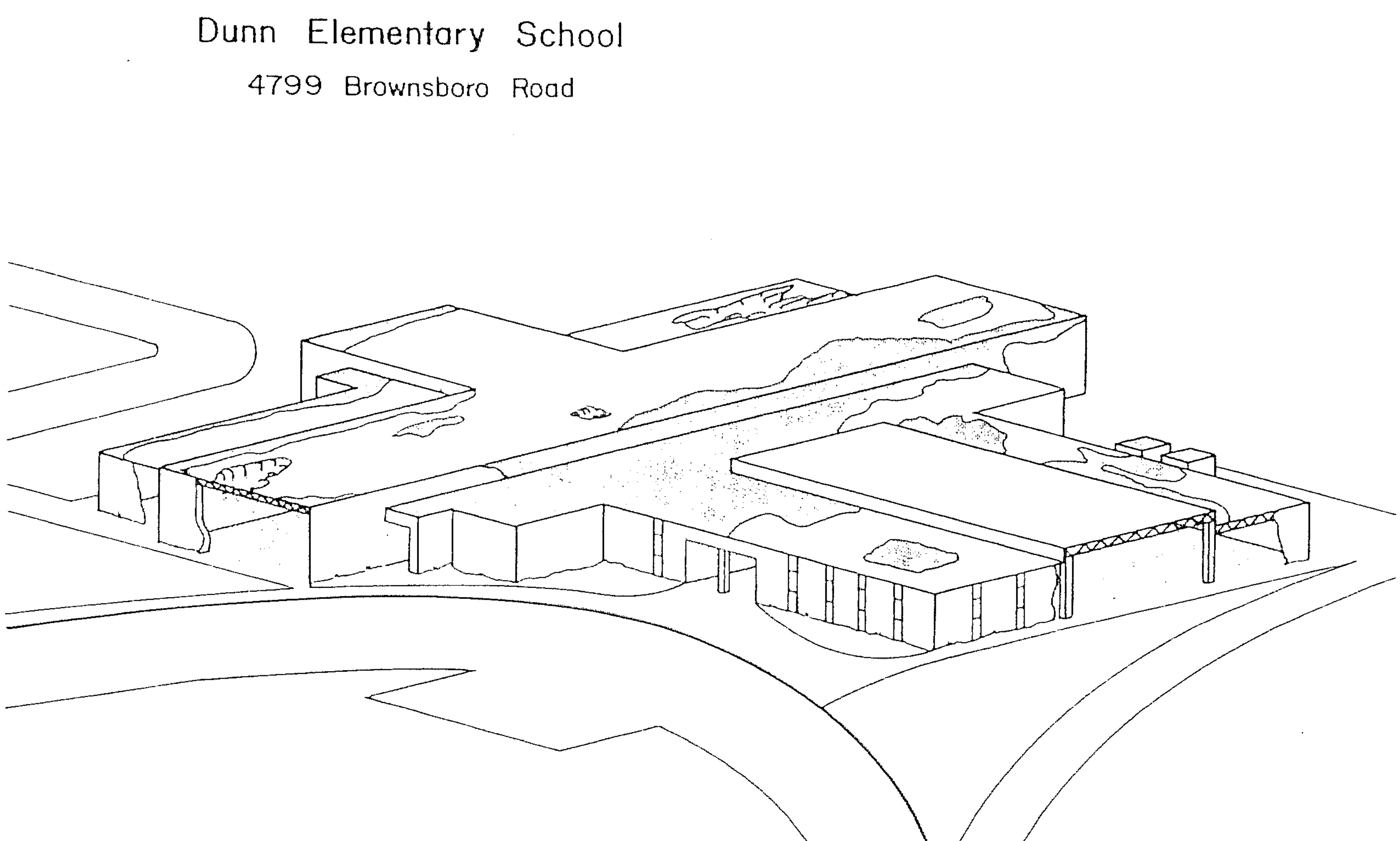


FIGURE 72. SCHEMATIC DRAWING OF DUNN ELEMENTARY SCHOOL. The view is looking southwest. The shaded areas indicate damage.

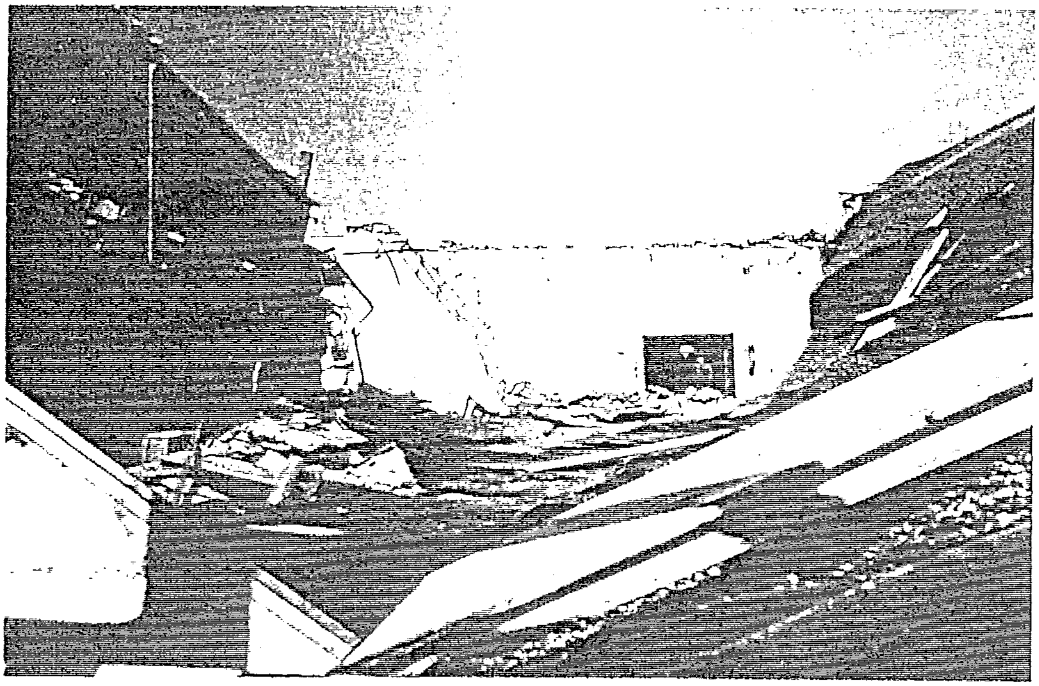


FIGURE 73. CHENOWETH ELEMENTARY SCHOOL. Progressive collapse of roof was precipitated by the toppling of an 8 ft incinerator chimney. Debris from chimney can be seen in background near wall.

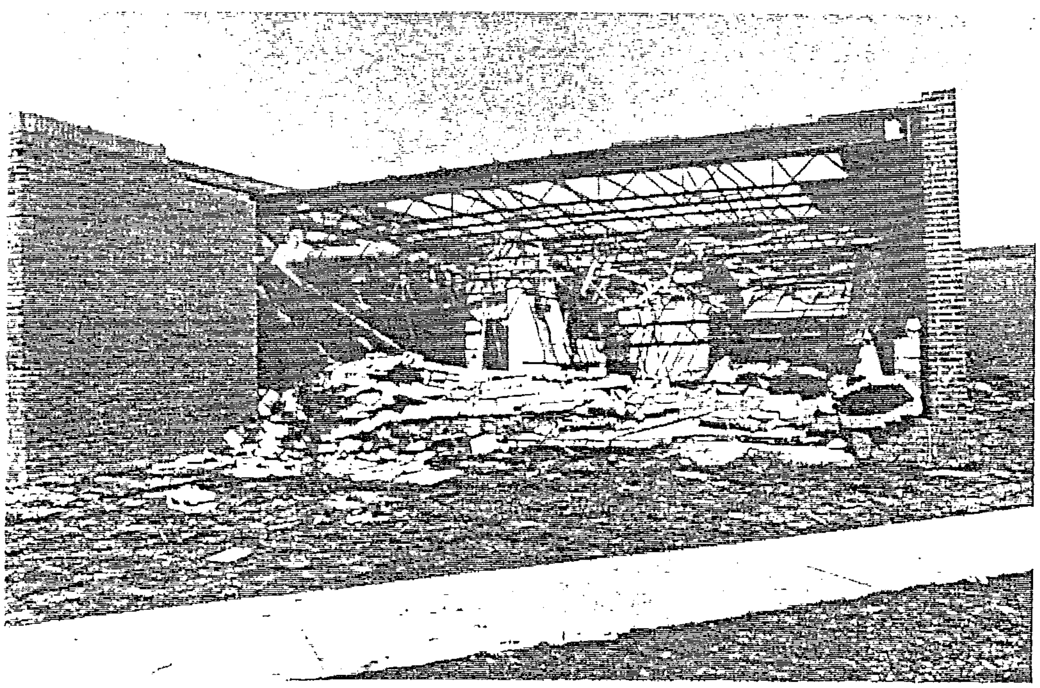


FIGURE 74. WINDWARD WALL FAILURE AT DUNN ELEMENTARY SCHOOL. Note the lack of anchorage at the roof level and across the masonry control joint.

FIGURE 75. MAP SHOWING TORNADO PATH THROUGH BRANDENBURG, KENTUCKY.

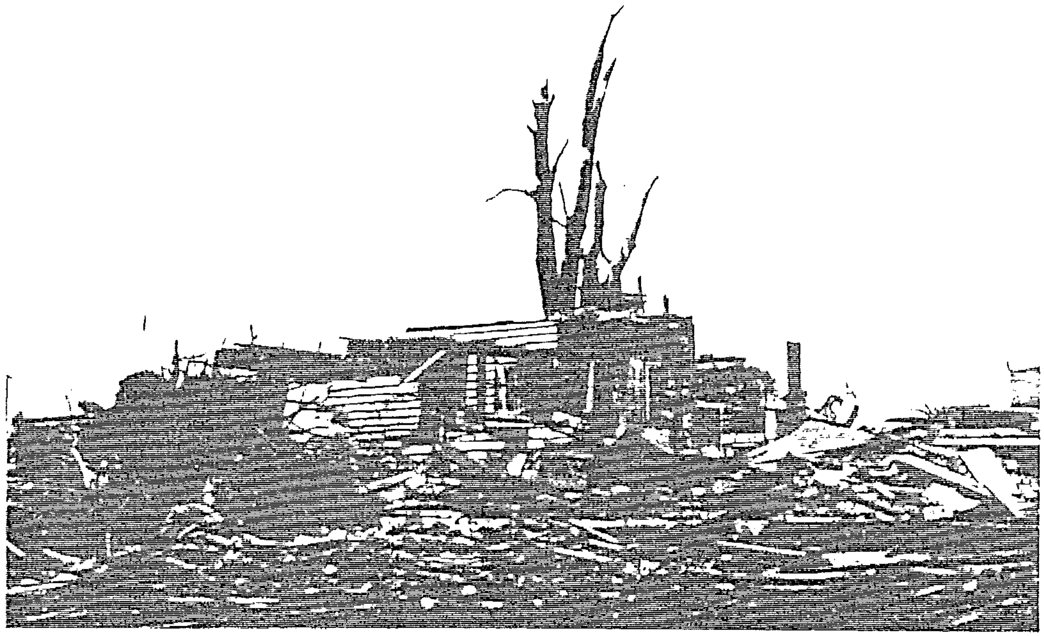


FIGURE 76. DAMAGED RESIDENCE IN BRANDENBURG. The damage shown here is typical of that to a well-constructed residence. Note the uprooted tree in the foreground and the tree stripped of its branches in the background.

FIGURE 77. RURAL ELECTRIC COOPERATIVE HEADQUARTERS. This view, looking northeast along the damage path, shows the overall view of the storage yard. Note the many potential tornado missiles.

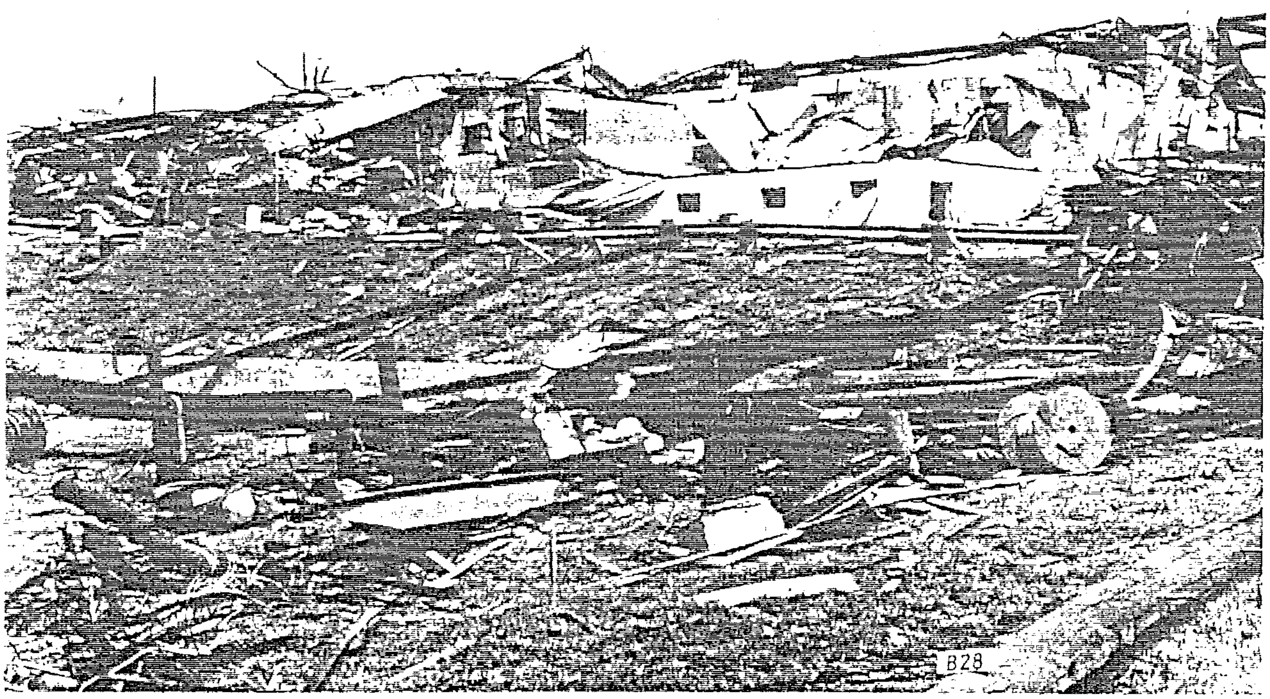


FIGURE 78. REC HEADQUARTERS. The utility poles were stored on the rack in the foreground. Although in an ideal position to become airborne, the poles did not move beyond what is shown in the photo.

VIII. TENNESSEE

Beginning in the early afternoon on April 3, 1974, thunderstorms in this State produced a number of reported tornadoes which killed a total of 58 persons. Dr. Fujita and his associates located 20 tornado tracks as shown in Figure 79. The hardest hit populated areas were Cookeville, Cleveland, and Etowah. Ground observations were limited to two tornado tracks: Track 1 which passes through the towns of Cleveland and Etowah, and Track 2 in the south-central part of the State. Track 2 originates in Alabama and is uninterrupted for approximately 110 miles. Most of the damage caused by these storms was sustained by residences, small businesses, and high voltage transmission line towers.

Tornado Track 1

This storm which killed four persons originated at approximately 3:00 P.M. just south of Cleveland and stayed on the ground from Cleveland to past Etowah, a distance of about 25 miles; the tornado damage path was about 1000 ft. wide; the translational velocity of the tornado was estimated to be 50 mph; and maximum windspeeds in this storm are estimated to be in the 75-100 mph range. The storm primarily damaged residences and small businesses.

Tornado Track 2

This storm originated approximately ten miles west of Moulton, Alabama at about 6:30 P.M. and the attendant tornado which killed 16 persons stayed in continuous contact with the ground from this point to south of Manchester, Tennessee--a total distance of 110 miles. The translational speed of this tornado was estimated to be 45 mph; the damage path varied in width from 2000 to 3000 ft.; and maximum windspeeds in this storm are judged to have been in the 150-175 mph range. The tornado appeared to be just as intense near its termination as at its origin. The storm damaged residences, small businesses and transmission line towers.

Transmission Line Towers

The Tennessee Valley Authority (TVA) lost approximately 100 transmission towers in Tennessee and Alabama. Officials at TVA indicate that the towers were designed to resist wind velocities up to 100 mph. In many tower failures it was obvious that only one or two towers were in the direct path of the storm, but because of tower to tower connections, several towers on either side of the tornado path also failed. It is interesting to note that failures in almost every case were related to the buckling of framing members or to the shearing of members across bolt holes.

Indicated Additional Work in Tennessee

Extensive ground documentation work was not accomplished in Tennessee, although the 20 tornado tracks and 58 deaths are indicative of a considerable amount of damage. A secondary effort should be made to assemble a more complete picture of Tennessee tornado damage. This could be accomplished through newspaper accounts, photographs taken by governmental agencies known to have been active in the area (e.g., FDAA, U.S. Corps of Engineers), and additional site visits. In addition, the 110 mile long tornado track which began in Alabama might provide valuable information on tornado characteristics as functions of time and terrain. Data on tree damage and structural damage along the tornado path are available.

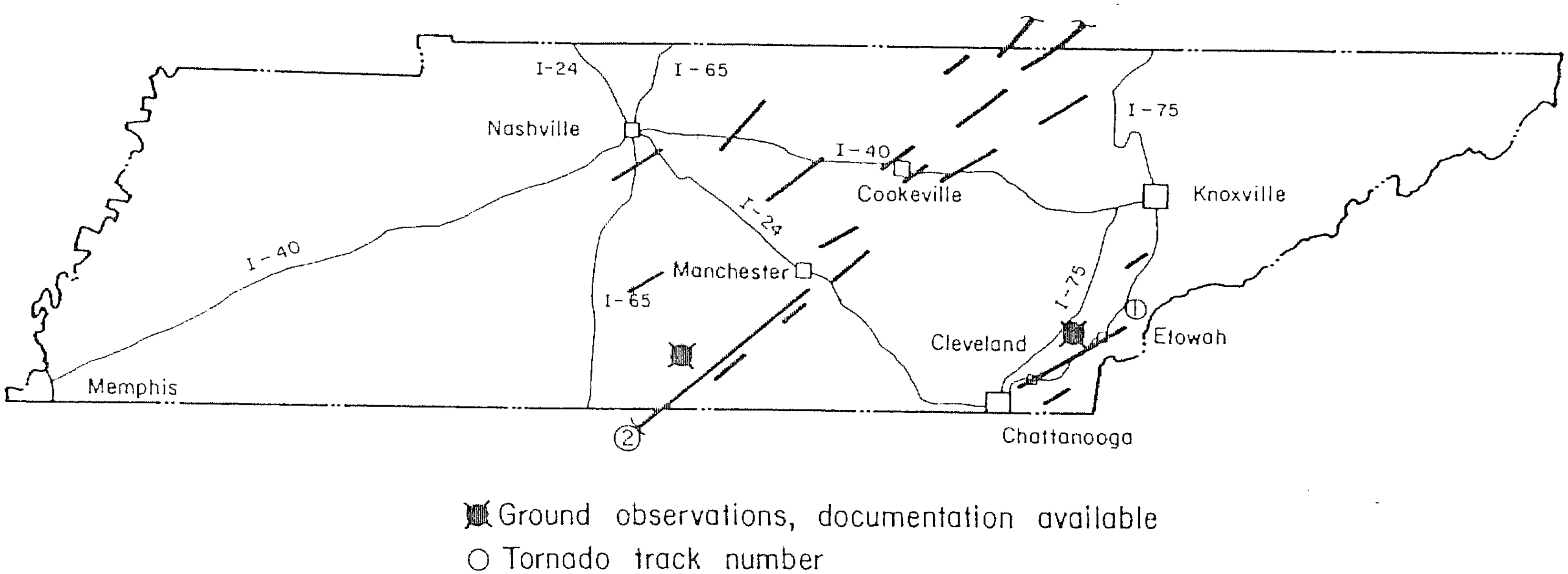


FIGURE 79. TORNADO TRACKS IN TENNESSEE. Tracks established by Fujita.

IX. NORTH CAROLINA

Three tornado tracks have been located in the southwestern corner of this State; these known tracks are shown in Figure 80. Two of the tornado tracks are continuations of the tornado tracks that originated in Georgia. The total death toll in tornadoes of April 3 in the State of North Carolina was reported to be five persons. One of the tornadoes did considerable damage in the town of Murphy, population 2500.

Murphy, North Carolina

The storm that hit Murphy in Cherokee County at 9:25 P.M. was a continuation of the storm that originated near Blue Ridge, Georgia. The total length of the tornado track is in excess of 30 miles. The track path width varied between 1000 and 1600 ft. The storm west of the town of Murphy appeared to be 10-15 ft. off the ground in some areas. Observations of damage to residences and small businesses indicate maximum windspeeds in this storm to be in the 125 to 150 mph range.

Indicated Additional Work in North Carolina

Significant features of the tornado which originated near Blue Ridge, Georgia, and extended into North Carolina include the terrain following character of the winds and the elevations over which the tornado passed. Photographs of tree damage and windspeed estimates derived from structural damage investigations might be analyzed and correlated to learn more about the influence of topography on the behavior of tornadoes.

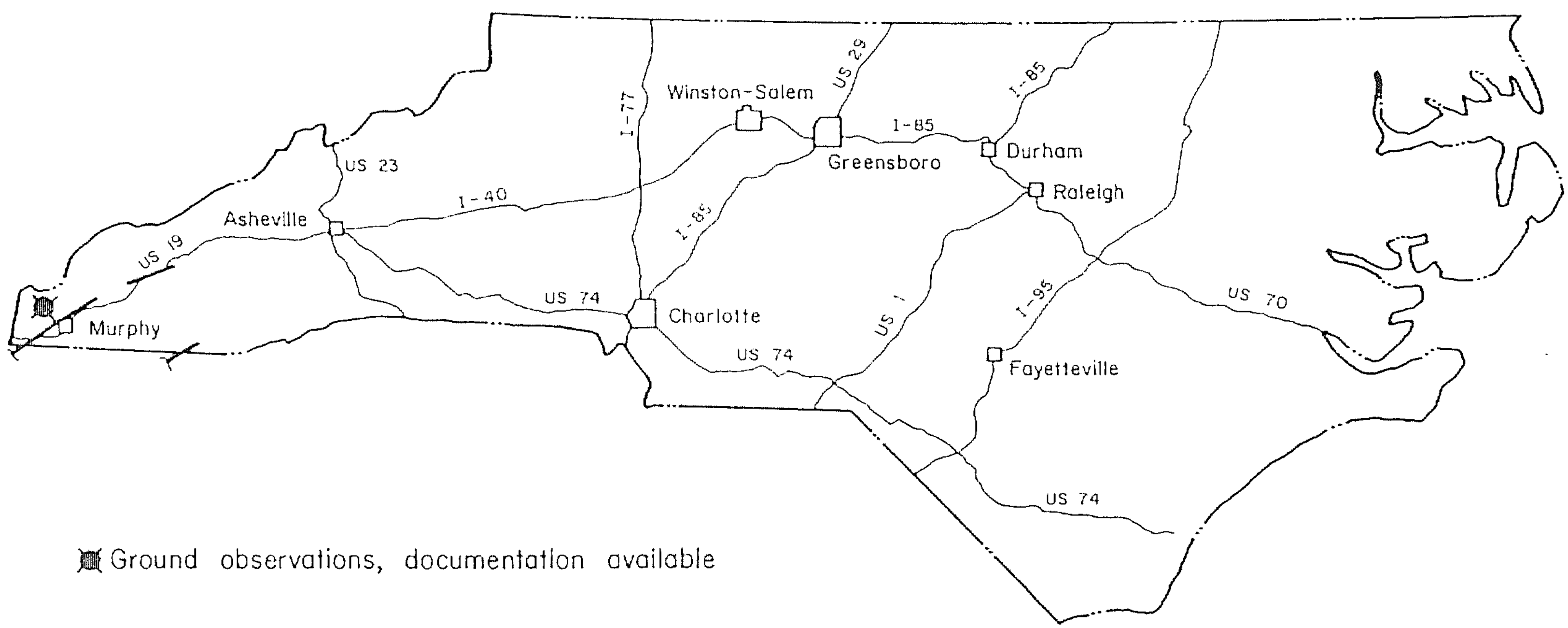


FIGURE 80. TORNADO TRACKS IN NORTH CAROLINA. Tracks established by Fujita.

X. ALABAMA

On the evening of April 3, 1974 four individual tornadoes struck northern Alabama. A total of 69 persons were killed and 350 were injured. Areas hardest hit were Jasper, Moulton, Huntsville and Guin. Damage investigators from Texas Tech and Auburn Universities made both ground and aerial surveys of all four tornado tracks. Approximate tornado track locations are shown in Figure 81.

Tornado One

This storm originated approximately 10 miles west of Moulton, Alabama, in Lawrence County at approximately 6:30 P.M., stayed in continuous contact with the ground through Lawrence County, crossed the Tennessee River south of Athens, remained in contact with the ground through Limestone and Madison Counties in Alabama, and crossed the Tennessee border north of Hazel Green. The storm continued in Tennessee until it lifted at Tullahoma. Total distance on the ground was approximately 110 miles. The storm had a translational velocity of approximately 45 mph and a path width that varied between 0.4 and 0.6 mile. Ground observations of damage to structures in the path--primarily residences, commercial buildings and transmission towers--indicated maximum windspeeds in the range 160-180 mph.

Tornado Two

This storm originated on the ground in the path of the first tornado just south of Athens in Limestone County at approximately 7:30 P.M. The path is located a maximum of two miles south of storm number one in Limestone and Madison Counties. It was on the ground for approximately 27 miles before lifting southwest of Hazel Green in Madison County. The storm had a translational velocity of approximately 40 mph and a path width that varied from 0.3 to 0.5 mile. Ground observations of damages to structures--primarily residences, mobile homes, small businesses and transmission towers--indicated windspeeds comparable to Tornado One (160-180 mph).

Tornado Three

This storm originated on the ground approximately 5 miles north of Aliceville in Pickens County, stayed in constant contact with the ground from Aliceville into the city of Jasper. Between Jasper and Cullman the storm did lose contact with the ground for 200-300 yards. The storm finally lifted about 10 miles northeast of the city of Cullman, and at that point had been in contact with the ground for approximately 110 miles. The storm had an estimated translational velocity of 60 mph and a path width which varied from 0.2 to 0.6 mile. Ground observations of damages to structures--including the Walker County Courthouse in Jasper and several other substantial structures in the cities of Cullman and Jasper--indicate that windspeeds were in the 160-180 mph range.

Tornado Four

This storm originated approximately 14 miles north of Columbus, Mississippi, and stayed in constant contact with the ground through Guin, across the Bankhead National Forest, across the Tennessee River, and through Huntsville. It finally lifted just north of Swaim, Alabama. The storm covered a distance of approximately 156 miles. The translational speed was approximately 40 mph. Its path width was quite erratic through its total length, varying from 1800 to 3000 ft. Observations made of damaged structures--primarily residences and small businesses--indicated windspeeds in the 160-180 mph range.

Engineered Structures

Very few engineered structures were in the paths of the four storms. Damage to the Walker County Courthouse and Fire Station in Jasper, several buildings on the Redstone Arsenal, a school in Huntsville, and numerous electric transmission towers are discussed below.

Walker County Courthouse, Jasper, Alabama

This relatively new structure is a three-story steel framed building with a basement partially above ground (Ref. Figure 82). The floors are of reinforced concrete pan joist construction. The pan joists are 8.5 in. deep, 5 in. wide and are spaced at 25 in. on centers. The floor deck is 2.5 in. thick. At the roof, steel trusses spanned 64 ft. across a courtroom. The trusses rest on W 6 x 20 columns, which are spaced at 14 ft. on centers. The walls are constructed of 8 in. solid brick and 4 in. of stone. The walls appeared to tie into the steel columns by extending the brick wall between the flanges to the web. The wall height in the area of the courtroom was 21 ft. The roof trusses extend 2.5 ft. above the top of the wall. The wind forces caused an 11 in. permanent deflection of the roof with respect to the third floor of the building. The roof elevation was 55 ft. above ground. On the side of the structure exposed to tornado impact, part of the second story and all of the third story were higher than adjacent buildings. It was determined that a minimum wind velocity of 130 mph would be required to produce the 11 in. deflection; this computation was based on the following assumptions:

(1) The columns at the third floor level were fixed and were unrestrained at the roof.

(2) The entire wind force on the wall was transmitted to the columns.

(3) A wind exposure corresponds to open country and no rebound occurs.

This velocity would be at elevation 43 ft. above ground. Connecting to 30 ft. using 1/7 power law gives a minimum (lower bound) wind velocity to cause the damage of 124 mph.

Fire Station, Jasper, Alabama

The Jasper City Fire Station was a relatively new structure designed in accordance with the Southern Building Code (windload requirements: 10 psf; i.e., 63 mph at 30 ft.). The roof over the damaged area (the apparatus bays) consisted of a built up roof over metal deck and open web steel joists. This structure failed as a result of the wind blowing the large overhead doors inward. The interior pressure resulting from this failure, combined with the typical negative pressure on the flat roof and side walls, caused the roof to be stripped from the frame and induced the outward collapse of the side walls.

McDonnell Elementary School, Huntsville, Alabama

This one-story steel framed building had non-loadbearing exterior walls constructed of concrete blocks and brick. The roof system consisted of a built up roof over 2 in. poured gypsum deck and open web steel joists. Four in. diameter pipe columns located inside the exterior wall supported the roof system. The only damage to occur from the estimated 110 mph winds was that a large portion of the roof deck was stripped from the open web steel joists.

The exterior walls did not collapse even though they were exposed to wind forces in excess of the design value (63 mph). The reason they did not fail was apparently the exterior wall configuration (see Figure 83). No segment of the exterior wall was greater than 16 ft. in length. In addition, there was a continuous bond beam at the top of each wall.

Transmission Towers

The Tennessee Valley Authority (TVA) lost approximately 100 transmission towers in Alabama and Tennessee. Officials at TVA indicated that the towers were designed to resist winds up to 100 mph. In many instances it was obvious that only one or two towers were in the direct path of the storm. However, because of tension in the conductor cables a "domino" effect caused adjacent towers to fail. Almost all failures were related to buckling of framing members and tensile failures across bolt holes. Some foundation anchorage failures were also observed.

Residences

Numerous residences--including apartments, individual homes and mobile homes--were destroyed in Alabama. The greatest number of homes were destroyed in the Guin, Athens (rural) and Huntsville areas. Most of the homes which were totally destroyed were slab on grade construction. In general, the degree of damage to a residence was dependent on how well the roof, walls, floor and foundation were tied together. The location of the residence relative to the path of the storm was also an important factor. In apartments and individual residences that suffered severe damage, there was, in almost every instance, a haven that would provide safety to the occupants. This was normally an interior hallway or closet. Mobile homes in the direct path of these storms were demolished. The only haven for a mobile home owner is a storm shelter exterior to the mobile home or some permanent structure such as a school or church.

Tree Damage

Miles of tree damage were observed from both the ground and air in Alabama. One of the objectives of the investigations was to determine if a correlation between observed tree damage in a forest and damage to structures could be made. Although the study is not complete, the extent of damage in a forest is clearly dependent on a number of factors which must be taken into account when attempting to make windspeed estimates from damaged forests (Ref. Figure 84).

(1) The variety of tree is probably the most significant. The variety determines the root system (deep roots or shallow roots). The surface area exposed to the winds (conifer versus deciduous) and the relative flexibility of the trunk and branches.

(2) The soil conditions determine if trees are likely to be uprooted or snapped off.

(3) The terrain variation in elevation affects the degree of damage to trees.

(4) The damage patterns can be used to identify areas of maximum wind velocity if terrain effects are not also present.

The wind velocity appears to be much higher in valleys and hollows of hilly and mountainous terrain. The tornado winds generally conformed to the contour of the earth surface for changes in ridge and valley elevations of 500 ft. or less. Changes in elevation greater than 500 ft. generally resulted in tree damage in the valleys and the windward sides of mountains or hills. Leeward sides usually were unscathed. The tornadoes appeared to lift over ridge lines and then set down again in valleys. Channeling effects in valleys were also observed.

Comparisons of observations from the ground and from the air indicate that air observations tend to minimize the effects of wind damage. Air observations are quite valuable, but only if correlated with ground observations.

Missiles

Tornadoes Number One and Two generated a number of missiles in Limestone and Madison Counties in the Athens-Decatur-Huntsville area. The missiles were primarily small timbers, concrete block, etc. In this area automobiles received considerable damage and could be found several hundred feet from their original locations. Observations of automobile bodies indicated they were rolled or tumbled to these locations. Tornado Three in Jasper, Alabama, created a number of timber missiles as the result of destroyed roofs. A 2 in. by 6 in. timber, 8 ft. long penetrated the exterior wall of the municipal auditorium at a height of 25 to 30 ft. above ground. Storm Number Four passed near a lumber yard in Guin (Ref. Figure 85). Few missiles were generated in this instance (for contrasting example see discussion on Brandenburg, Kentucky). Several wood bundles were broken, but the distance traveled by the timbers was less than 100 ft. A small bus in Guin was moved 330 ft. from its original position. The amount of damage incurred by the body indicated that the bus rolled this distance.

The generation of missiles in the Alabama storms were basically the same as in other states. No examples of "incredible" missiles were found.

Additional Work in Alabama

Additional work with the data obtained from Alabama storm damage investigation is needed in several areas.

(1) Research to determine design criteria and construction methods to decrease the number of tower failures from extreme winds. (This study must relate to economics.)

(2) Further surveys of rural areas to develop a better correlation between observed tree damage and structural damage. Determine if reliable windspeed estimates can be made from observed tree damage, especially when the damage is viewed from the air.

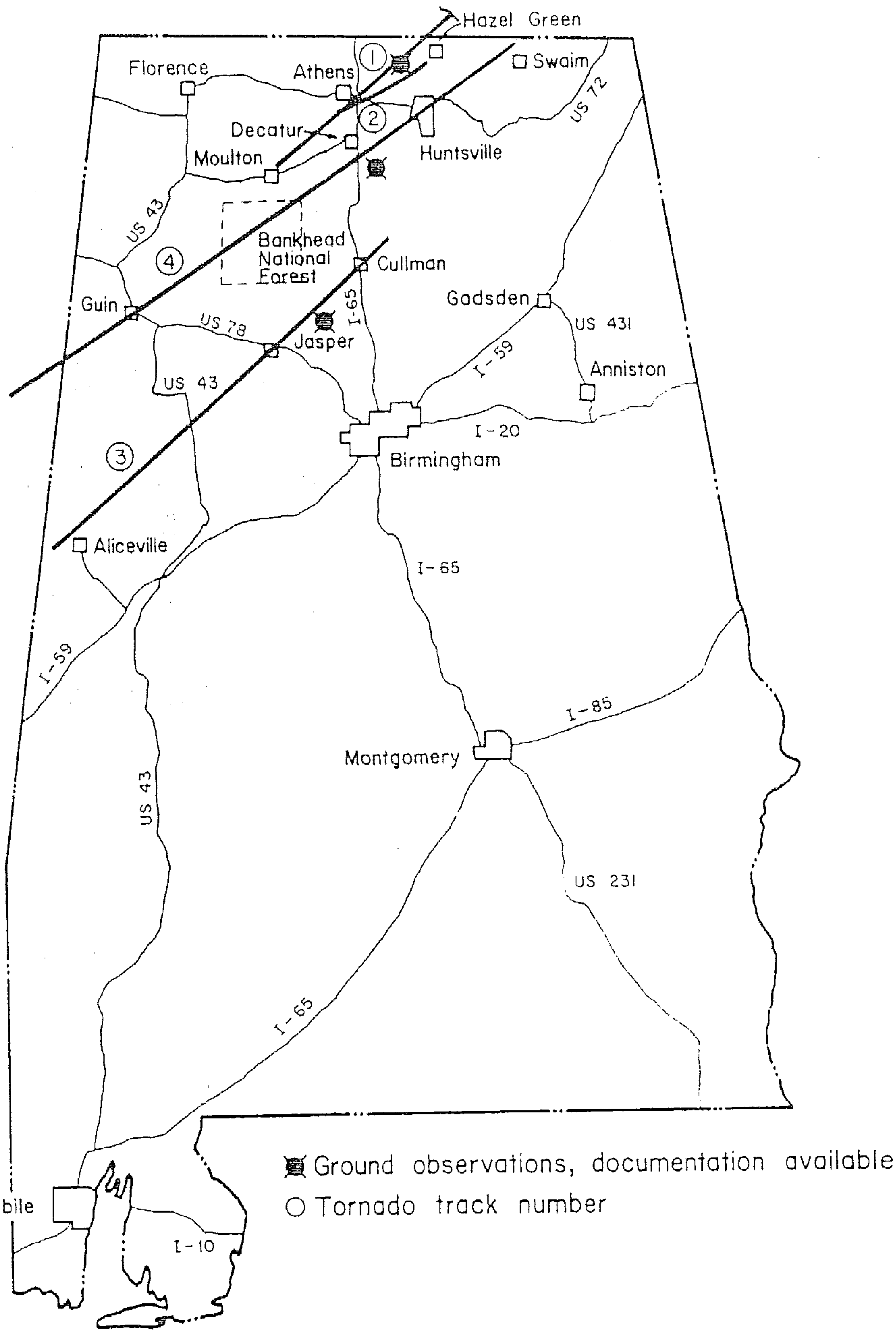


FIGURE 81. TORNADO TRACKS IN ALABAMA. Tracks were established by Fujita.

FIGURE 82. WALKER COUNTY COURT HOUSE, JASPER, ALABAMA. Force of winds caused an 11 in. permanent deformation of the steel frame at the third floor. (photograph courtesy B. R. Manning, Auburn University-PASC)

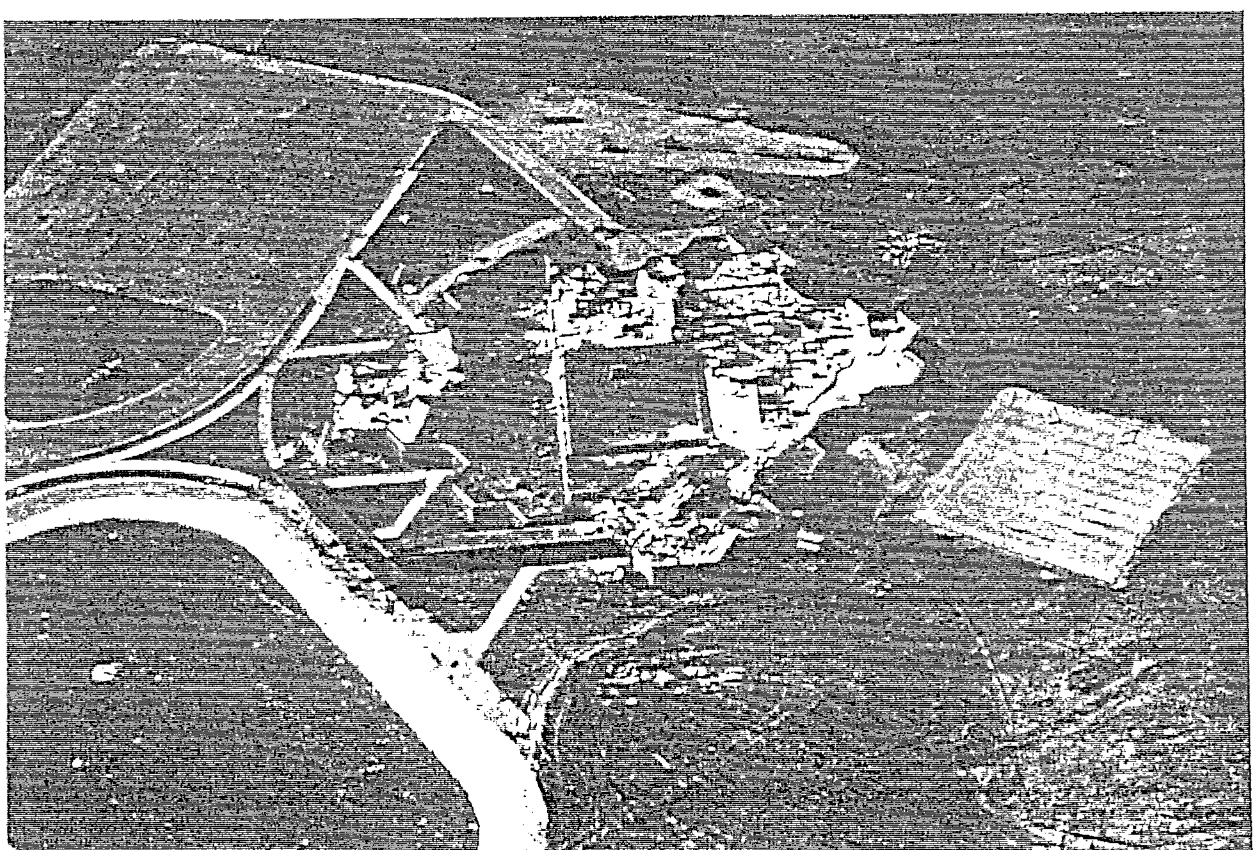


FIGURE 83. MCDONNELL ELEMENTARY SCHOOL, HUNTSVILLE, ALABAMA. Short exterior wall segments, cast in place bond beams and vertical reinforcement in the walls contributed to favorable performance of this structure. Damage was restricted to the roof. (photograph courtesy City of Huntsville Police Department)

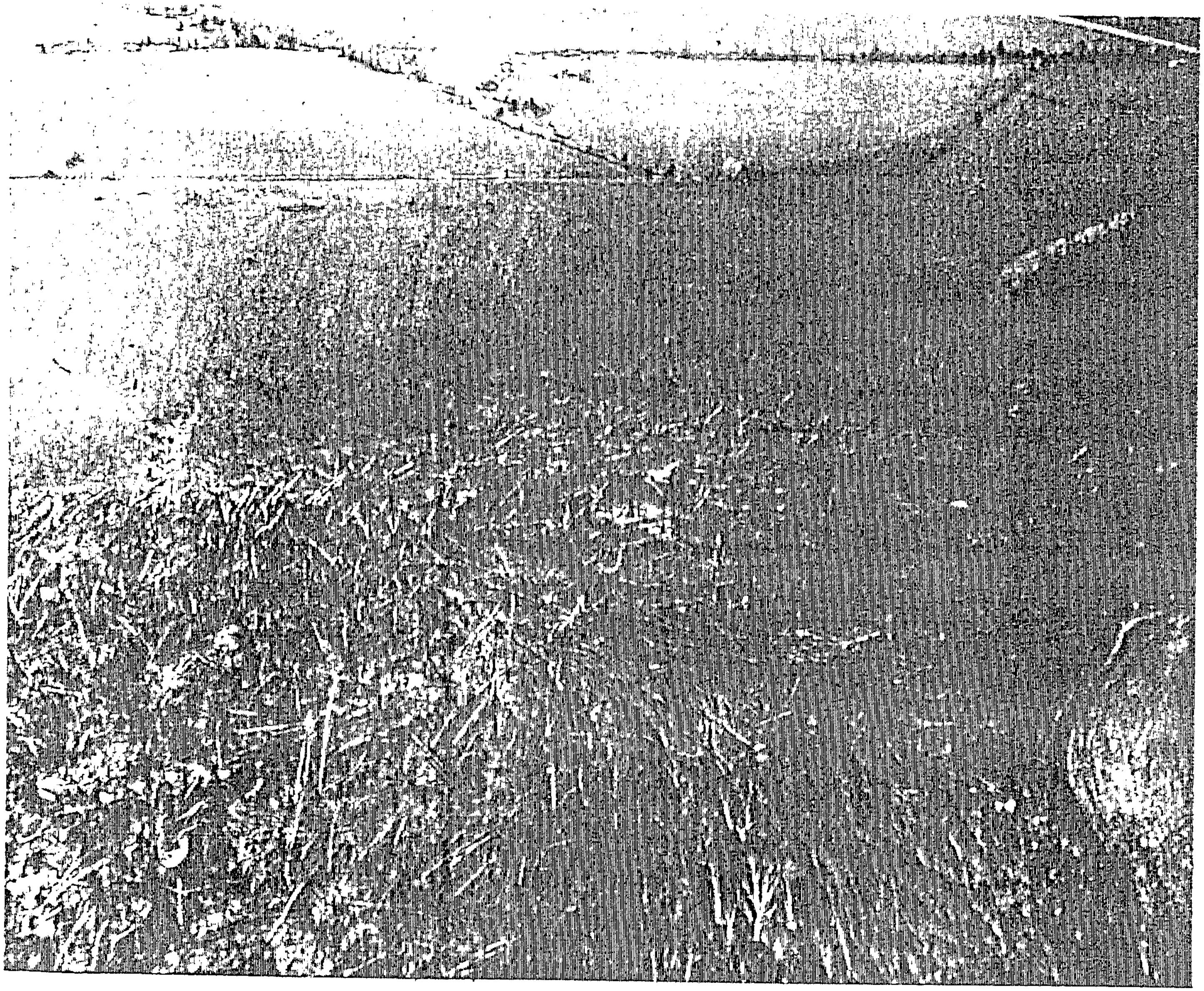


FIGURE 84. TREE DAMAGE NORTHEAST OF MOULTON, ALABAMA (TORNADO NO. 2). Note that some trees are snapped off while others are uprooted. (photograph courtesy B. R. Manning, Auburn University-PASC)

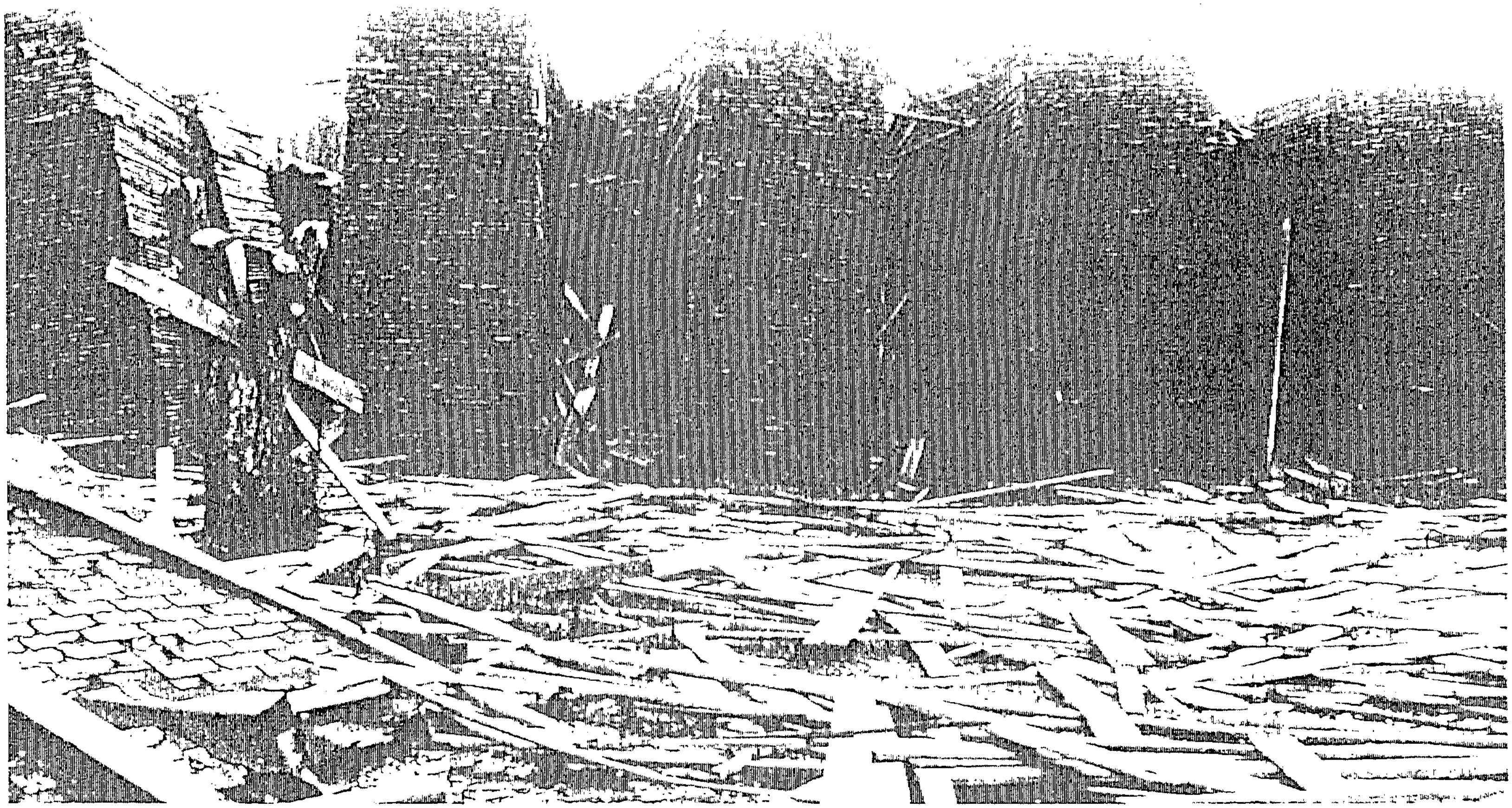


FIGURE 85. LUMBER STORAGE YARD, GUIN, ALABAMA. Although some bundles were broken, individual pieces of lumber did not travel more than 100 ft. (photograph courtesy B. R. Manning, Auburn University-PASC)

XI. GEORGIA

There were numerous tornadoes reported in this State during the afternoon, evening, and night of April 3, 1974. Dr. Fujita and his associates have located five separate tracks shown in Figure 86. The tornadoes which killed 16 persons traversed primarily rural areas, demolishing residences and trees. There were no heavily populated areas or engineered structures in the paths of the storms. The storms were of low intensity, relatively narrow and short, but showed an unusual characteristic of staying in touch with the ground while passing over ridges and valleys. Exhibition of this characteristic warrants further detailed investigation to establish the nature of tornado movement in mountainous regions.

Track 1

This storm originated three miles south of Blue Ridge (see Figure 86) at approximately 3:00 P.M. and stayed on the ground for approximately 18 miles. Maximum windspeeds in this storm are judged to be in the range of 90 to 120 mph. The width of the damage, restricted to residences, farm buildings, and a large number of trees, varied between 500 and 1000 ft. Near Blue Ridge the damage was more severe than near the terminal point of the track.

Track 2

This storm passed north of Resaca at approximately 7:45 P.M. and subsequently passed through Chatsworth. The storm stayed in contact with the ground for approximately 33 miles along the path shown in Figure 86. Translational velocity of the storm was estimated to be 45 mph. Observations of damage indicate that maximum windspeeds were in the range 130 to 160 mph. The width of damage, sustained primarily by residences and trees, varied between 500 and 1500 ft. Fallen trees around an undamaged mobile home in Chatsworth can be seen in Figure 87. The mobile home was double wide and strapped to the ground, which made it more wind resistant. The storm path went over several ridge lines in the Cohutta National Park. Some tree damage occurred at elevations above 2500 ft. This storm had two characteristics which warrant further study: (1) crossing of ridges and valleys while continuing to stay in touch with the ground, and (2) indications of less severe tree damage at higher elevations when compared to tree damage at lower elevations.

Track 3

This storm which killed nine persons originated four miles south of Holcomb at about 8:30 P.M. and terminated near Emma (see Figure 86). Maximum windspeeds are estimated to be in the range of 150 to 180 mph. The storm was in contact with the ground for approximately 14 miles.

Damage path width varied from 1500 to 2500 ft. Only residences and trees sustained damage in the path of this storm.

Track 4

This storm originated in northern Georgia at approximately 9:25 P.M. and traversed the Georgia border into North Carolina (see Figure 86) for a total path length of approximately 18 miles. The path width of the damage varied from 1000 to 1500 ft. The storm gave an impression of being 10-15 ft. off the ground in Georgia. The maximum windspeed estimate from examination of the damage is in the range of 120 to 150 mph. In this State the damage was sustained primarily by trees.

Indicated Additional Work in Georgia

Although this State experienced relatively few storms, the storms exhibited several unique characteristics. The following specific items are suggested for additional work in Georgia.

(1) The ability of tornadoes to stay in touch with the ground while traversing ridges and valleys should be evaluated using data from these storm tracks. Tree damage data have potentials for answering questions regarding behavior of tornadoes in mountainous regions.

(2) Comparisons of observations of damage from the air and from the ground in forest areas can be made from the data collected in this State. There were indications that observations from air can be misleading in judging windspeeds and the amount of damage which has accrued to trees in forests.

(3) More data should be obtained for this State to establish locations of individuals who lost their lives. Current data indicate that death rates were high in rural areas when compared to the size of population affected by the tornadic storms.

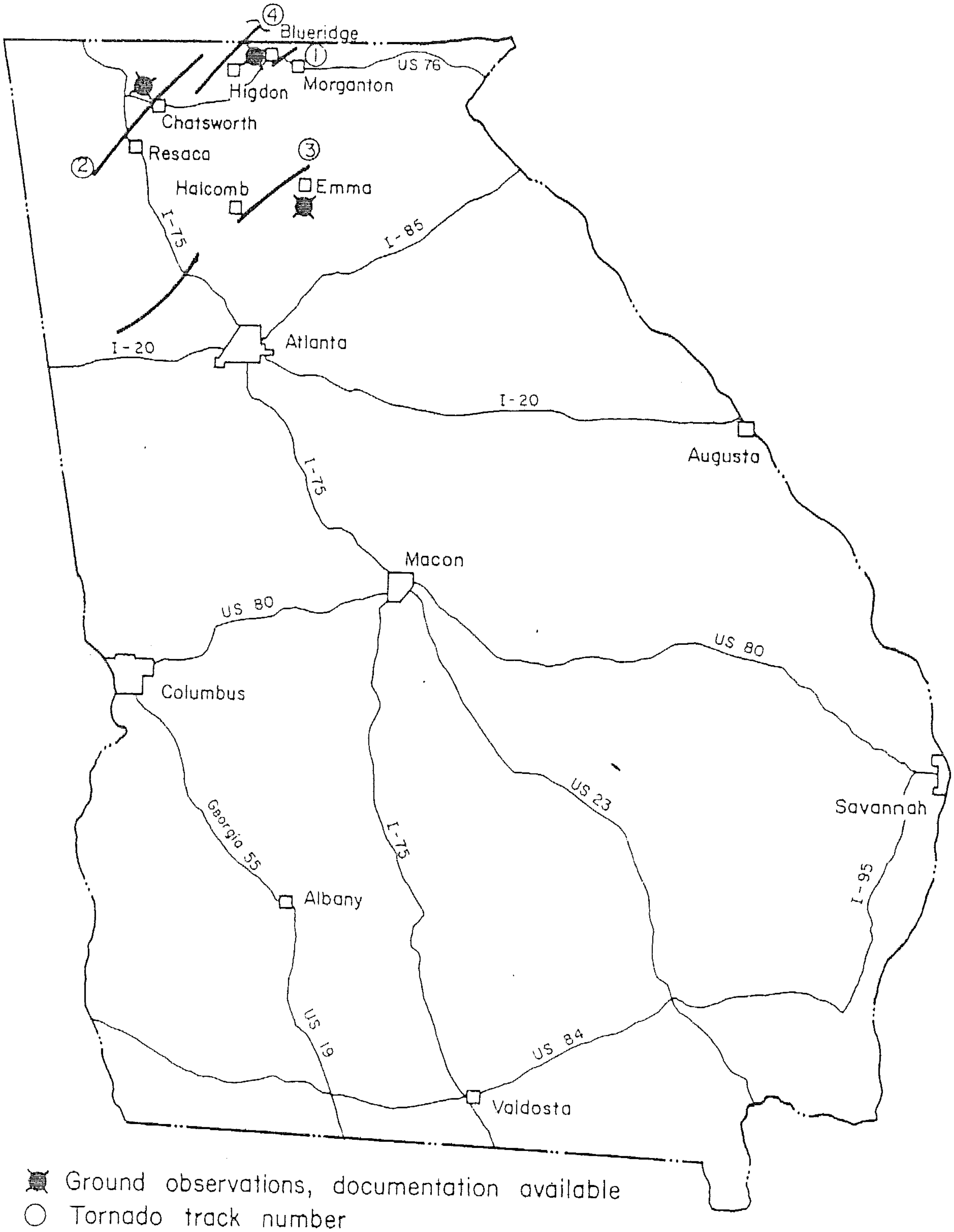


FIGURE 86. TORNADO TRACKS IN GEORGIA. Tracks were established by Fujita.

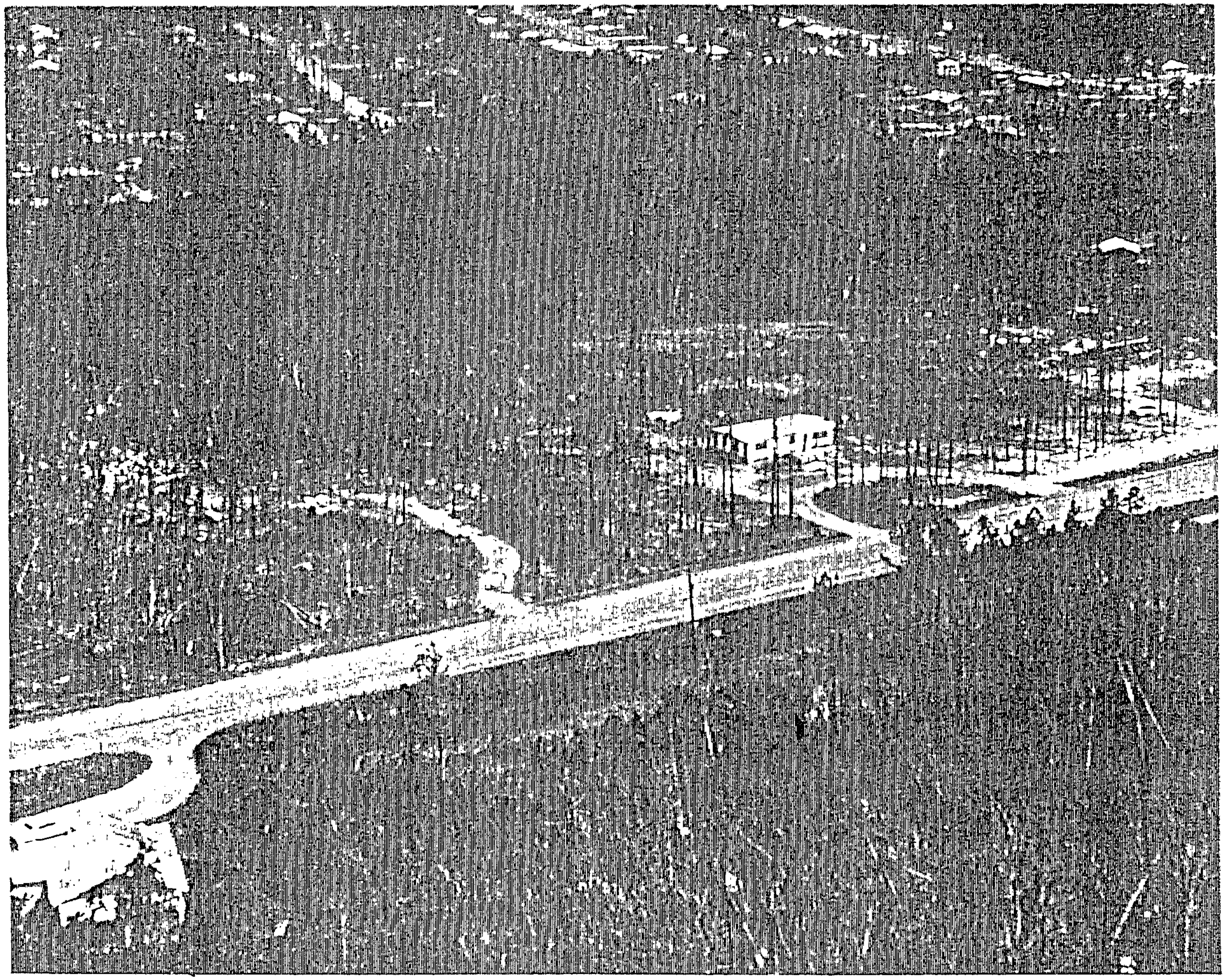


FIGURE 87. MOBILE HOME IN CHATSWORTH. This mobile home was double-wide and anchored to the ground. It did not sustain damage. There was considerable tree damage in the surrounding area. (photograph courtesy B. R. Manning, Auburn University-PASC)

XII. SUMMARY AND RECOMMENDATIONS

The overviews of storm meteorology and effects contained in this document serve to establish for the written record the nature and extent of the storms of April 3-4, 1974. Far more important, however, are two other benefits gained through this effort. First, this effort serves as an initiation point for the conduct of detailed evaluations of specific wind damage events--evaluations which will contribute both to the scientific understanding of tornadoes and to the engineering of structures and warning systems which will achieve disaster mitigation. Secondly, this document contains specific recommendations regarding future detailed documentation, analysis, and systems engineering work which must be accomplished if knowledge regarding the effects of extreme winds is to be focused upon appropriate "implementers": government agencies, building code administrations, and professional practitioners.

General Observations

Several general observations can be made regarding storm effects. The observations must be classified as preliminary because detailed investigations of specific incidents have not been completed. It was considered important to list several of these subjective observations and opinions, selected from reports of the contributing investigators, because these comments may have a significant influence on the planning and conduct of future research and engineering efforts:

(1) Preliminary estimates of maximum ground level (30 ft. or less) windspeeds in the tornadoes which appear to be the most intense (such as the Xenia, Ohio and Brandenburg, Kentucky tornadoes) are in the range of 200 to 250 mph. No evidence has been found in the documented damage to lead investigators to expect that ground level windspeeds in excess of 250 mph occurred in the storms of April 3-4, 1974.

(2) The tornadoes damaged many engineered structures such as school buildings, water towers, railroad bridge spans, and public buildings. Thorough analyses of damage to engineered structures have potentials for contributing to the scientific understandings of windspeeds in tornadoes, as well as contributing significantly to understandings of the behavior of structures in extreme winds.

(3) Some of the tornadoes of April 3-4 exhibited unusual characteristics in that they stayed in contact with the ground while passing over ridges and valleys. In many instances, the influence of topographical features (such as hills up to 500 ft. above surrounding terrain) on the behavior of the tornadic storms seemed to be minimal.

(4) This 24 hour, record outbreak of tornadoes affected areas equivalent to one-half of the total tornado path area covered in the entire United States in an average year. Inclusion of tornado path areas from this time period in the available tornado track data of the past years may affect tornado strike probability computations in the corresponding specific areas of the country.

Specific Recommendations

At the end of discussions of damage within each state paragraphs are devoted to recommended additional work in the specific states. These discussions deal principally with structures, missile events, or other incidents that occurred within the states which warrant additional, detailed attention. The discussions of recommended additional work for each state are condensed and are listed below. In this list additional studies, evaluations, and actions which can be formulated at this time are also outlined. The list of specific recommendations is as follows:

(1) Specific schools in Indiana, Ohio, Kentucky, and Alabama (see appropriate state discussions for identification) should be evaluated in detail with respect to (a) failure modes as a function of building type, and (b) naturally occurring protected areas. This information should be used as the basis for extending recommended design practice concerned with the design of tornado resistant school structures.

(2) Specific structures (listed below) should be analyzed, in detail, to gain the best estimates possible regarding windspeeds which caused the damage and failure modes. This information should be employed as input to the scientific community that is concerned with tornado morphology, as well as to the engineering community concerned with designing structures for extreme winds.

(a) Twin Lakes High School, Monticello, Indiana

(b) Monroe Central School, Parker/Farmland, Indiana

(c) Penn Central Railroad Bridge, Monticello, Indiana

(d) Water Tower, Hanover, Indiana

(e) Xenia High School, Xenia, Ohio

(f) West Junior High School, Xenia, Ohio

(g) Furniture Manufacturing Plant and Missiles, Xenia, Ohio

(h) County Courthouse, Jasper, Alabama

(i) McDonnell School, Huntsville, Alabama

(j) Tree Damage, and Transmission Towers, Alabama-Georgia-Tennessee

(k) Windsor Curling Club, Windsor, Canada

(3) Detailed evaluations of the locations, circumstances, and causes of deaths of each of the more than 300 windstorm caused fatalities should be made. Such data will prove invaluable as an input to the development of shelter design criteria, warning system designs, and pre-disaster instructions to the public. Similar accountabilities of injuries requiring hospitalization should also be considered in planning this effort.

(4) The role of mobile homes in contributing to deaths and injuries, and to property damage totals, should be examined. Since a national trend toward this type of housing is clearly evident, attention should be given to the design of warning systems, tie down standards, and community shelters as applied to mobile home parks.