U.S. DEPARTMENT OF COMMERCE

WEATHER BUREAU

RESEARCH PAPER NO. 42

A Detailed Analysis of the Fargo Tornadoes of June 20, 1957

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FREDERICK H. MUELLER, *Secretary*
WEATHER BUREAU
F. W. REICHELDERFER, *Chief*

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A Detailed Analysis of the Fargo Tornadoes of June 20, 1957

TETSUYA FUJITA
University of Chicago, Chicago, Ill.

The research reported on in this paper has been conducted by the University of Chicago for the U.S. Weather Bureau under contracts Cwb 9231 and 9530.

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Partial presentations have been made at the following meetings:
National AMS, May 6, 1958, Washington, D.C.
National AMS, November 17–20, 1958, Miami Beach, Fla.
First Conference on Cumulus Convection, May 20, 1959, Portsmouth, N.H.
Second Conference on Precipitation, June 3, 1959, Woods Hole, Mass.

PREFACE

A few weeks after one of the tornadoes of June 20, 1957 leveled a part of the residential area of Fargo, N. Dak., Mr. Ferguson Hall of the U.S. Weather Bureau, Washington, D.C., visited our Department to show us a series of tornado pictures collected during his trip to the Fargo-Moorhead area. Not only were they unusually good in quality, they included moreover the greater portion of the rotating cloud from the base of which the tornado which hit Fargo dropped.

Impressed by the photographs, the author decided to make a complete analysis of the storm by collecting all available photographs from the local people. During three visits to the Fargo area he made photographic measurements and damage surveys in cooperation with Mr. Dewey Bergquist, WDAY-TV weatherman. As the research continued, the number of tornadoes, originally thought to be only three, was confirmed to be five. Each of them left a continuous damage path extending up to 10 miles. Further study also confirmed that these tornadoes were produced by a rotating cloud something like a miniature hurricane.

Using the abundant photographs—color, black and white, movie, and still—dimensions of the system from the tornado funnel to the entire rotating cloud were successfully triangulated. It became evident that the tornadoes in the Fargo area did not occur by chance but were the product of well organized conditions very favorable for tornado formation.

Animation of a series of charts showing the successive stages of the tornadoes and the rotating cloud resulted in a rather successful film. The test film projected on a screen was found to be capable of showing the features of the rotating cloud as it produced tornadoes one after another in a narrow zone extending across the North Dakota-Minnesota border.

Important results leading to future theoretical studies of tornadoes and their related systems were obtained. For instance, an intense vertical motion inside the ring-shaped wall cloud in rotation resulted in a convergence at the surface of as high as 3000×10^{-5} sec.$^{-1}$. It will be interesting to discover why such a high value of convergence is initiated and maintained in spite of the filling action taking place beneath the cloud base. Of interest also is the liquid water storage inside the rotating cloud, which was postulated from the existence of a high-pressure ring indicated by the two barograph traces.

The author will be very happy if this technical report is widely used by those who are interested in studying tornadoes, the most intense natural vortices on the surface of the earth.

ACKNOWLEDGMENTS

The research reported in this paper has been supported by the United States Weather Bureau under contracts Cwb 9231 and 9530. The author is most grateful to Dr. Harry Wexler, Dr. Morris Tepper, Mr. William A. Hass, and Mr. Ferguson Hall of the U.S. Weather Bureau, Washington, D.C., for their useful comments and suggestions.

Numerous citizens of the Fargo-Moorhead area cooperated in the successful completion of this research by supplying the author with their valuable photographs, taken under dangerous conditions during the time of the tornadoes. All photographs collected by the closing date of this report are published in section 3. Throughout the time of this study, Mr. Ralph W. Shultz, meteorologist in charge of the U.S. Weather Bureau station at Hector Airport, Fargo, rendered kind assistance in collecting and organizing information from the local people.

In particular the author wishes to express his sincere gratitude to Mr. Dewey Bergquist, WDAY–TV weatherman, for his contribution in collecting tornado pictures and surveying damage paths. Without his active cooperation this report could not have been completed.

The author is also indebted to Dr. H. R. Byers, chairman, Department of Meteorology, with whom he discussed this research from time to time, and to Mr. Henry Albert Brown, Mrs. Charlotte Battino, and other members of the staff of the Severe Local Storms Project, Department of Meteorology, University of Chicago.

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A Detailed Analysis of the Fargo Tornadoes of June 20, 1957

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University of Chicago

1. GENERAL WEATHER SITUATION

On the afternoon of June 20, 1957, a cone-shaped funnel dropped over the rural area west of Fargo, N. Dak. The time was approximately 1830 CST. Figure 1 shows the general weather situation at the time the tornado occurred. It is, of course, not possible to see meteorological features of the tornado itself on such a large-scale weather chart; however, the chart will help us to study the general weather conditions which gave rise to the formation of that particular tornado.

At the time when the storm hit the city, a small mesoscale thunderstorm High accompanied by heavy convective activity was approaching Fargo from the northwest. A wave cyclone with a central pressure of 994 mb. was about to be filled up by the mesoscale High.

The 700-mb. chart seen in figure 2 covers the same area as that of the surface map. The chart includes height contours, isodrosotherms, areas of low cloud coverage of 5/10 or larger, and the precipitation areas occurring during the one-hour period ending at 1800 CST.

It seems evident that the tornado appeared near the eastern edge of the precipitation area inside the surface warm sector. A narrow area of the 700-mb. moist air extending from Wyoming to upper Minnesota is closely related to the areas of precipitation and low cloud coverage. Careful examination of these charts leads us to the conclusion that the tornado under discussion occurred at the point where the low-level southerly flow extended deeply northward beneath the 700-mb. moist-tongue.

The vertical cross section of wind, temperature, and dew point temperature shown in figure 3 reveals further a rather complicated structure of dry and moist layers overrunning the lowest moist

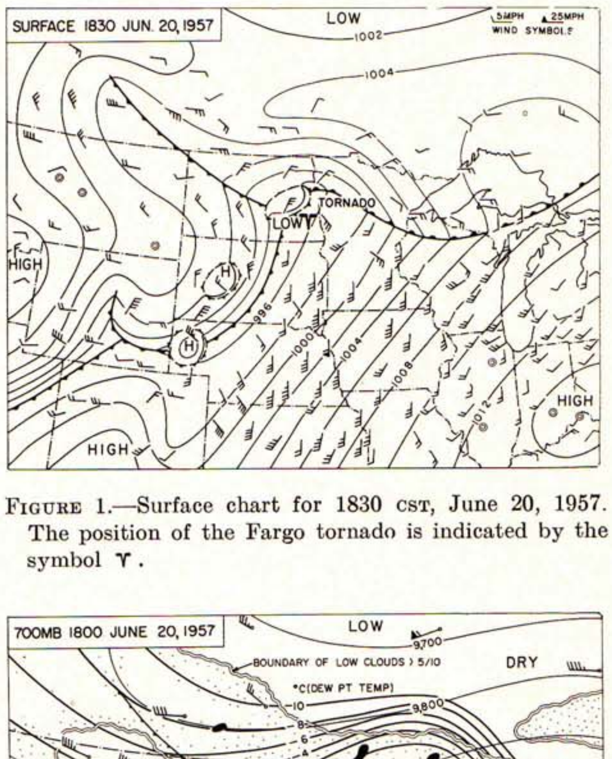

FIGURE 1.—Surface chart for 1830 CST, June 20, 1957. The position of the Fargo tornado is indicated by the symbol ϒ.

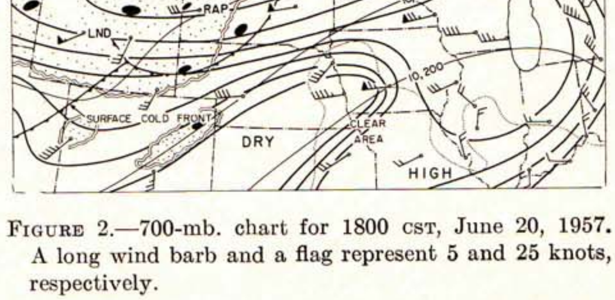

FIGURE 2.—700-mb. chart for 1800 CST, June 20, 1957. A long wind barb and a flag represent 5 and 25 knots, respectively.

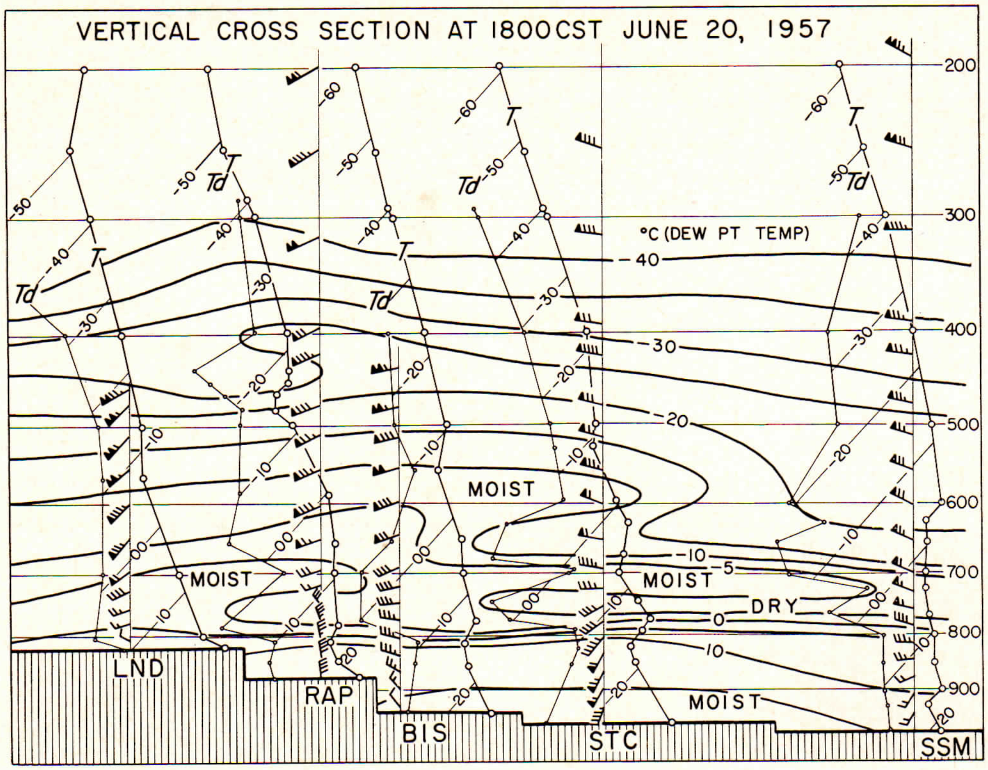

FIGURE 3.—Vertical cross section of wind, temperature, and moisture along Lander, Wyo.; Rapid City, S. Dak.; Bismarck, N. Dak.; St. Cloud, Minn.; and Sault Ste. Marie, Mich.

layer and extending up to about the 800-mb. level. The low-level jet is pronounced in the St. Cloud sounding. It should be noted, however, that the existing stations of the upper air network in the area of the northern Great Plains were not dense enough to obtain any quantitative knowledge in the immediate vicinity of the tornado.

An attempt was made to construct three hourly charts, presented in figures 4, 5, and 6. In analysing these charts, time-section sheets including traces obtained from each weather station were prepared beforehand; then the standard meso-analysis techniques were applied (c.f. [1]).

The areas of precipitation occurring in the hour prior to each map time are shown by three types of stippling corresponding to the amounts 0.01, 0.1, and 1 inch. A long wind barb and a flag denote the speeds of 5 and 25 knots, respectively.

The chart at 1800 (fig. 4) shows that the tornado was very close to Fargo when a mesoscale High began filling up a low pressure center. In one hour (fig. 5) the tornado moved into Minnesota, where the boundary of the meso-High almost caught up with the tornado, which was moving at about 16 m.p.h. After the next hour or so, the meso-High covered a large area near the North Dakota-Minnesota border and the tornado funnel was completely lifted.

It is greatly to be regretted that no radar equipped with camera was in operation within an effective range from the tornado. However, the following radar reports reveal that the tornado-related thunderstorm was high enough to be detected by radar stations over 200 miles away:

ADC Station, 205 miles SSE of Fargo

1900 CST: Tops of echoes near Fargo were 65,000–75,000 feet.

ADC Station, 90 miles ESE of Fargo

1905 CST: Top of the tornado parent cloud at 47,000 feet.

1955 CST: Top of the cloud at 60,000 feet.

WB Station Sioux Falls, 225 miles S of Fargo

1830 CST: Radar observers noted an echo in the Fargo area.

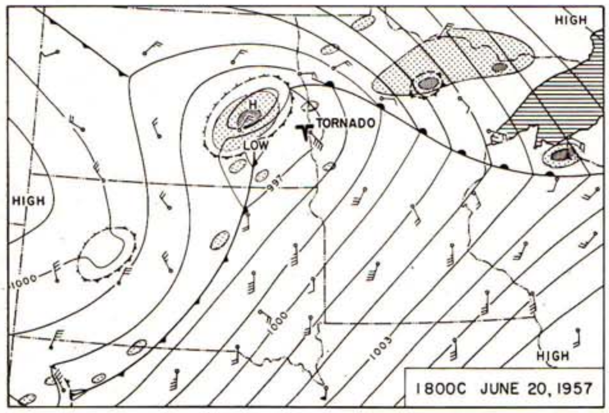

FIGURE 4.—Surface chart for 1800 CST, June 20, 1957. Precipitation amounts for the 1-hour period ending at map time are shown by the stippling: light stippling shows 0.01 in., medium stippling shows 0.1 in.

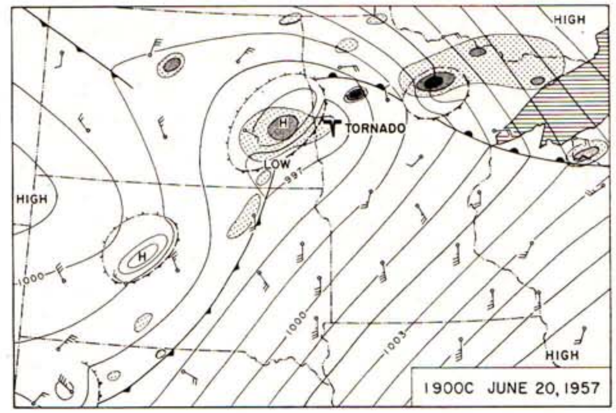

FIGURE 5.—Surface chart for 1900 CST, June 20, 1957.

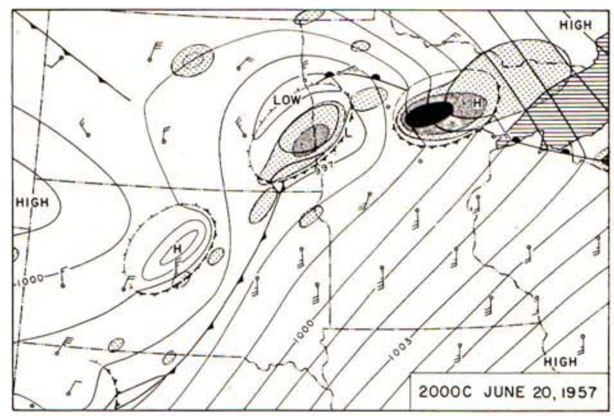

FIGURE 6.—Surface chart for 2000 CST, June 20, 1957. Three degrees of stippling here and in figure 5 show the area of precipitation amounts 0.01, 0.1, and 1.0 in. occurring in the 1-hour period ending at map time.

2. FIVE TORNADOES OF JUNE 20, 1957

The Fargo tornadoes, the most active part of which hit the residential districts of Fargo, were thought to be several separate tornadoes. Extensive investigations of the field carried out by the author with the assistance of Mr. D. Bergquist, television weatherman, WDAY–TV, Fargo, confirmed this impression: the storm consisted of five separate tornadoes, each of which was identified as having completed its entire life cycle.

Figure 7 shows the distribution of these tornadoes, which are designated by the author as:

Tornado No. (1) Wheatland tornado
(2) Casselton tornado
(3) Fargo tornado
(4) Glyndon tornado
(5) Dale tornado

The term "Fargo tornadoes" will be used hereafter to designate these five tornadoes taken together.

WHEATLAND TORNADO

This tornado was observed around 1630 CST to the east of the Wheatland grain elevator by Mr. Jacobson, operator of the elevator (see fig. 8). The exact position of the storm when it was first sighted was later determined to be in Section 29 of Buffalo Township. The storm, described as a dust cloud picked up by a whirlwind, moved east-northeastward across the Northern Pacific Railway tracks.

Soon after, observers at the Holland farm north of Cass County Route 10 saw an automobile

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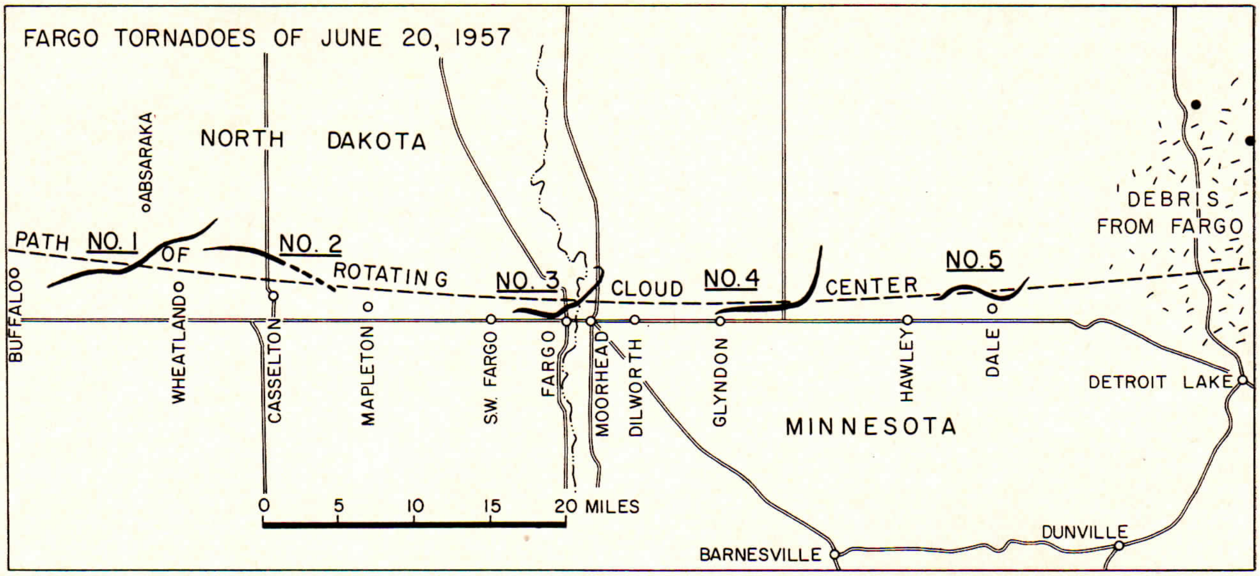


FIGURE 7.—Fargo tornado family of June 20, 1957. The family consisted of the Wheatland, Casselton, Fargo, Glyndon, and Dale tornadoes.

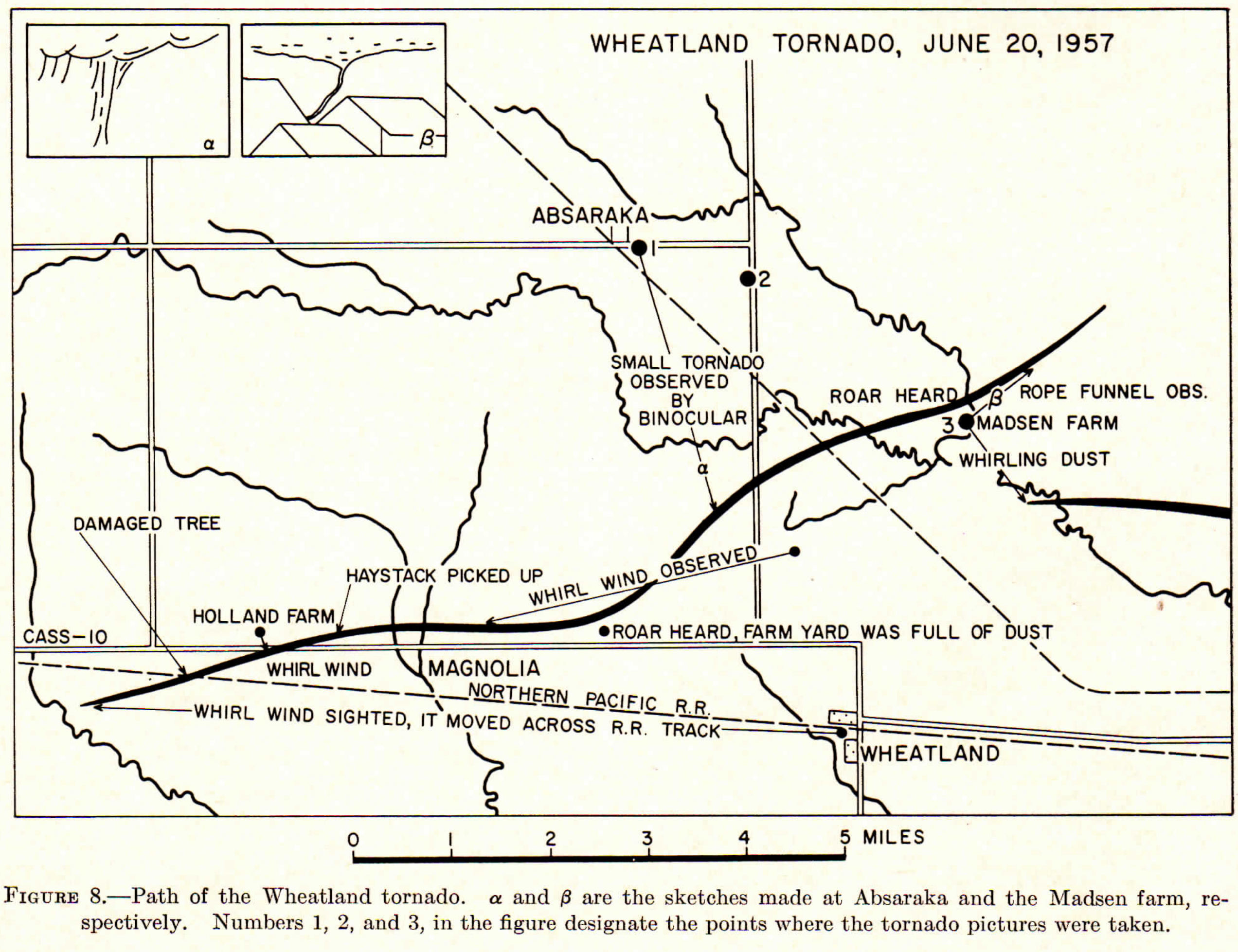


FIGURE 8.—Path of the Wheatland tornado. α and β are the sketches made at Absaraka and the Madsen farm, respectively. Numbers 1, 2, and 3, in the figure designate the points where the tornado pictures were taken.

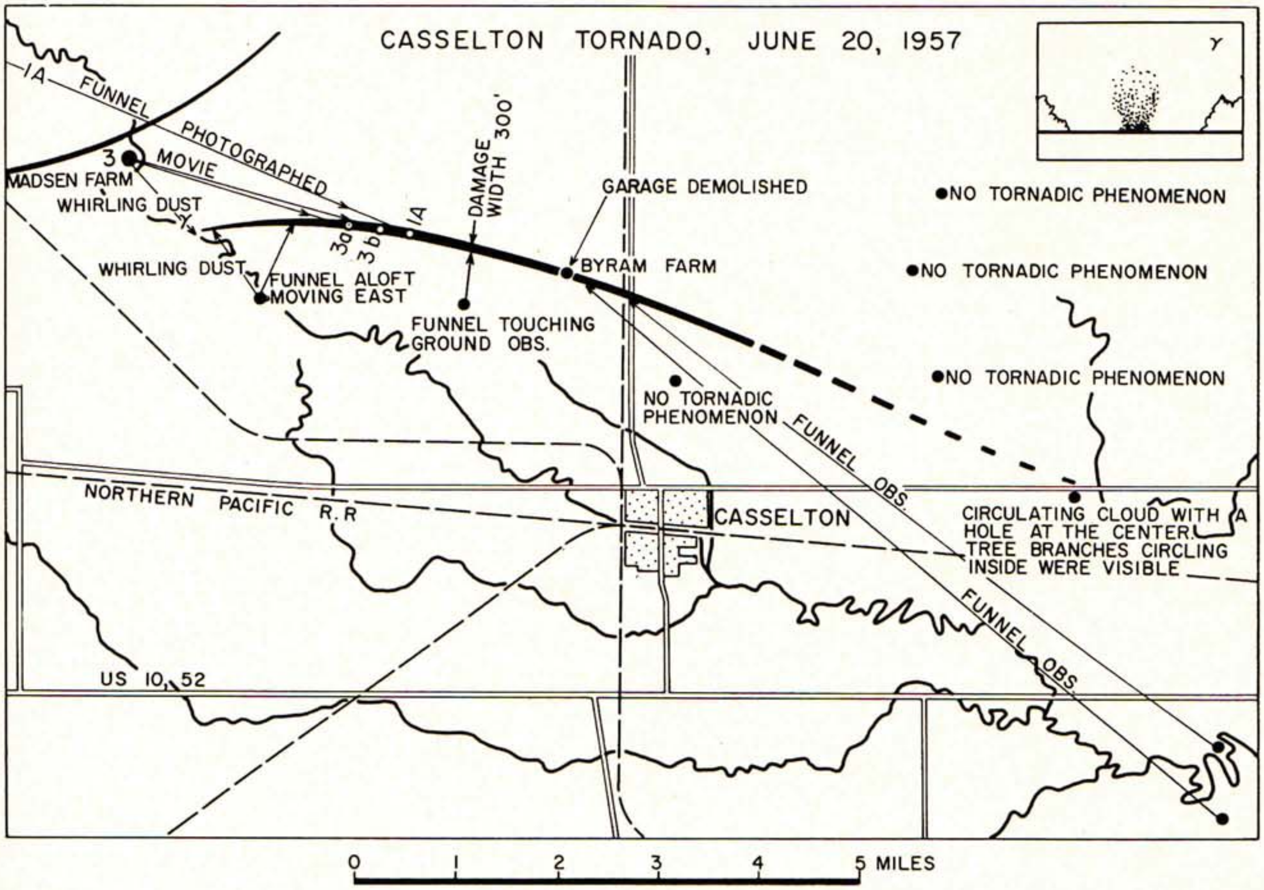


FIGURE 9.—Path of the Casselton tornado. Sketch γ was made by Mrs. Madsen. Photographs 1A, 3a, and 3b are the only photographs of the tornado funnel.

stopped by eastward-moving whirling dust. In a few minutes they observed haystacks east of their farm being picked up by the storm. Although the storm at this stage was not strong enough to produce any damage on farms, the rising dust was observed by many people working in the farms along its path.

Observation of the funnel of this small tornado was made first from Absaraka by a group of people standing on a hill with a wide-open view to the south. In figure 8, sketch α, made by one of these observers, suggests that the storm was more or less a waterspout type with a diameter of less than 100 feet. The tornado appeared like a rope or a light-colored snake to observers from the Madsen farm, who would have seen the last stage of the storm.

Summary.—This storm, with its path of about 11 miles, was accompanied by a funnel aloft. Throughout the life of the storm the funnel remained narrow and long like a rope or a snake, as described by local observers. No property damage was reported in its path. The storm merely picked up haystacks and dust, causing some damage to crops such as beans.

CASSELTON TORNADO

This storm was first witnessed by Mrs. Madsen, who later took two continuous strips of motion pictures of the funnel in the mature stage of the storm. As shown in figure 9, sketch γ, she reported that the storm was picking up quite a lot of dust while moving eastward in a direction southeast of the Madsen farm. People on the farms south of the storm observed a funnel moving eastward.

The outlines of the funnel appearing in every tenth frame of the movie film 3a* (see fig. 15) are reproduced in figure 10. The movie was taken at an estimated distance of 2¼ miles from the funnel.

*The picture numbering system used to identify photographic observations collected in figures 15–39 is explained in section 3.

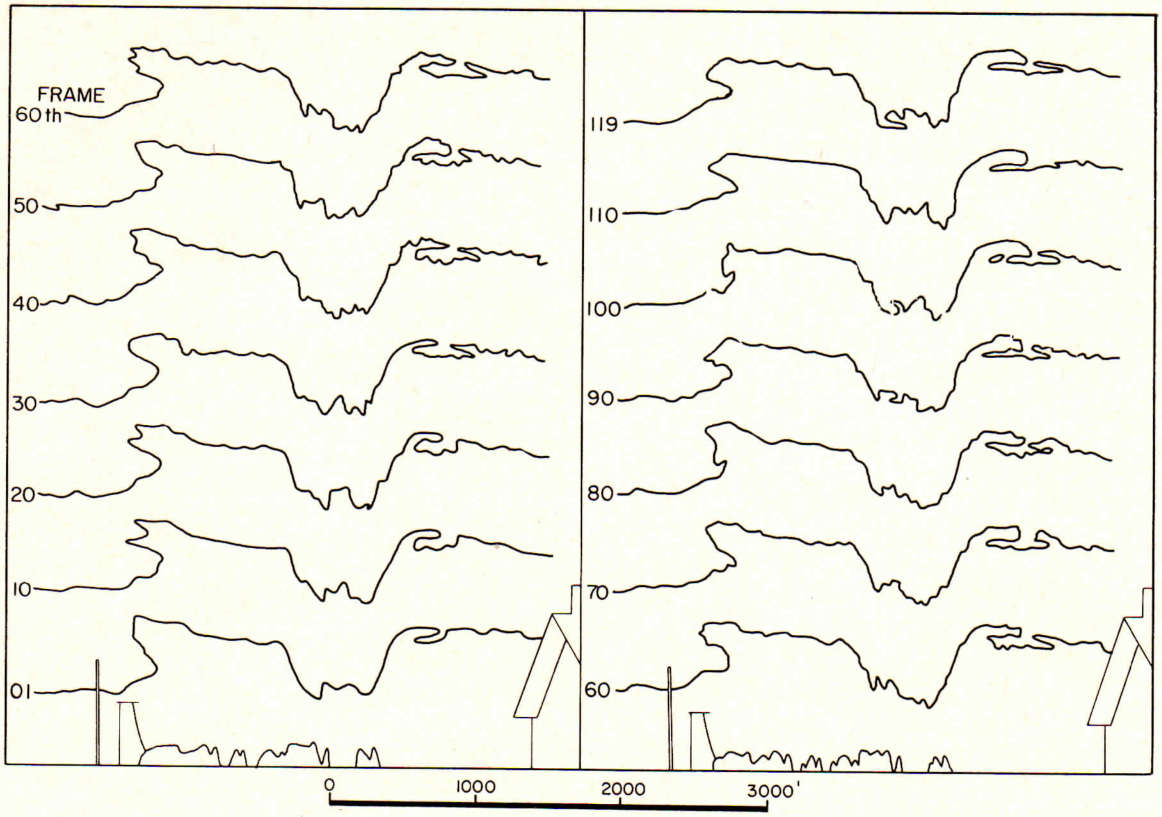


FIGURE 10.—Every tenth frame of the movie film 3a taken at the Madsen farm, 1735 CST, June 20, 1957.

The computed diameter of the ragged bottom funnel was about 400 feet. The height of the cloud base was fairly low—only 900 feet above the ground.

The second shot, 3b (fig. 15), made by Mrs. Madsen reveals that the funnel, with its bottom almost touching the ground, was accompanied by a cloud of dust. The time interval between her shots 3a and 3b cannot be determined; however, a comparison of the two pictures shows that the elevation angle of the cloud base and the location of the black low cloud base to the left of the funnel remained practically unchanged and that the white mass of the cloud in the foreground moved only 10 degrees to the right. Therefore it will be reasonable to assume that 3b was taken within a few minutes after 3a. We can further assume that the still photograph 01A (fig. 15) by Mr. Faught was taken almost at the same time as 3a because of the position of the white cloud in the foreground. As a result of the triangulation of the funnel using these pictures, the tornado can be placed 1½ miles west-northwest of the Byram farm, where a garage was picked up and trees were badly damaged.

Observers from two spots 7 miles east-southeast of Casselton reported a cone funnel moving eastward from a point northwest of them. It is evident that they observed the storm approximately at the time when it was over the Byram farm. An attempt to trace the tornado path farther east beyond the Byram farm was unsuccessful.

It is of extreme interest to examine photograph 02B (fig. 15), which was made about five minutes after Mr. Faught took his 01A. No funnel is noticeable in the picture, which shows the same general clouds appearing in the previous photograph. It is very likely that the funnel was lifted rapidly after damaging the Byram farm.

Mrs. Askew's observation from the point 4 miles east of Casselton is spectacular. When she looked up she saw a black bag hanging down from a dark cloud. At its center was a hole, inside which circled a number of objects resembling tree branches. In spite of such a spectacular display aloft, nothing particular was felt on the ground.

Summary.—This tornado, appearing approximately when the first one disappeared, left a

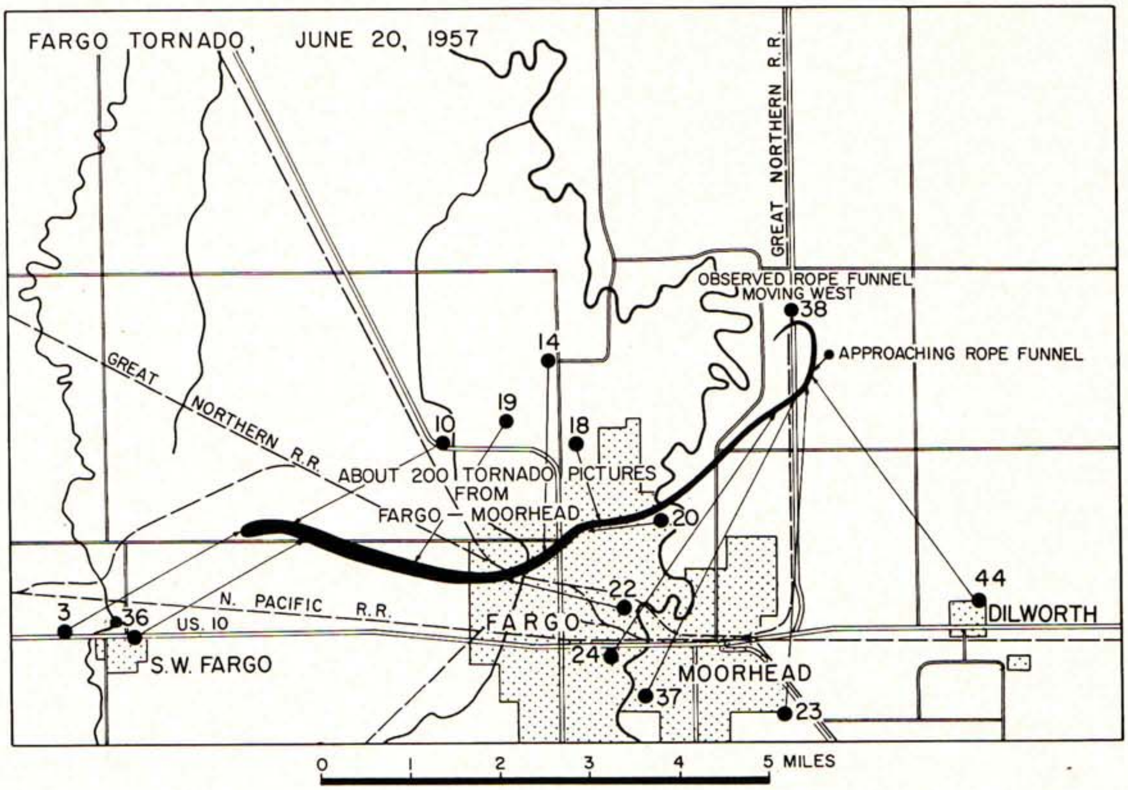


FIGURE 11.—Path of the Fargo tornado.

path of 5 miles in Casselton Township. The storm in its mature stage was accompanied by a cone-shaped funnel which probably touched the ground north-northwest of Casselton, then was lifted rapidly. The traceable damage path was 5 miles, but the system aloft would have drifted at least a few miles toward the east-southeast.

FARGO TORNADO

Prior to the appearance of the funnel, citizens of Fargo started taking pictures of a rotating cloud approaching from the west. About 200 still and motion pictures taken from various points in the Fargo-Moorhead area cover the entire life history of this storm, enabling us to make a quantitative study of it. The path of the storm is shown in figure 11.

Summary.—This was the third tornado to drop in the rural area some 2½ miles west of the Fargo city limits. The total damage path was 9 miles, extending into Minnesota. This storm will be fully discussed in the following chapters.

GLYNDON TORNADO

The first indication of this tornado was confirmed by its damage to the Great Northern Railway fence north of Glyndon. In its development stage the storm damaged a bean field and some trees along its path.

The mature stage of the storm occurred as it crossed the Buffalo River. Trees along the banks were severely damaged; and north of the river, the Wyland farm was practically demolished. The width of appreciable damage was estimated to be about two blocks. Then the storm moved eastward, weakening considerably. No one observed the funnel at this stage except Mr. Wilson, a meteorologist, who described it as a dark cone. He was separated from the funnel by a distance of at least 10 miles. The extent of the damage also suggests that the storm would have been accompanied by a very large and powerful cone-shaped funnel.

A cylindrical funnel which gradually changed into a light-colored rope while moving northeastward was observed from the Wyland and Ackerson farms after the passage of the storm. See sketches δ and ϵ in figure 12.

Observers from the vicinity of the Sandal farm, which was demolished, witnessed a splash of water sucked up by the rope-type tornado as it crossed

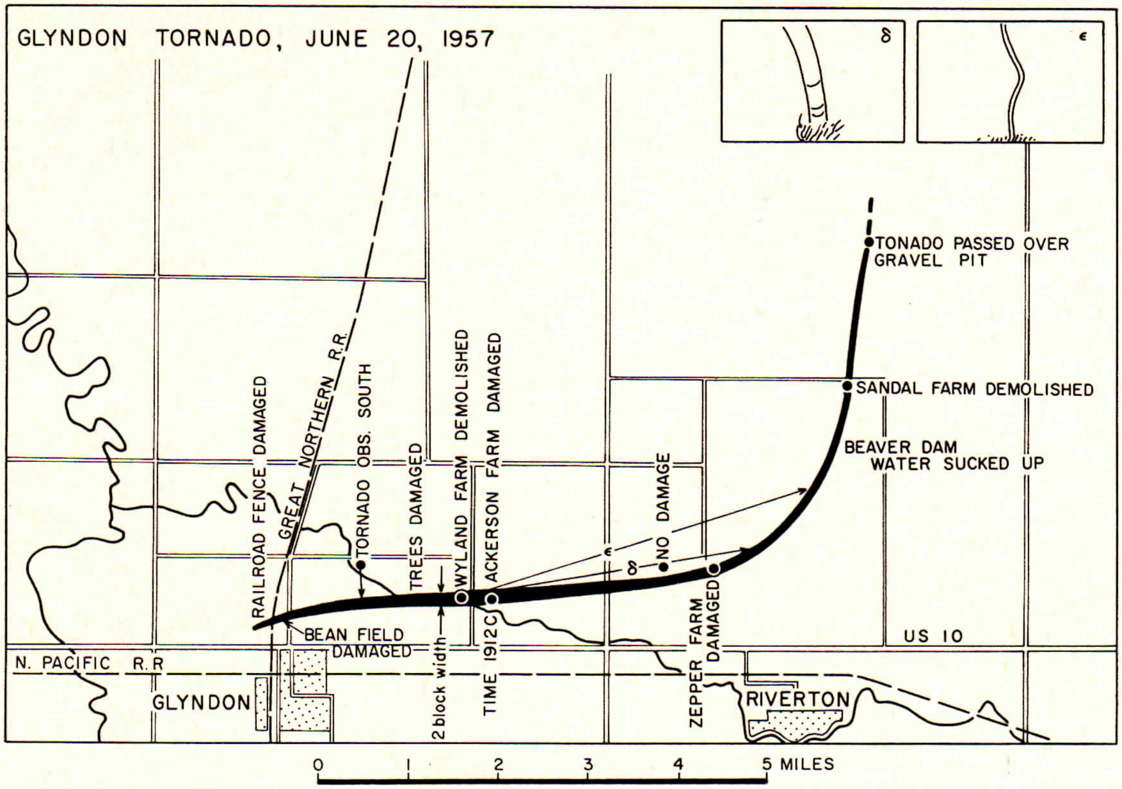


FIGURE 12.—Path of the Glyndon tornado. Sketches δ and ε were made at the Wyland and Ackerson farms, respectively.

over the Beaver Dam some one mile south of the farm. Thereafter, the storm kept moving northward until it disappeared in the direction of a gravel pit north of the farm.

Summary.—The storm, appearing in the form of a large cone-shaped funnel, left a damage path of about 10 miles in length and two blocks in maximum width. Before it dissipated, the storm resembled a huge rope.

DALE TORNADO

The last tornado of the Fargo tornado family started disturbing the surface in Section 32 of Highland Grove Township. As shown in figure 13, a cone funnel dropped to the ground just east of Minnesota Highway 32, 1½ miles north of U.S. Highway 10.

Then the storm moved northeastward, damaging the Carlson farm, where the course changed toward due east. The Gol farm was hardest hit. An electric clock there stopped at 2005 CST, when a high-voltage pole was shattered. The tornado at this time was characterized by a dark cone funnel.

Observations from nearby farms revealed that the funnel gradually changed into a big black hose and finally into a long rope-type funnel which disappeared over Stinking Lake.

Summary.—The fifth or last tornado left a surface damage path of as much as 7 miles in Highland Grove Township, Minnesota. It began, as commonly seen in the other cases, in the shape of a cone funnel and ended in the form of a rope.

CHARACTERISTICS OF FARGO TORNADOES

Five tornadoes occurring in the afternoon of June 20, 1957, are summarized in figure 14. Although the shape of the funnel of the Wheatland tornado in its early stage and the Casselton tornado in the dissipating stage necessarily remain unknown to the author, their life cycles are considered to involve the redevelopment of a cone-shaped funnel into a rope-type funnel.

As far as the shape of the funnel is concerned, the rope-type funnels witnessed during the time of the Fargo tornadoes would have been of the waterspout type if they were traveling over a lake

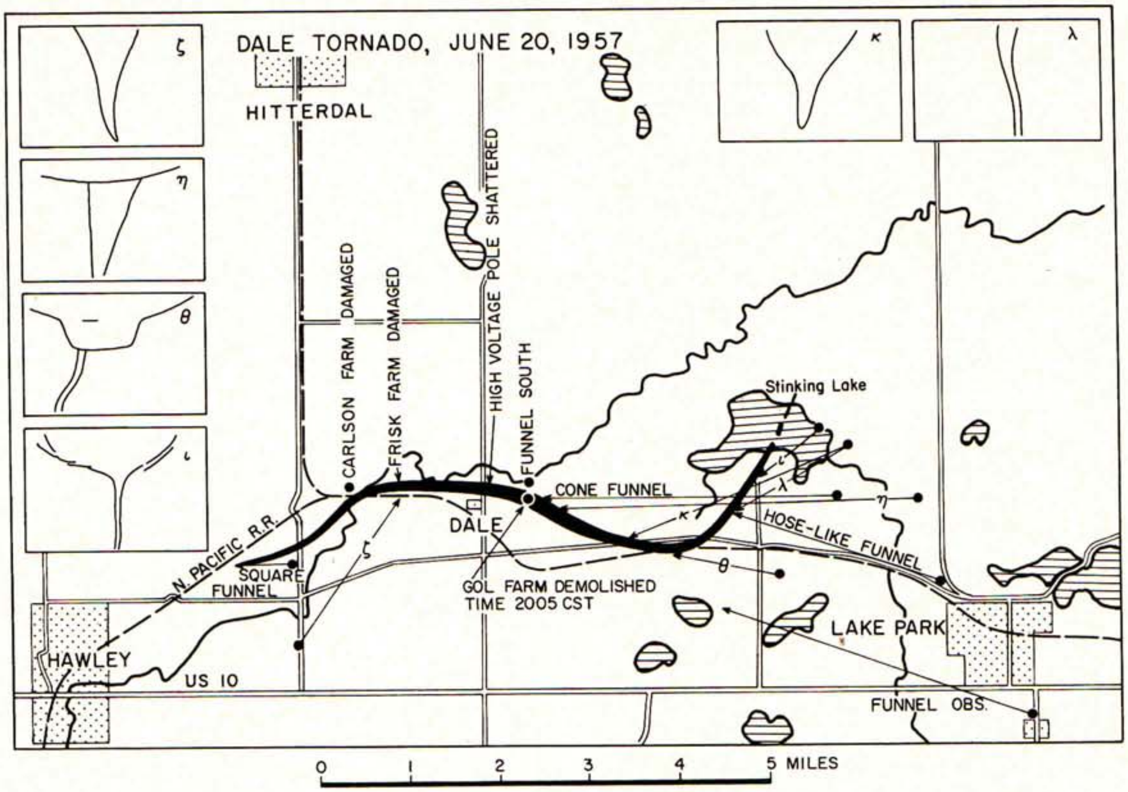


FIGURE 13.—Path of the Dale tornado. Sketches ζ, η, θ, ι, κ, λ show how the funnel shape changes. No photographs were made to show the funnel.

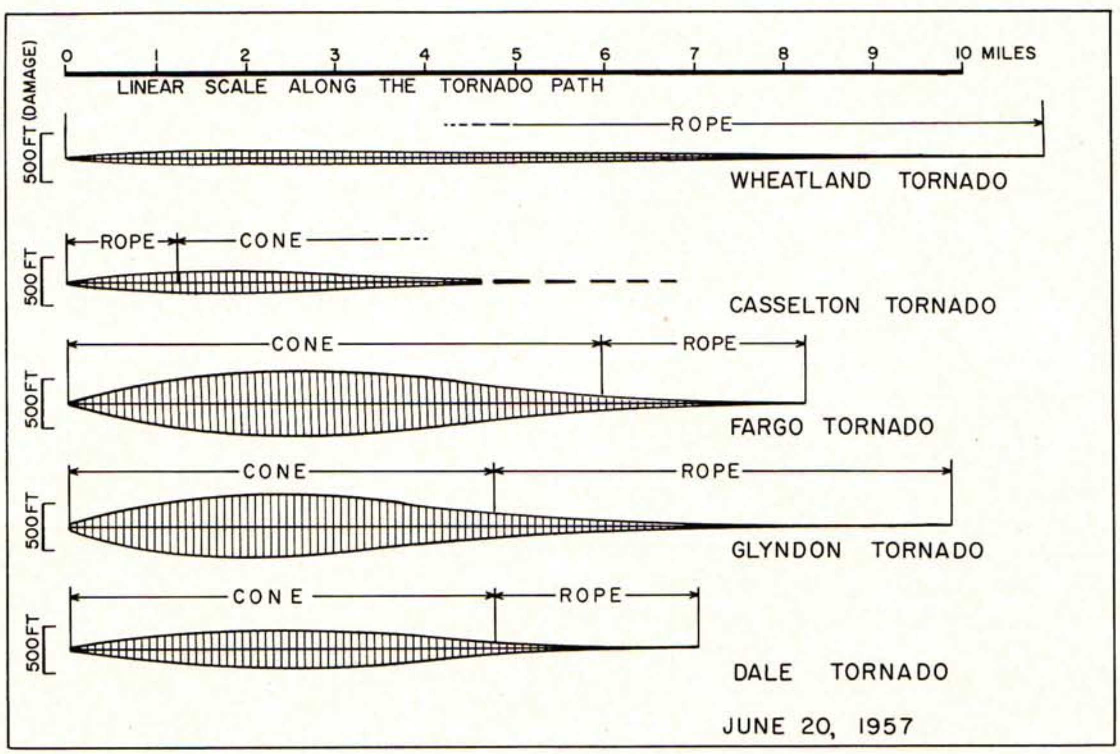


FIGURE 14.—Summary of the paths of the five tornadoes.

or an ocean. It might be stated that many tornadoes characterized by majestic cone-shaped funnels change into rope-like vortices before they dissipate. The Wheatland tornado, which probably remained as a rope-type funnel throughout its lifetime, would perhaps not be called a tornado in a strict definition. There is, however, no reason why we should not call it a tornado, since other tornadoes belonging to the same family went through a similar rope-like stage before their dissipation.

The extreme east and west ends of the Fargo tornado family mark an area extending for 64 miles, of which 35 miles are in North Dakota and 29 miles in Minnesota. The average length of the damage path produced by each tornado was only 8 miles, 11 miles being the longest and 4 miles the shortest.

Widths of each damage path varied from practically zero to 700 feet. The maximum width occurred in Fargo, where the residential areas in the western suburbs were practically leveled. By an examination of figure 14, we may postulate the existence of one or two small tornadoes next to the Dale tornado.

3. TORNADO PICTURES

An unusual number and quality of photographs were collected from citizens of the Fargo-Moorhead area. Some of the pictures were taken long before the tornado funnel started dropping from the base of a huge rotating cloud. After hearing radio and television reports of the U.S. Weather Bureau's tornado warning, some people apparently mistook the black rotating cloud, at least 10 times larger than a tornado in horizontal dimensions, for the tornado itself and began taking pictures of the cloud.

Table 1 lists the photographers ("observer") who made the excellent observations used in completing this report, the township where each observation was made, point of observation designated by number, type of observation, and frame identification. The frames of still photographs are designated by capital letters chronologically in the order of each shot. The first frame of each movie strip is identified by lower case letters. Reproductions of reliable sketches made at the time of the storm are designated by Roman numerals.

Figures 15–39 show reduced reproductions of all the photographs and sketches available for the study of the Fargo tornadoes.

Figure 40 indicates the exact position of all observation points distinguished by the type of observations. It will be seen that the observation points are concentrated in the area southeast of the Weather Bureau station at Hector Airport (No. 28). The author found, when his visits were made, that the area, with a wide southeast-northwest view, was excellent for the observation of the storm to the west.

In the upper left section of figure 40 are shown the points where the early activities of the Fargo tornadoes were photographed.

TABLE 1.—*Summary of photographic observations of the Fargo tornadoes. The distribution of the points is shown in figure 40*

Township	Observation point	Observer	Type of observation	Frame
Absaraka	1	Faught	35 mm. color	A.
Do	2	do	do	B.
Wheatland	3	Madsen	8 mm. color	a, b.
West Fargo	4	Fradet	35 mm. color	A–E.
Do	5	Payne	35 mm. b & w	A.
Do	6	do	do	B, C.
Do	7	Stensrud	do	A–C.
Fargo	8	Beaton	120 b & w	A–C.
Do	9	Bergquist	4 x 5 b & w	A, B.
Do	10	do	do	C, D.
Do	11	do	do	E, F.
Do	12	do	do	G, I.
Do	13	do	do	H.
Do	14	do	do	J, K.
Do	15	do	do	L.
Do	16	do	do	M, N.
Do	17	do	do	O.
Do	18	Byers	120 b & w	A, B.
Do	19	do	do	C, D.
Do	20	Frank	35 mm. color	A.
Do	21	do	do	B.
Do	22	do	do	C, D.
Do	23	Gebert	120 b & w	A–H.
Do	24	do	4 x 5 b & w	I, J
Do	25	do	120 b & w	K, L
Do	26	Hutchinson	35 mm. b & w	A–H.
Do	26	do	4 x 5 b & w	I–M.
Do	26	do	35 mm. b & w	N–V.
Do	27	Jennings	do	A–E.
Do	27	do	16 mm. b & w	a–m, p–s.
Do	27	Dooley	do	n, o.
Do	28	Kittelsrud	35 mm. color	A–O.
Do	28	Jensen	sketches	I–III.
Do	29	Olsen	120 b & w	A, B.
Do	30	do	do	C, D.
Do	31	Pilato	8 mm. color	a–d.
Do	32	Schrader	16 mm. b & w	a–f.
Do	33	do	do	g.
Do	34	do	do	h.
Do	35	Wild	35 mm color	A, B.
Moorhead	36	Arhart	polaroid	A.
Do	37	Helmeke	35 mm. b & w	A.
Do	38	do	do	B, C.
Do	39	Mickelson	8 mm. color	a, b.
Do	40	Stenerson	35 mm. color	A.
Do	41	Tenold	do	A, B.
Dilworth	42	Littke	do	A–C.
Do	43	do	do	D–F.
Do	44	do	do	G, H.
Moorhead	45	Arhart	sketch	I.
Do	46	Oksendahl	do	I.
Do	47	Wilson	do	I–VII.
Fargo	48	Hagen	120 b & w	A.
Do	49	do	do	B–K.
Do	50	Frahm	35 mm. color	A–F.
West Fargo	51	Payne	35 mm. b & w	D, E.
Fargo	52	Gregornick	120 b & w	A–K.
Moorhead	53	Jahnke	polaroid	A–F.

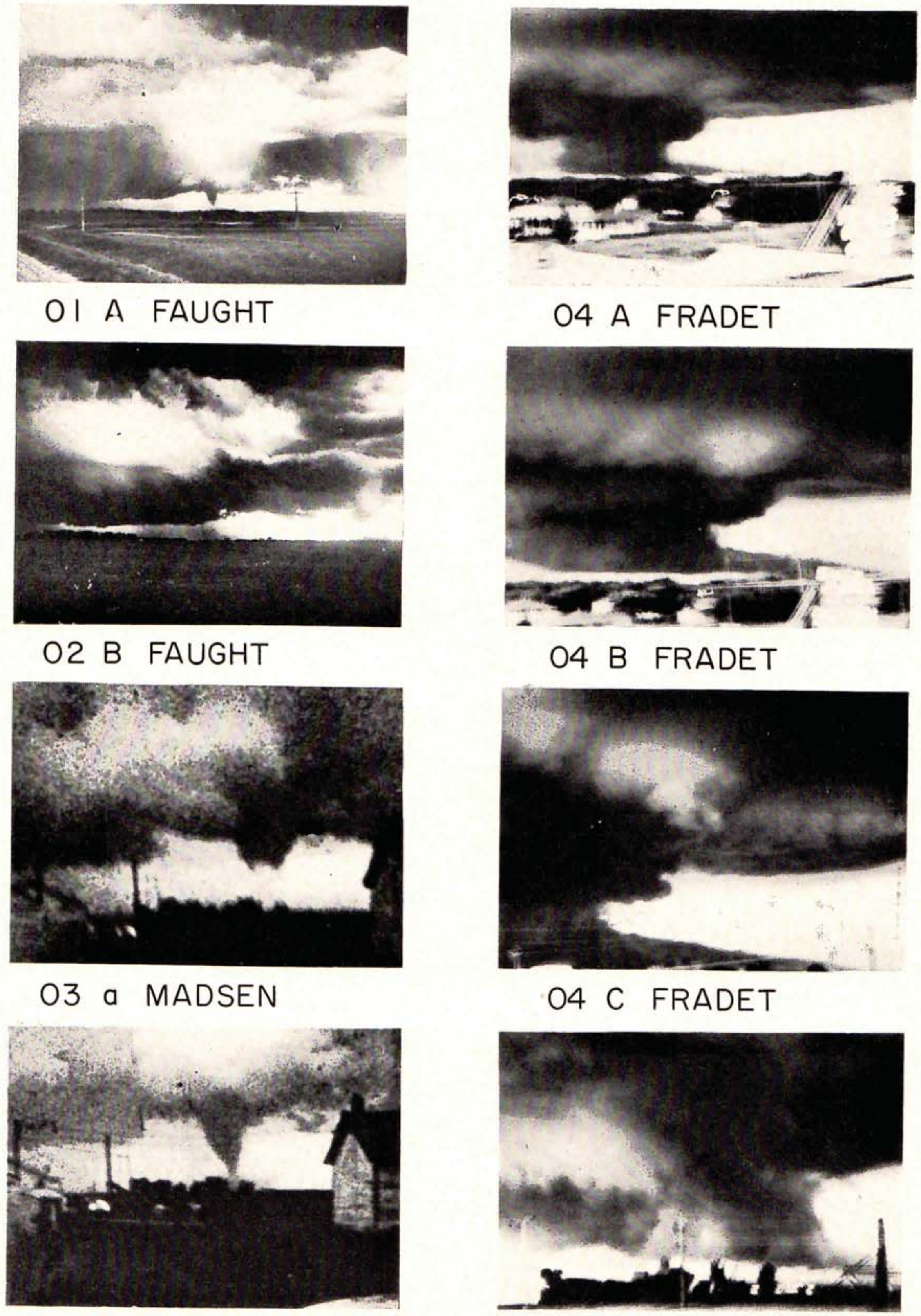
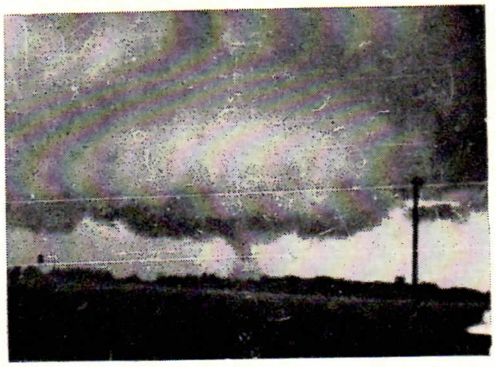


FIGURE 15.—Photographs by Faught, Madsen, and Fradet.

05 A PAYNE



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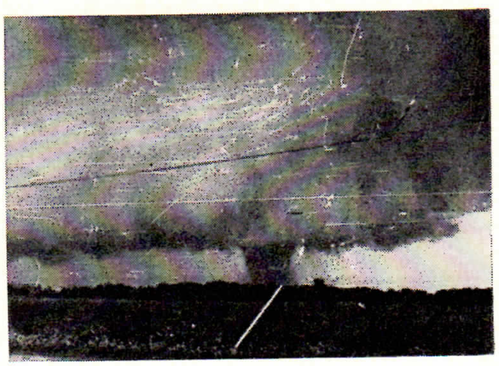

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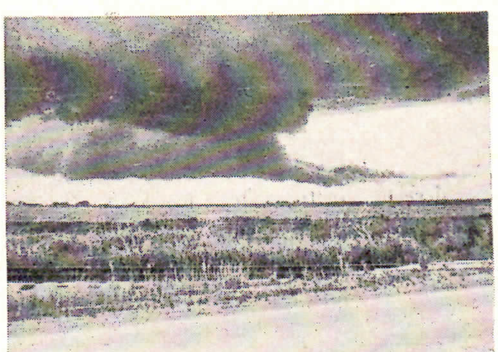
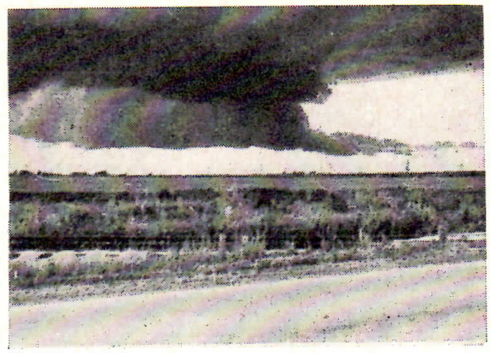
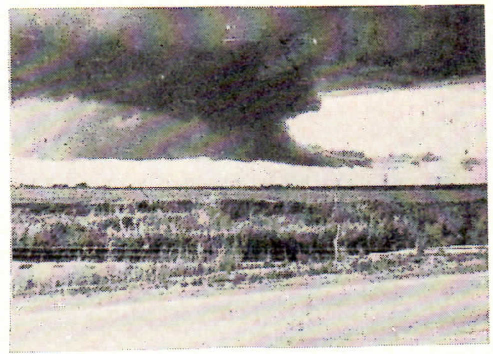


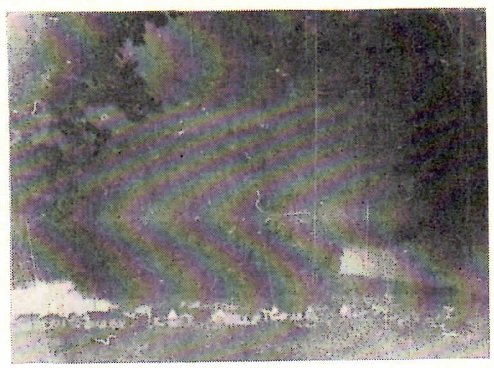
07 A STENSRUD



07 B STENSRUD



07 C STENSRUD



08 A BEATON

08 B BEATON

FIGURE 16.—Photographs by Payne, Stensrud, and Beaton.

08 C BEATON

09 A BERGQUIST

09 B BERGQUIST

10 C BERGQUIST

10 D BERGQUIST

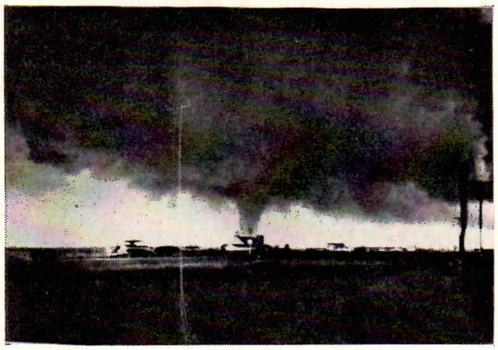
11 E BERGQUIST

11 F BERGQUIST

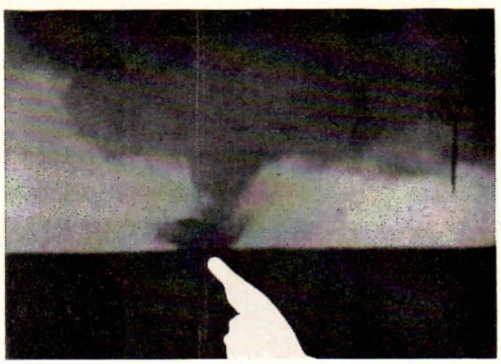
12 G BERGQUIST

FIGURE 17.—Photographs by Beaton and Bergquist.

12 I BERGQUIST

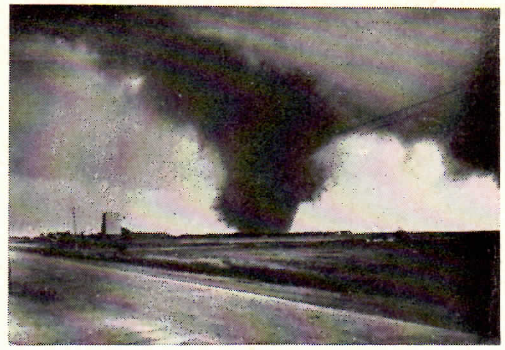


13 H BERGQUIST



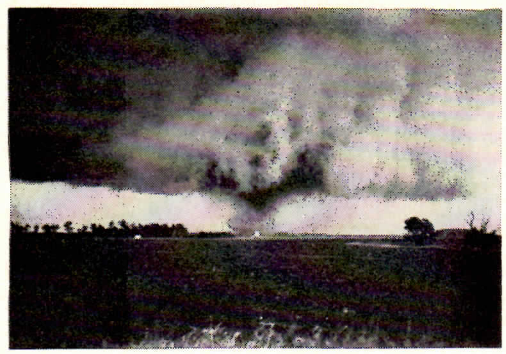
14 J BERGQUIST

14 K BERGQUIST



15 L BERGQUIST

16 M BERGQUIST



16 N BERGQUIST

17 O BERGQUIST

FIGURE 18.—Photographs by Bergquist.

18 A BYERS

18 B BYERS

19 C BYERS

19 D BYERS

20 A FRANK

21 B FRANK

22 C FRANK

22 D FRANK

FIGURE 19.—Photographs by Byers and Frank.

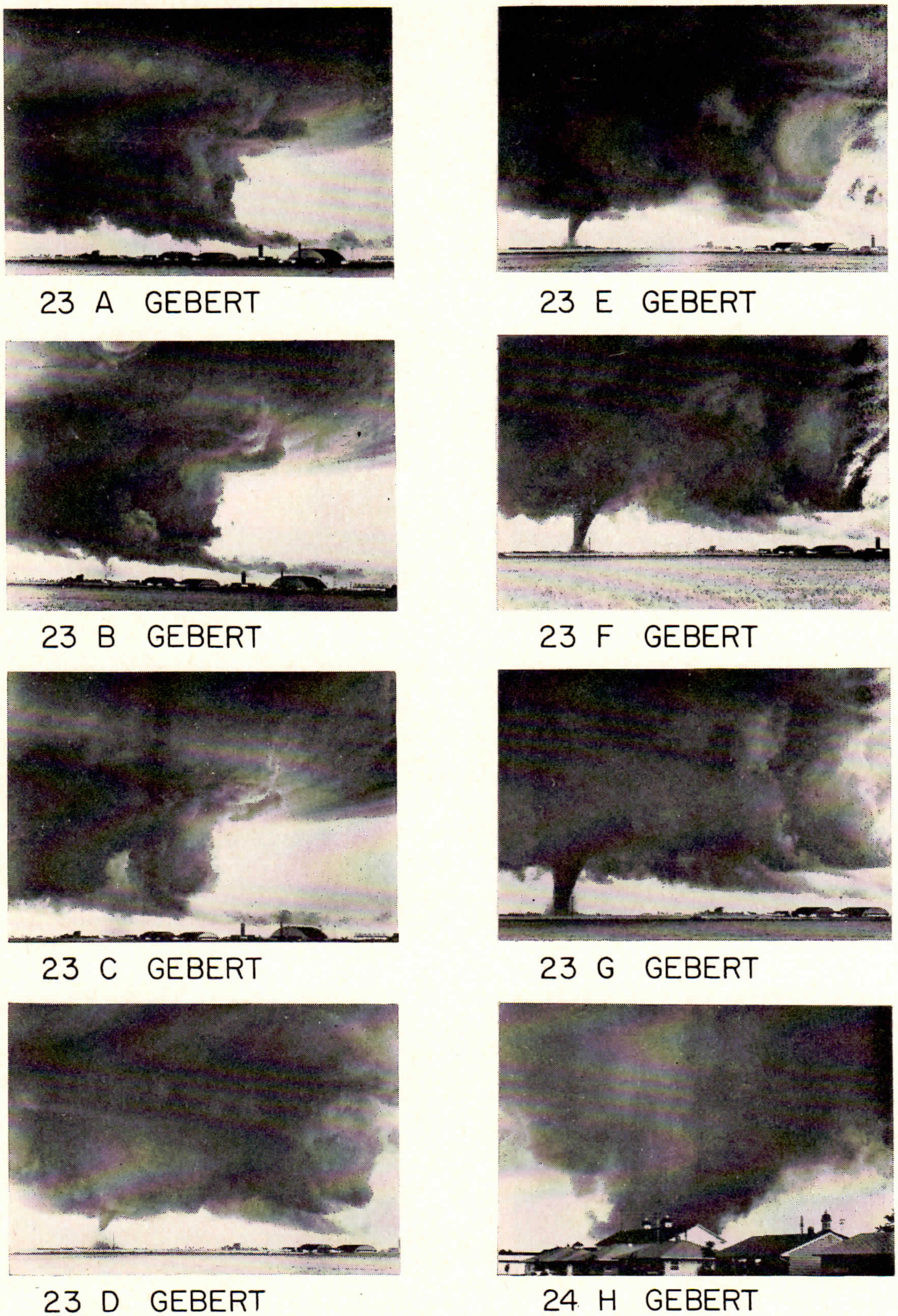


FIGURE 20.—Photographs by Gebert.

24 I GEBERT

24 J GEBERT

25 K GEBERT

25 L GEBERT

26 A HUTCHINSON

26 B HUTCHINSON

26 C HUTCHINSON

26 D HUTCHINSON

FIGURE 21.—Photographs by Gebert and Hutchinson.

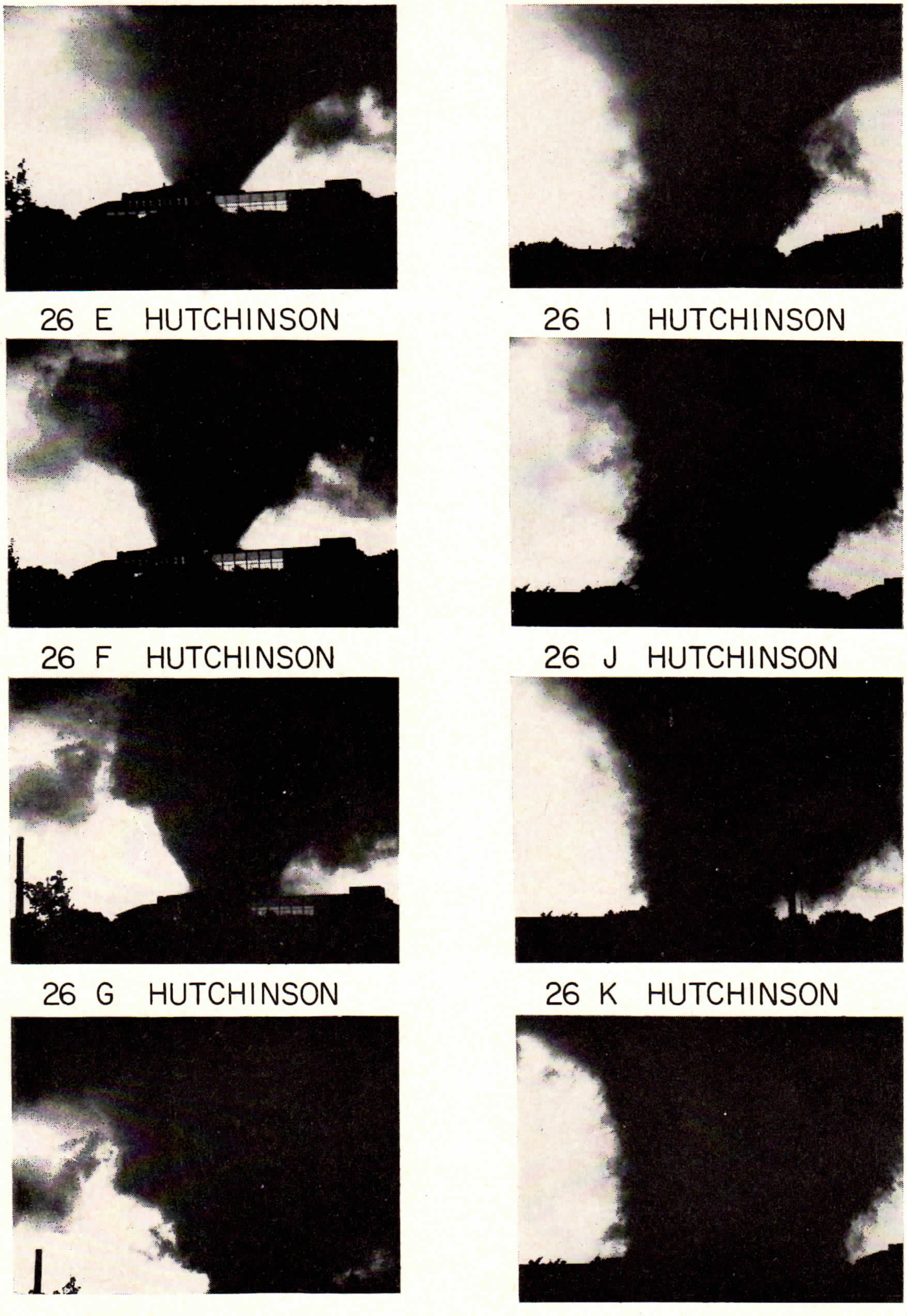


FIGURE 22.—Photographs by Hutchinson.

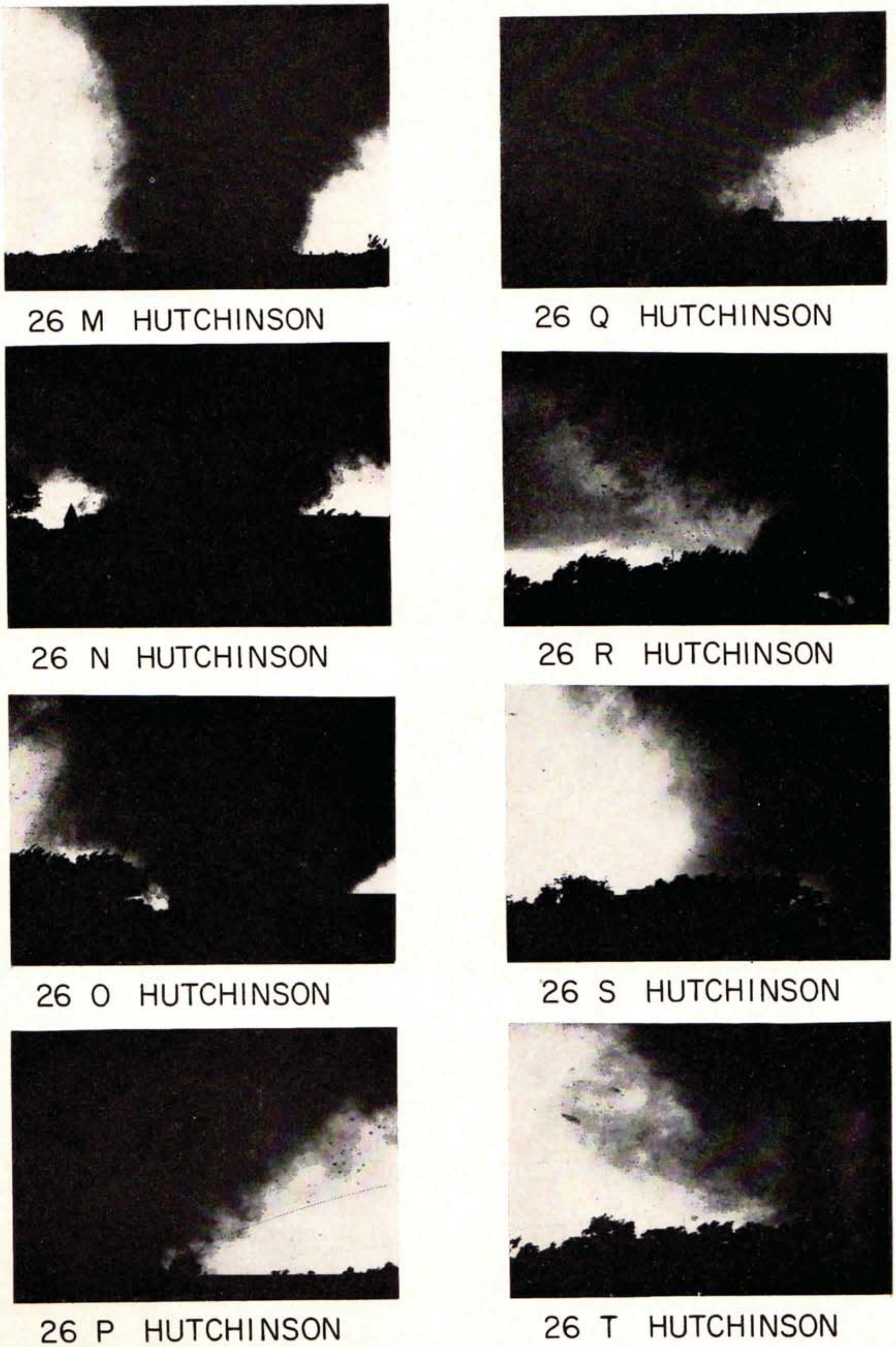
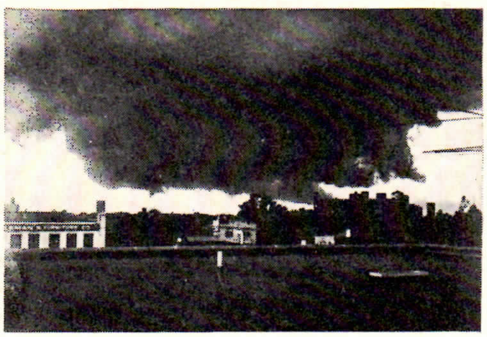


FIGURE 23.—Photographs by Hutchinson.

26 U HUTCHINSON

26 V HUTCHINSON



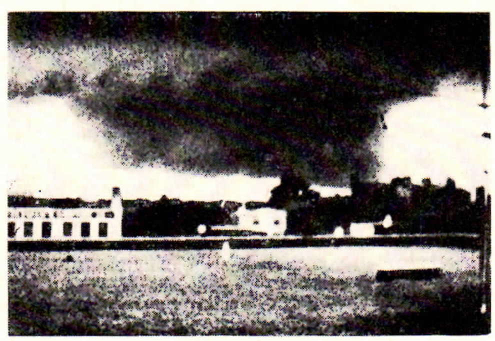
27 A JENNINGS

27 B JENNINGS

27 C JENNINGS

27 D JENNINGS

27 E JENNINGS



27 a JENNINGS

FIGURE 24.—Photographs by Hutchinson and Jennings.

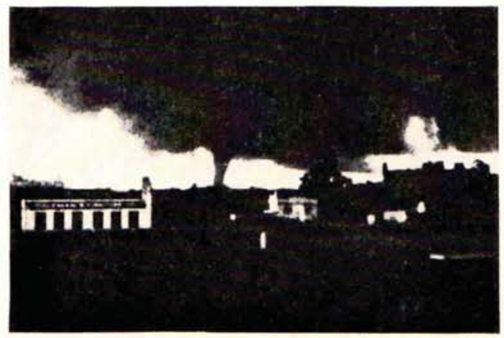
27 b JENNINGS

27 c JENNINGS

27 d JENNINGS

27 e JENNINGS

27 f JENNINGS



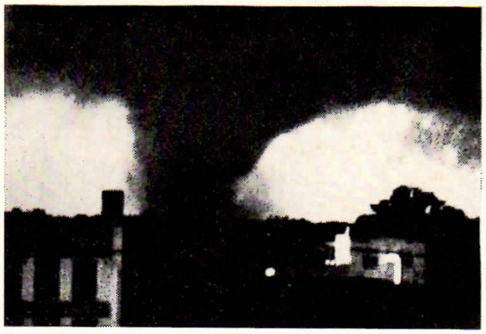
27 g JENNINGS

27 h JENNINGS

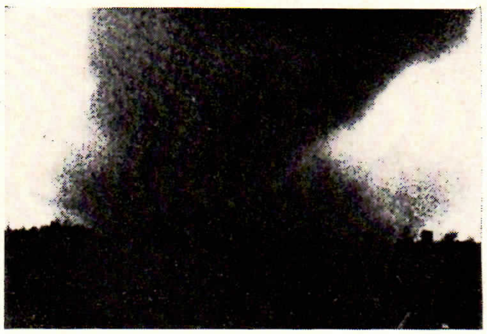
27 i JENNINGS

FIGURE 25.—Photographs by Jennings.

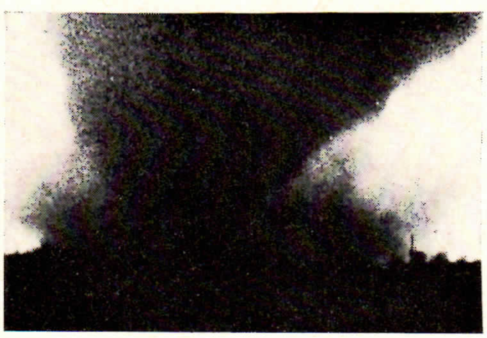
27 j JENNINGS



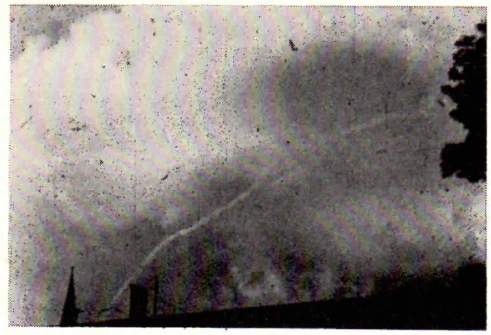
27 k JENNINGS



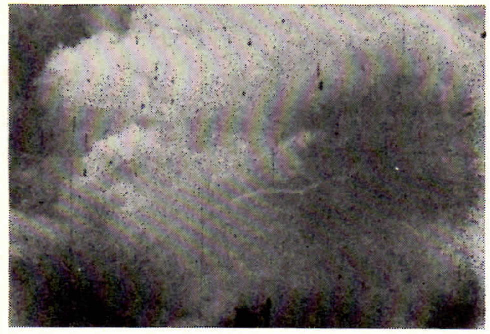
27 l JENNINGS



27 m JENNINGS



27' n DOOLEY



27' o DOOLEY

27 p JENNINGS

27 q JENNINGS

FIGURE 26.—Photographs by Jennings and Dooley.

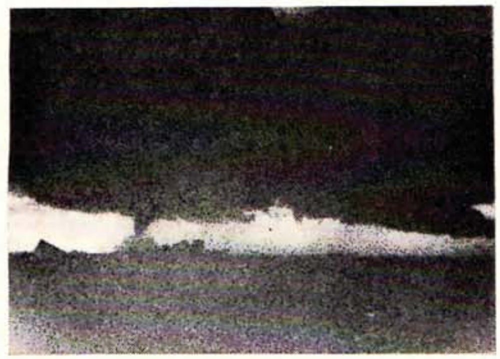
27 r JENNINGS

27 s JENNINGS

28 A KITTELSRUD

28 B KITTELSRUD

28 C KITTELSRUD

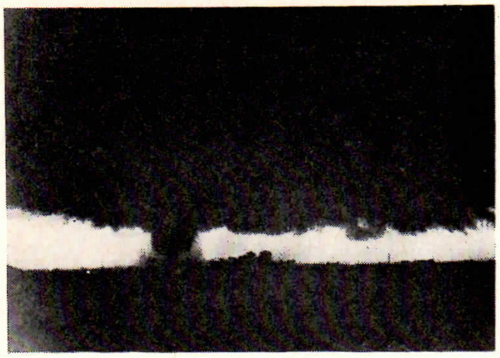


28 D KITTELSRUD

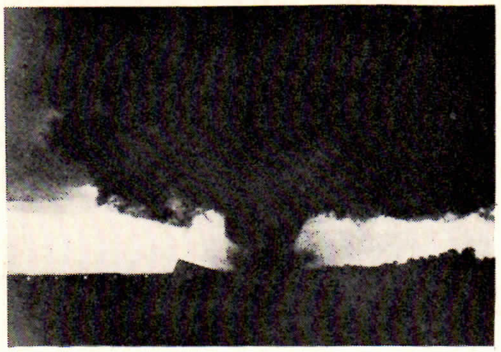
28 E KITTELSRUD

28. F KITTELSRUD

FIGURE 27.—Photographs by Jennings and Kittelsrud.



28 G KITTELSRUD

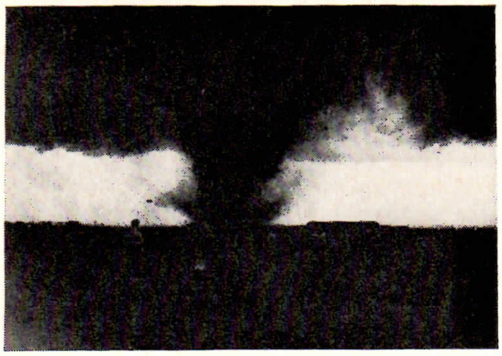


28 H KITTELSRUD

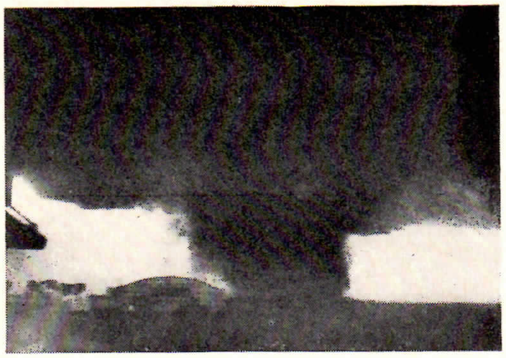
28 I KITTELSRUD

28 J KITTELSRUD

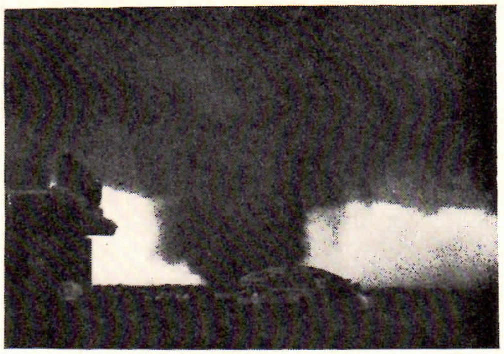
28 K KITTELSRUD



28 L KITTELSRUD



28 M KITTELSRUD



28 N KITTELSRUD

FIGURE 28.—Photographs by Kittelsrud.

28 O KITTELSRUD

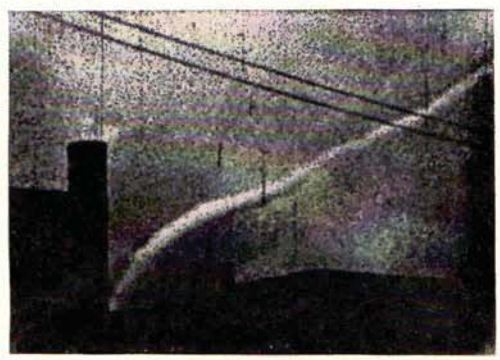
29 A OLSEN

29 B OLSEN

30 C OLSEN

30 D OLSEN

31 a PILATO



31 b PILATO

31 c PILATO

FIGURE 29.—Photographs by Kittelsrud, Olsen, and Pilato.

31 d PILATO

32 a SCHRADER

32 b SCHRADER

32 c SCHRADER

32 d SCHRADER

32 e SCHRADER

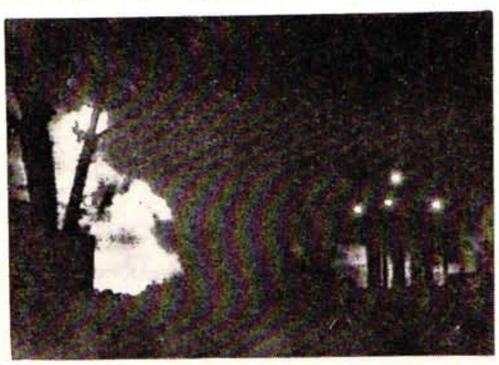
32 f SCHRADER

33 g SCHRADER

FIGURE 30.—Photographs by Pilato and Schrader.

34 h SCHRADER

35 A WILD



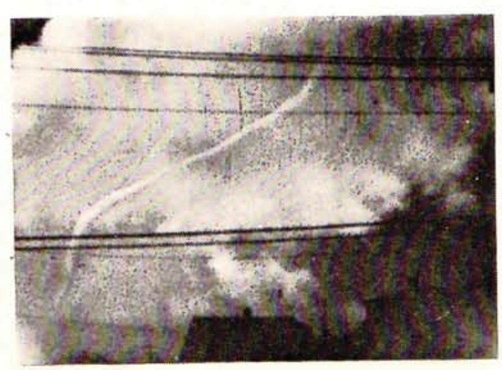
35 B WILD

36 A ARHART

37 A HELMEKE

38 B HELMEKE

38 C HELMEKE



39 a MICKELSON

FIGURE 31.—Photographs by Schrader, Wild, Arhart, Helmeke, and Mickelson.

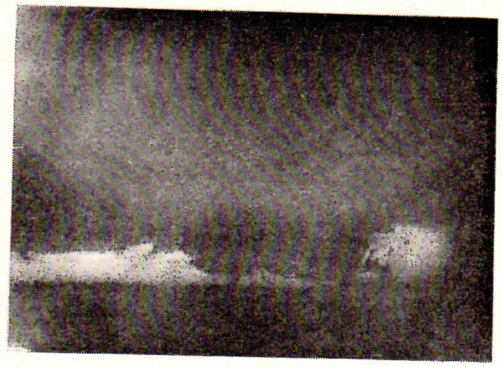
39 b MICKELSON

40 A STENERSON

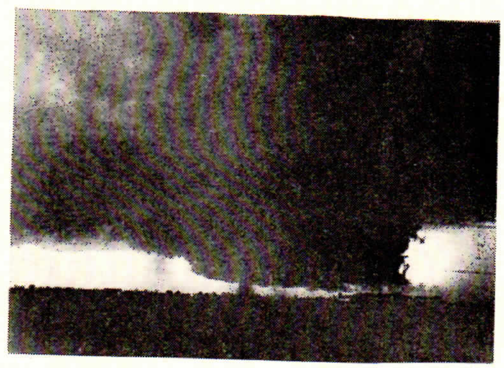
41 A TENOLD

41 B TENOLD

42 A LITTKE



42 B LITTKE

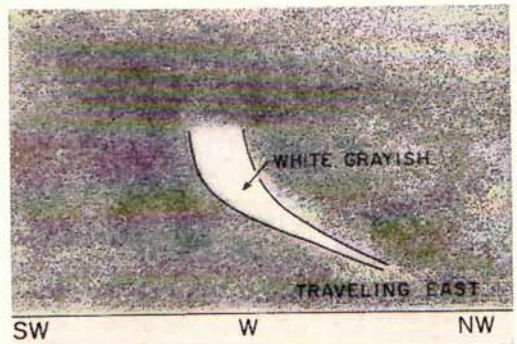


42 C LITTKE

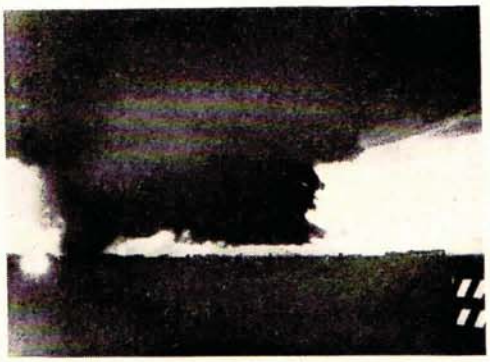
43 D LITTKE

FIGURE 32.—Photographs by Mickelson, Stenerson, Tenold, and Littke.

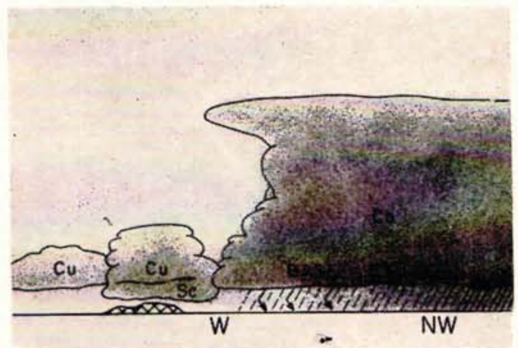
43 E LITTKE



45 I ARHART

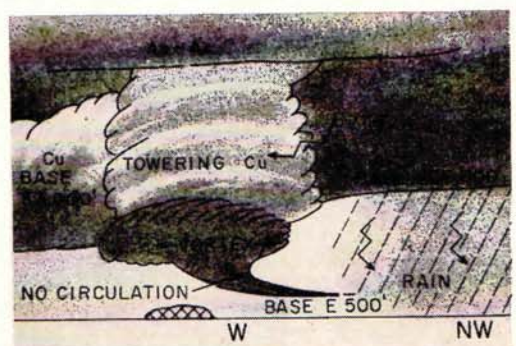


43 F LITTKE



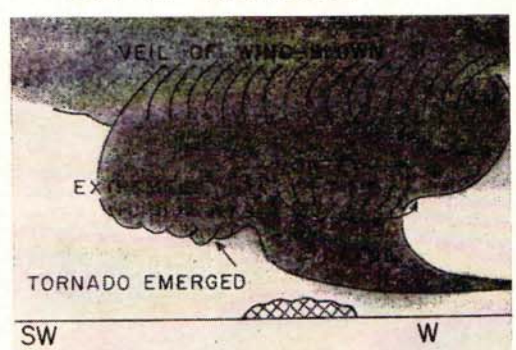
28 I JENSEN

44 G LITTKE



28 II JENSEN

44 H LITTKE



28 III JENSEN

FIGURE 33.—Photographs by Littke; sketches by Arhart and Jensen.

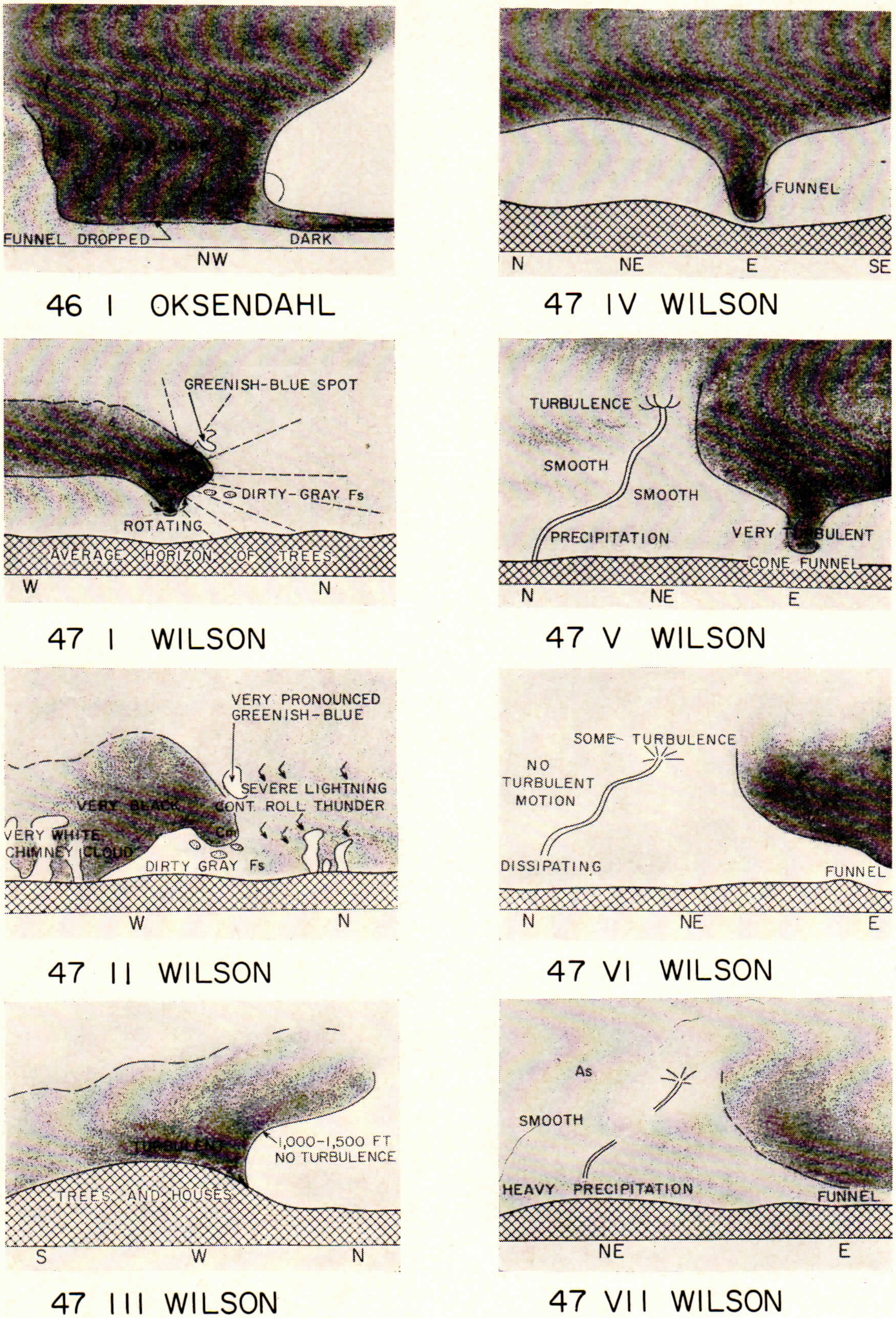


Figure 34.—Sketches by Oksendahl and Wilson.

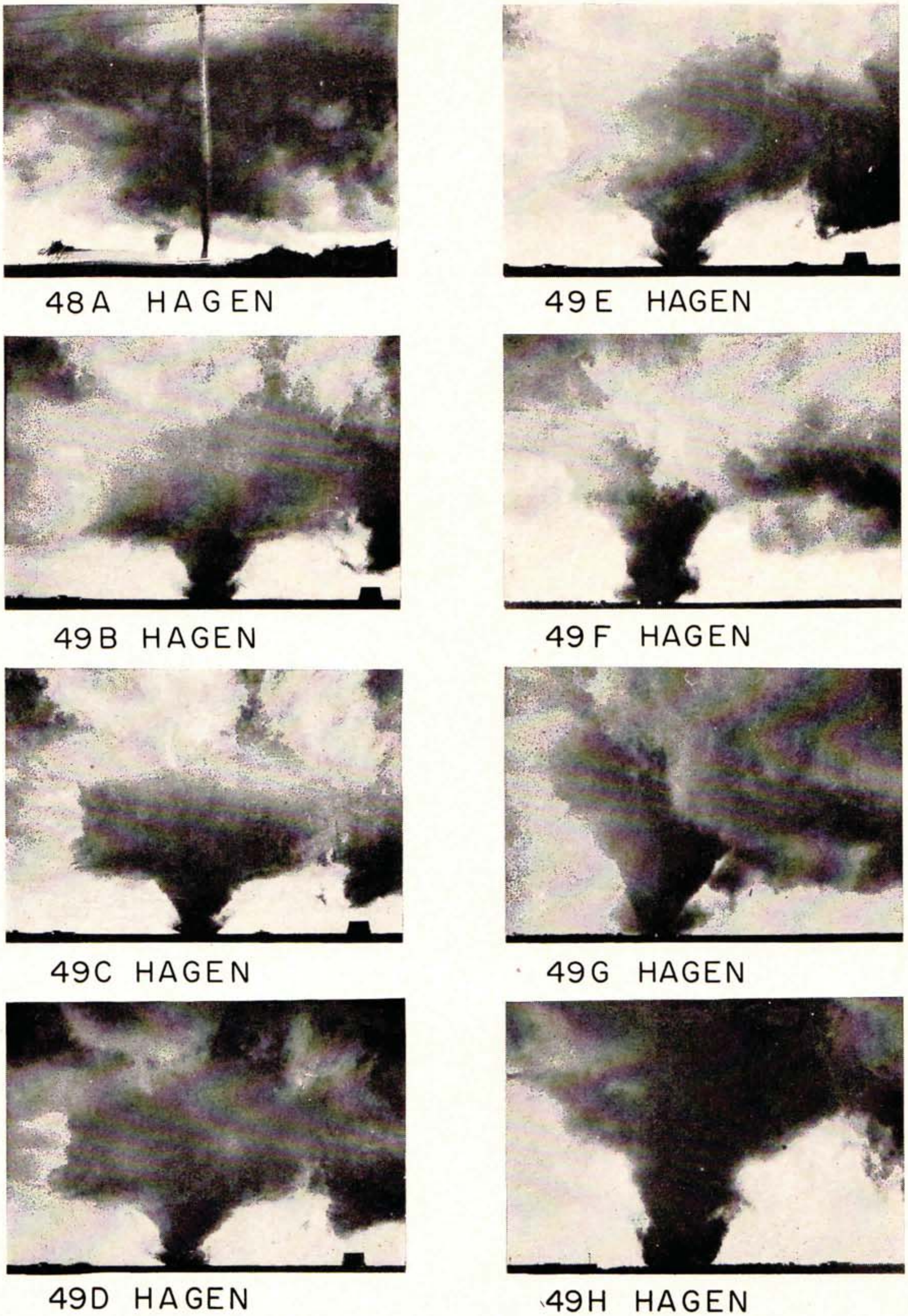
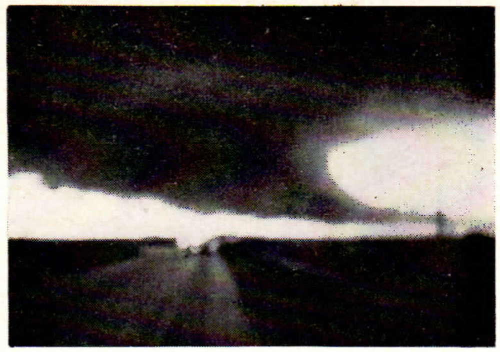


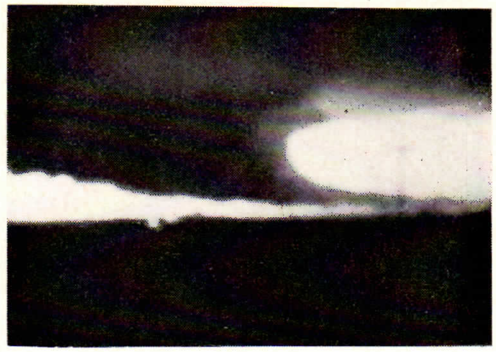
FIGURE 35.—Photographs by Hagen.

49 I HAGEN



50 A FRAHM

49 J HAGEN



50 B FRAHM

49 K HAGEN

50 C FRAHM

4 E FRADET

50 D FRAHM

FIGURE 36.—Photographs by Hagen, Fradet, and Frahm.

50E FRAHM

51D PAYNE

50F FRAHM

51E PAYNE

52A GREGORNICK

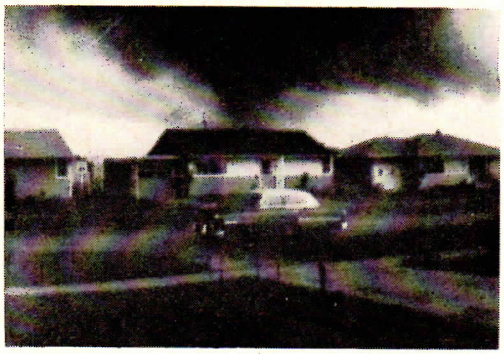
52C GREGORNICK

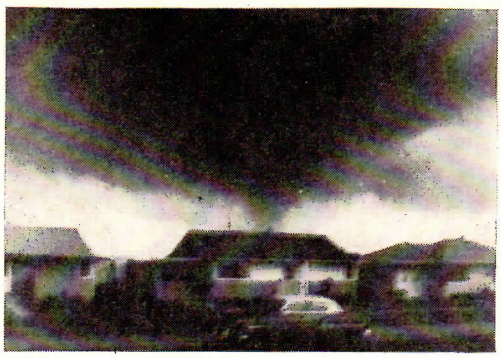
52B GREGORNICK

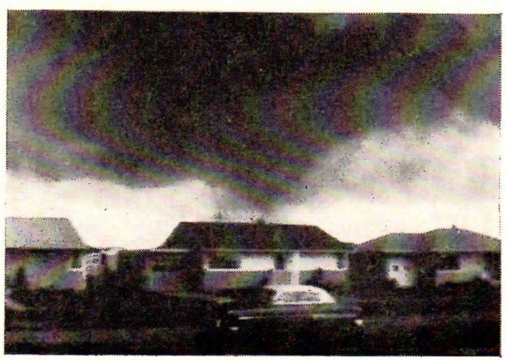
52D GREGORNICK

FIGURE 37.—Photographs by Frahm, Gregornick, and Payne.


52E GREGORNICK


52F GREGORNICK


52G GREGORNICK


52H GREGORNICK


52I GREGORNICK


52J GREGORNICK


52K GREGORNICK

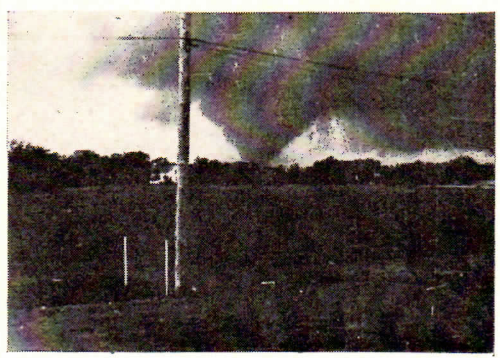

53A JAHNKE

FIGURE 38.—Photographs by Gregornick and Jahnke.

53B JAHNKE

53D JAHNKE

53C JAHNKE

53E JAHNKE

53F JAHNKE

FIGURE 39.—Photographs by Jahnke.

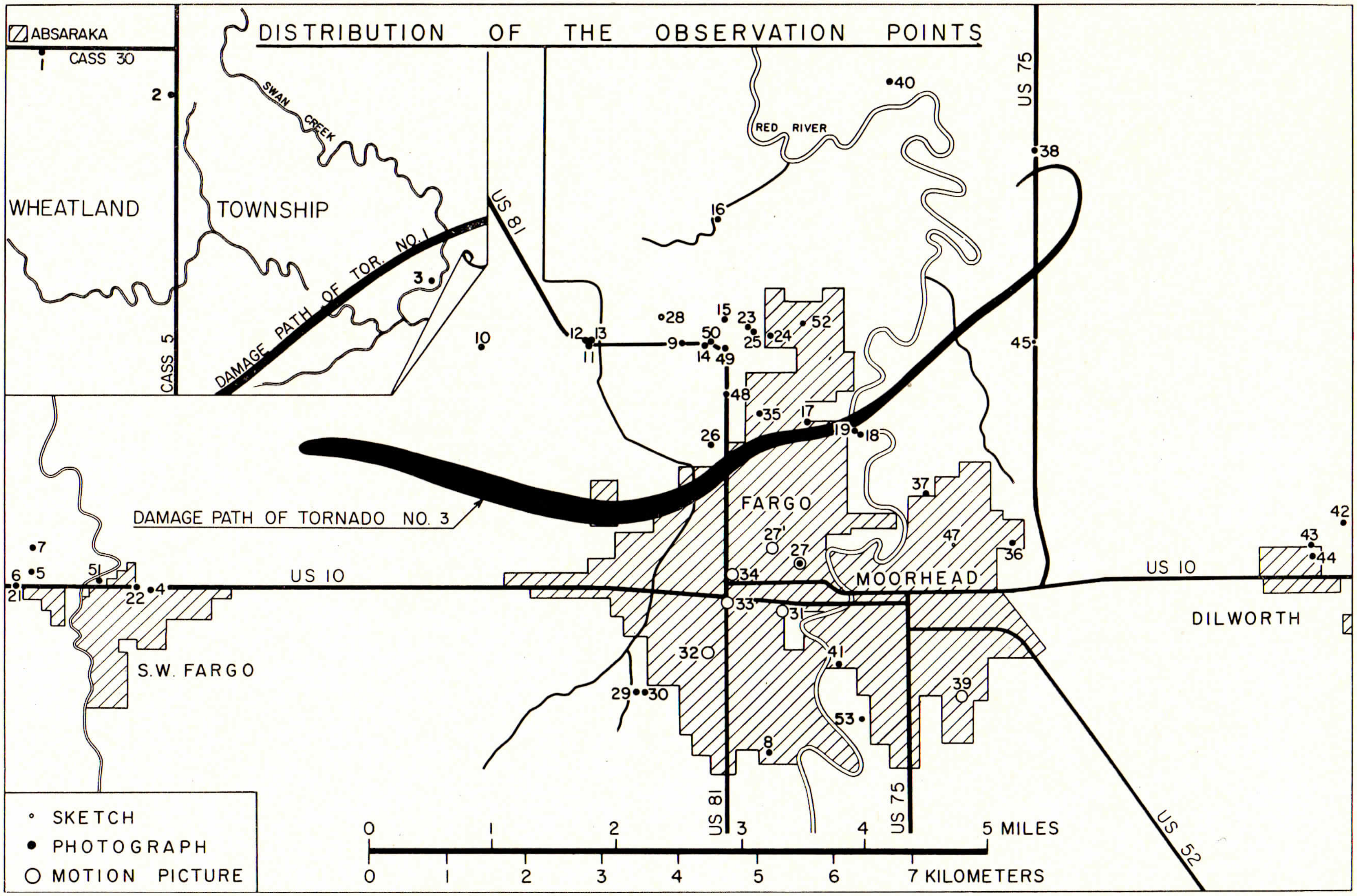


FIGURE 40.—Distribution of the observation points of the Fargo tornadoes of June 20, 1957. A summary of the observations is given in table 1.

4. MOTHER CLOUD OF FARGO TORNADO FAMILY

In view of the successive formations of five independent tornadoes in a narrow zone 6×64 miles centered around Fargo, N. Dak., it is of importance to investigate a tornado-producing system which moved eastward over that zone.

A rotating cloud system was successfully photographed (see photographs 04B (fig. 15); 09A ,B (fig. 17); 10C, D (fig. 17); 23A, B, C (fig. 20); and 40A (fig. 32), some of which show a funnel sticking out from the base of the rotating cloud). Interviews in Wheatland, Casselton, Glyndon, and Dale all revealed that the rotating cloud was in existence at the time of the tornadoes.

The rotating cloud was characterized by the following significant features:

(1) Wall cloud—a main mass of circulating cloud with a very low cloud base. Its outer boundary was very steep, forming a cylindrical wall.

(2) Tail cloud—a low tail-like cloud extending outward from the wall cloud.

(3) Collar cloud—a circular cloud surrounding the upper portion of the wall cloud.

(4) Disc cloud—disc-like cloud with spiral streaks on it. The diameter of the disc was about 10 miles.

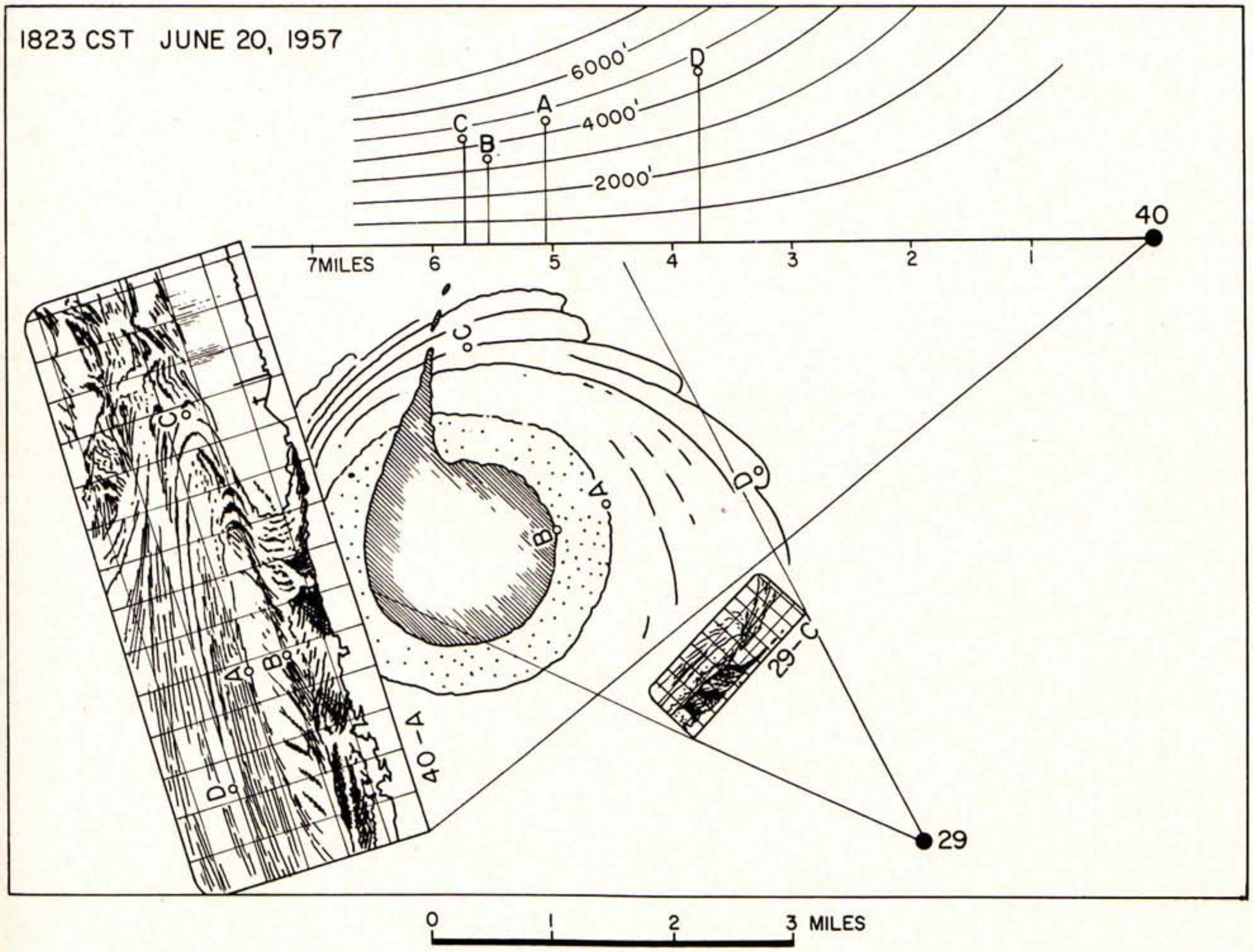


FIGURE 41.—An example of triangulation of the rotating cloud. Photographs 40A and 29C were used for the triangulation.

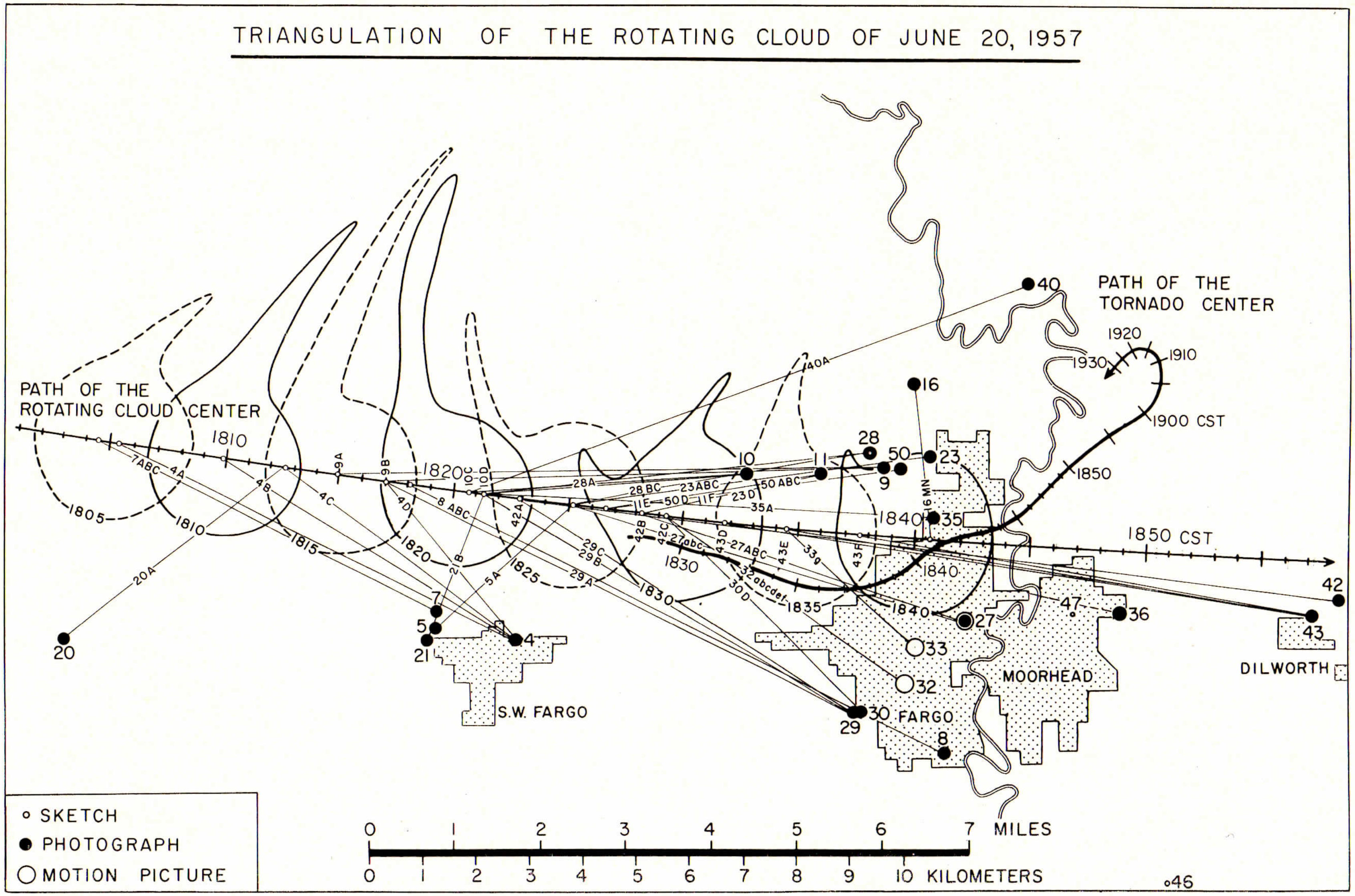


FIGURE 42.—Triangulation of the rotating cloud of June 20, 1957.

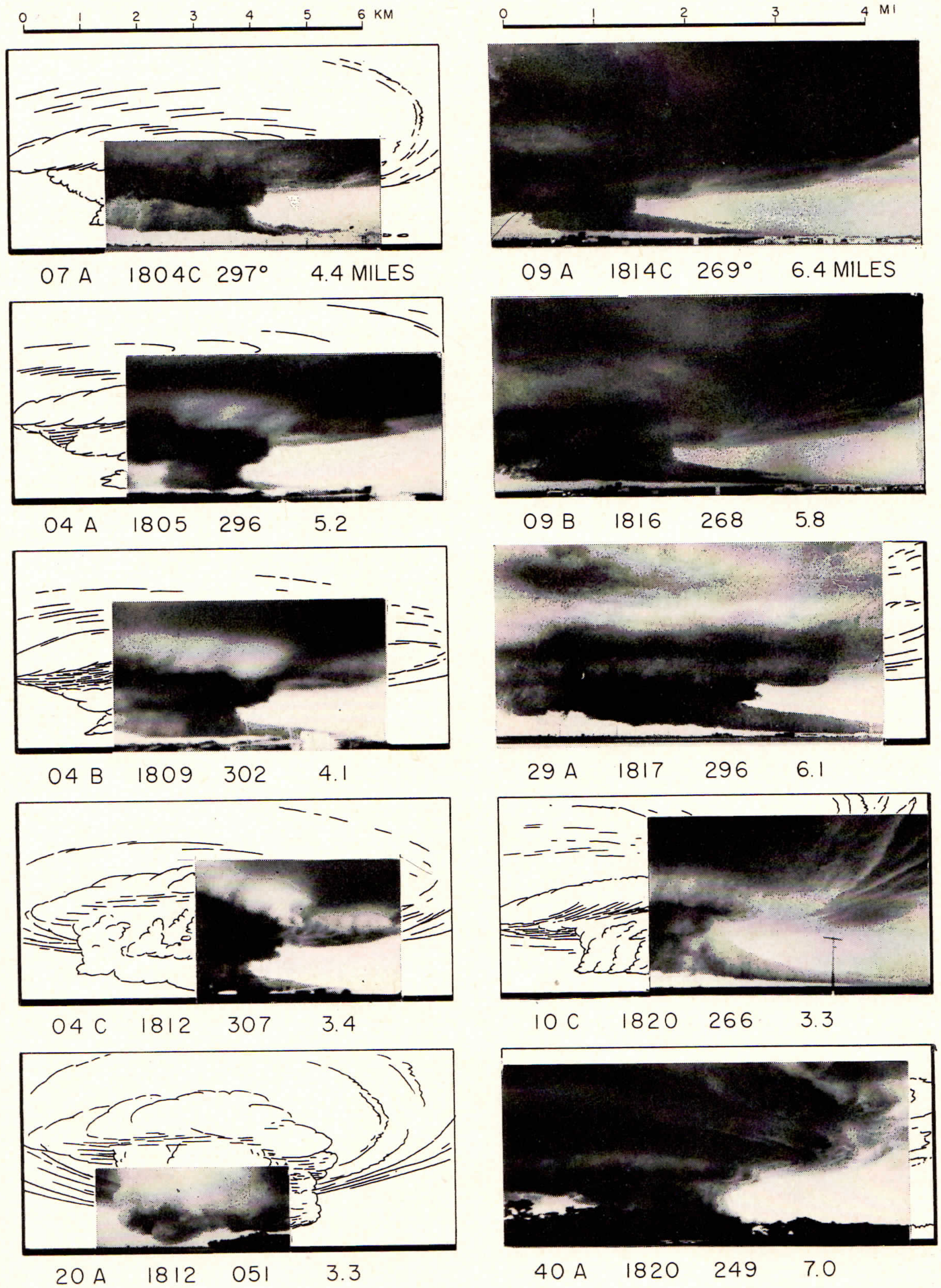


FIGURE 43.—Rotating cloud shown in the same scale, 1804–1820 CST.

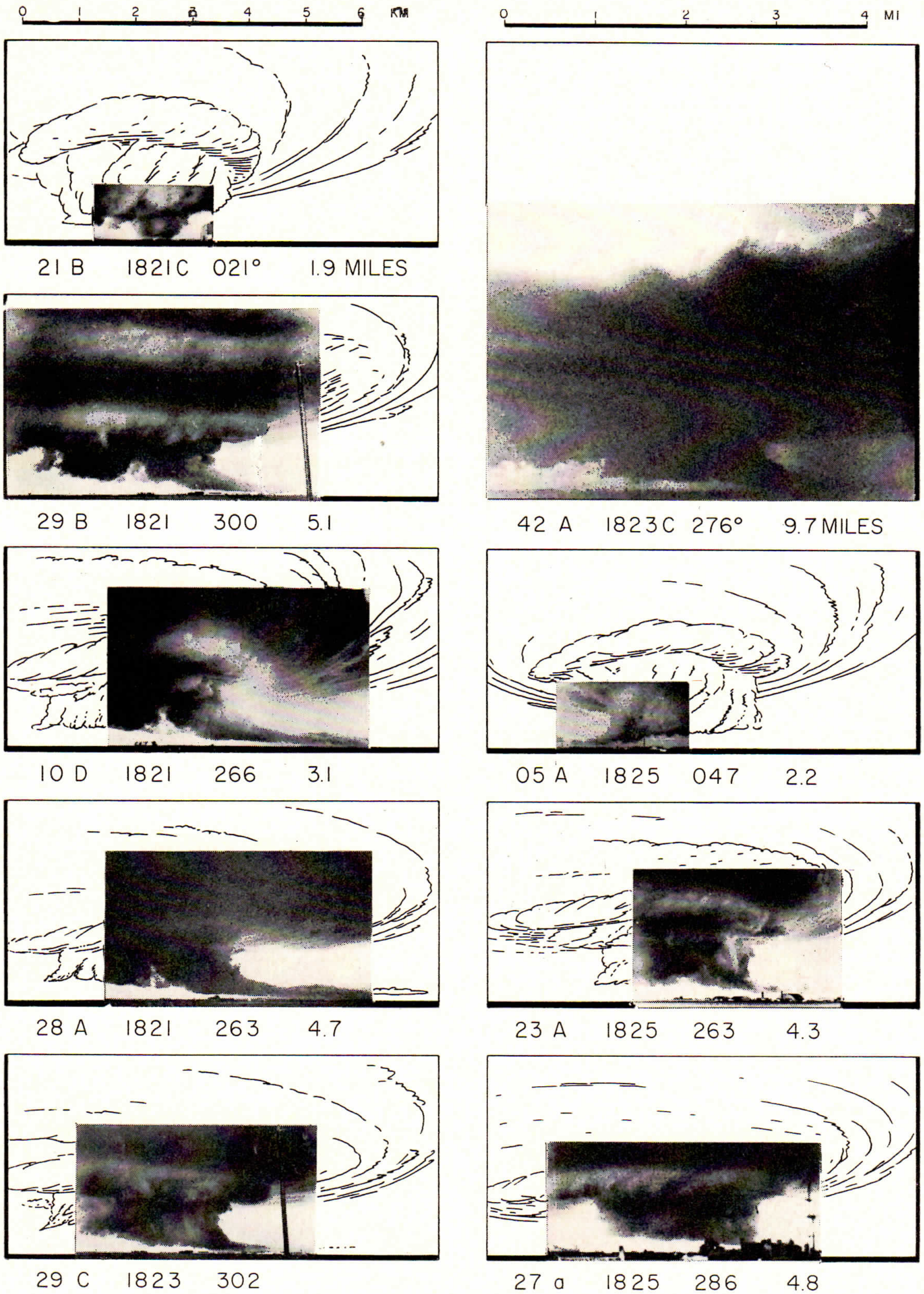


FIGURE 44.—Rotating cloud shown in the same scale, 1821–1825 CST.

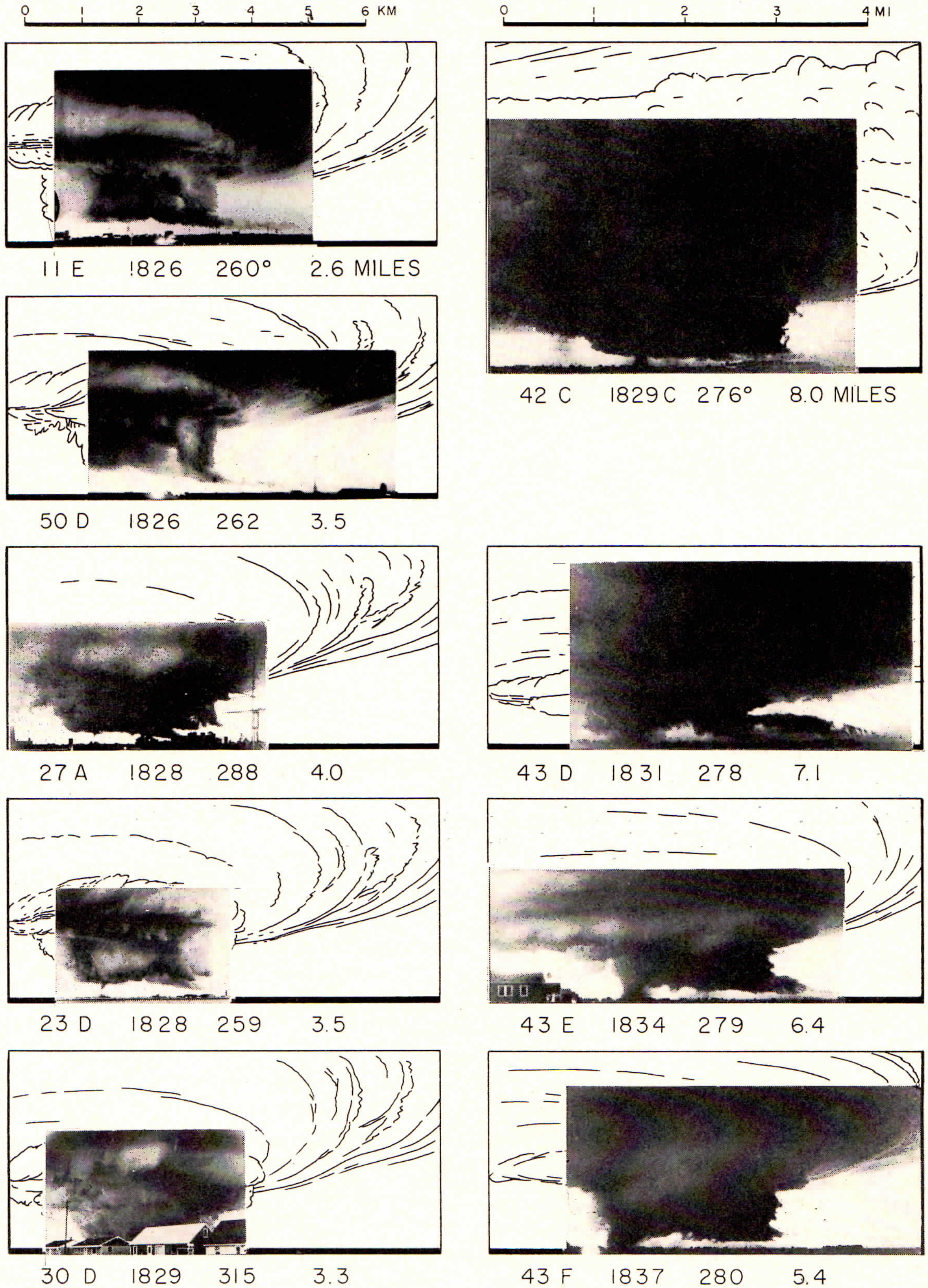


FIGURE 45.—Rotating cloud shown in the same scale, 1826–1837 CST.

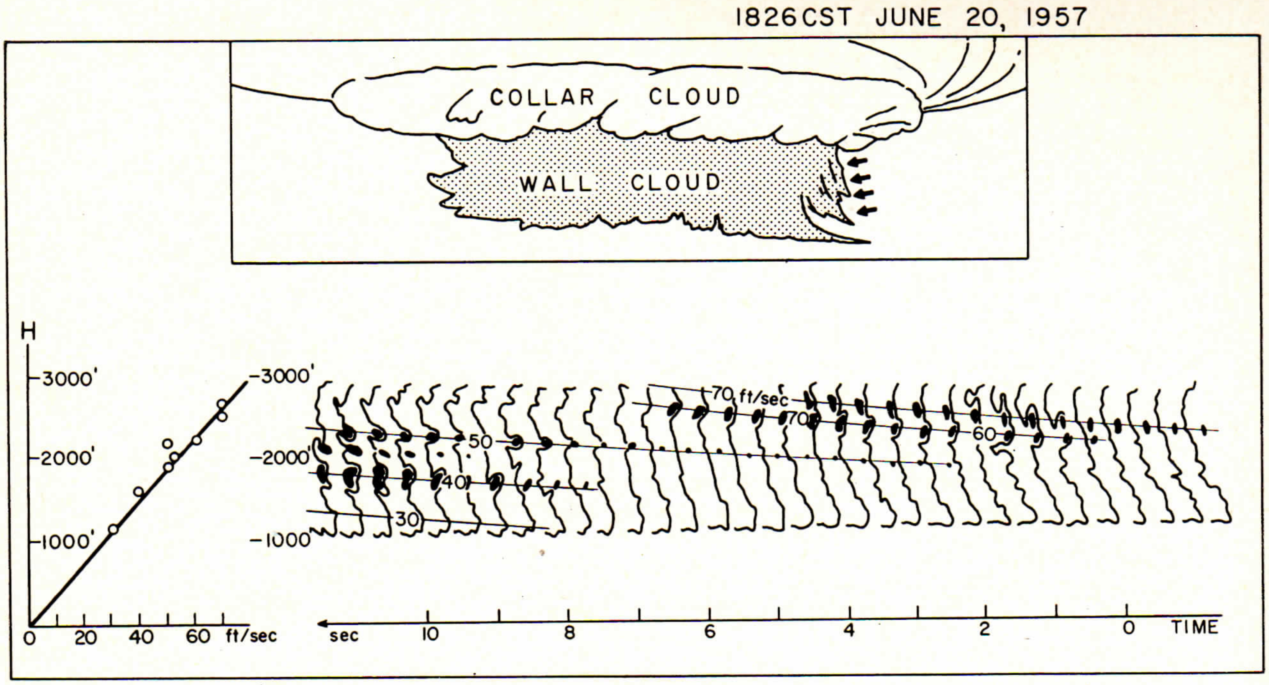


FIGURE 46.—Computation of the vertical motion at the edge of the wall cloud. Arrows in the upper figure show the portion of the cloud used for the computation.

After careful examination, some of the photographs of the rotating cloud under discussion were found to have very similar features, suggesting that they were taken within a very short time interval. They were classified into several groups according to time. Figure 41 shows a triangulation technique by means of which the true dimensions of the rotating cloud were obtained for plan position representation.

Triangulation also permits computation of the height of each point on the cloud. For example, the heights of four points (A–D) on the cloud were obtained by using the technique appearing in the figure. First the iso-height lines, indicated as a group of hyperbolas at 1000-foot intervals, were drawn. By combining the plane and vertical cloud figures, it is possible to place any point on the cloud on the upper diagram of the figure for height computations.

After carrying out the photographic analysis of the rotating cloud before and during the time of the Fargo tornado, an organized presentation was achieved. The result is given in figure 42. It can be seen that the tail cloud grew in length and width as it moved northwest of South West Fargo. When the tail had completely disappeared, the second tail appeared to the north of the main mass of the cloud. Both tail clouds rotated cyclonically around the center of the main rotating cloud.

Motion and still pictures reveal that each tail cloud was sucked into the dark, stationary wall cloud, while the formation of the new tail cloud was taking place at the far north end of the wall cloud.

The figure also shows the path of the Fargo tornado, which formed at 1827 ½ CST about ½ mile to the south of the rotating cloud center. No funnel was seen in the cloud pictures taken between 1805 CST and the first appearance of the Fargo tornado funnel. After its formation the funnel gradually moved east-southeastward away from the center of the rotating cloud. After a few minutes it changed course and weakened as it moved to the northeast and crossed the path of the rotating cloud center.

An attempt was made to reduce or enlarge the rotating cloud photographs to a single scale so that successive stages of the cloud could be directly compared. Figures 43, 44, and 45 show the photographs arranged in chronological order. Each photograph is identified by observation point number and frame order. Since the outlines of the cloud extended even beyond the area of the photographs, each box in the figures includes only the greater portion of the rotating cloud.

The degrees and miles are the direction and the distance of the center of the rotating cloud from the photographer. As seen in most of the photographs, a tail-like cloud extended to the right, with the exception of 20A (fig. 43) and 21B (fig. 44) photographed facing toward the axis of the tail, and 05A (fig. 44) with the tail extending to the left.

Very intense vertical motion was observed on the side of the wall cloud. Observers described the motion as boiling or turbulence. A movie strip taken by Jennings (observation point 27) was usable for the computation of the vertical motion occurring in the portion of the cloud indicated by arrows in figure 46. Shown in the lower portion of the figure is the profile of the side of the wall cloud appearing in every tenth frame of the movie, which was taken at 24 frames per second. The time scale in seconds appears at the bottom.

Using the height scale to the left, vertical velocities of several sections of the rising cloud were computed. Speeds were very high, reaching 80 ft. sec.$^{-1}$ at the 3000-foot level. Below that level the velocity decreased in proportion to the height above the ground, where the vertical velocity is zero. It is of interest to compute the horizontal convergence, $\Delta w/\Delta z$, using the values $\Delta w=80$ ft. sec.$^{-1}$ and $\Delta z=3000$ ft. The value thus obtained is about 3000×10^{-5} sec.$^{-1}$. It is evident that the convergence does not change with height in the portion of the cloud under discussion. If we postulate that the same divergence value as obtained above is applicable up to the 10,000-foot level, the vertical velocity at that level would be about 333 ft. sec.$^{-1}$. Although this value seems too high, an incloud updraft of 100–200 ft. sec.$^{-1}$ can be considered a relatively realistic value.

In order to compute the rotational motion of the cloud under discussion, every 30th frame of Jennings' movie (27 a, b) was transcribed in figure 47. This film includes 810 frames taken at 24 per second. The results of computation revealed that the ring cloud circling around the uprising cloud mass was rotating at only 25 m.p.h., a very slow speed compared with the vertical velocity involved.

Another independent computation of the circulation velocity of the rotating cloud was made by using four still photographs (49 B, C, D, E) taken by Mr. Hagen. Although the time interval of these photographs is unknown, the displacement

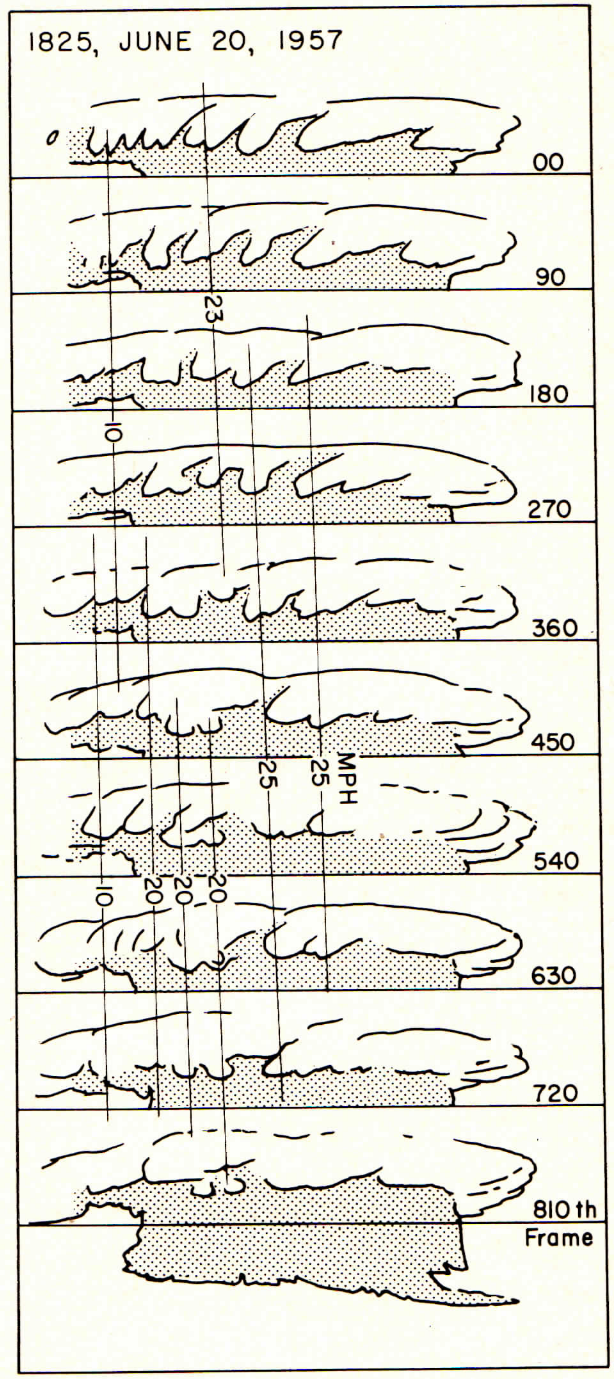


Figure 47.—Every 90th frame of Jennings' movie used in obtaining the rotational speed of the collar cloud.

of the tornado center determined by the photographs enables us to estimate the approximate time to be about 25 seconds. Using this estimate and photographs 49 B–E (fig. 35) and 43 D (fig. 32) figure 48 was made. The individual move-

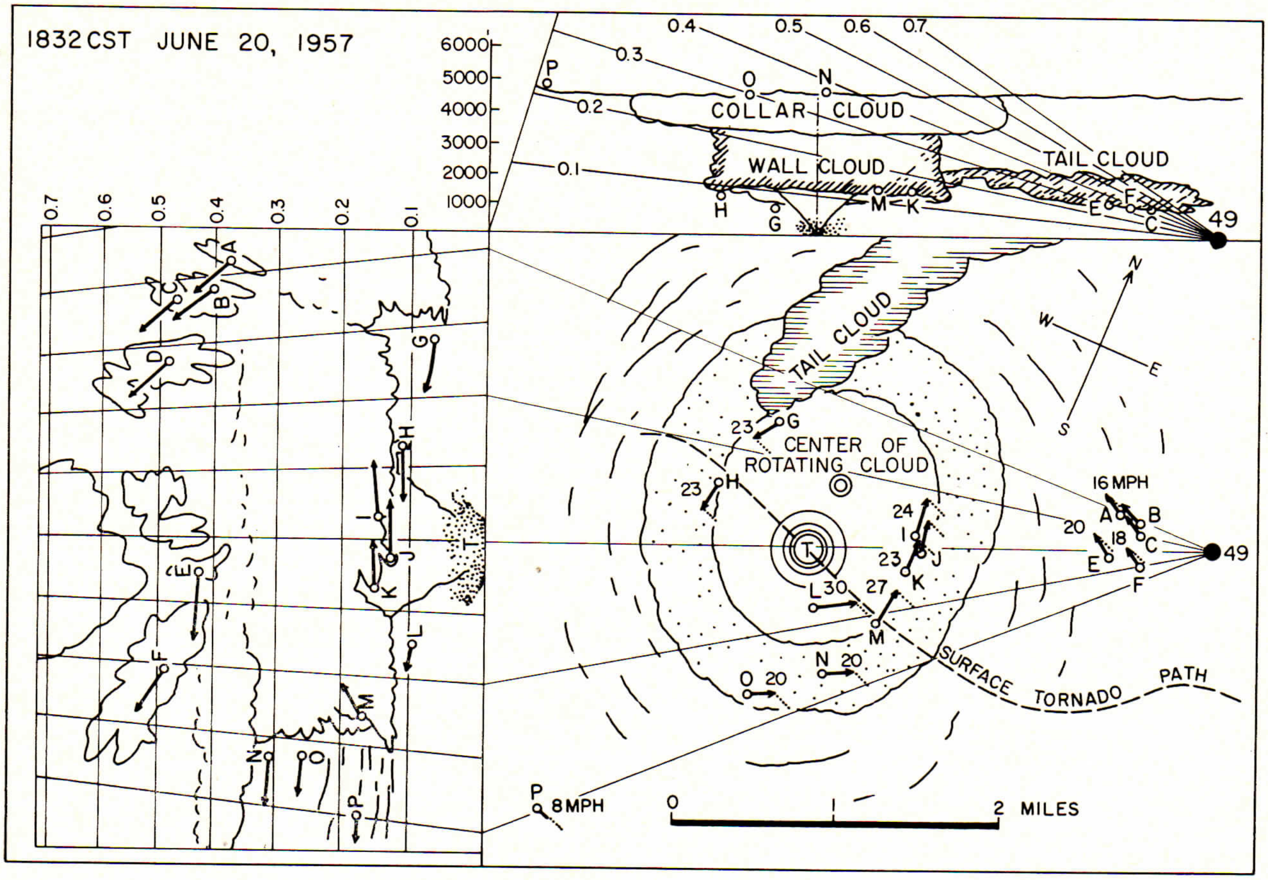


FIGURE 48.—Determination of the rotational speed of the rotating cloud.

ment vectors of significant portions of the cloud were determined on four prints of Hagen's photographs and projected on a plan-position chart. Then the dotted vector, corresponding to the displacement of the circulating system, was subtracted from each vector in order to determine the relative motion of the cloud portion with respect to the circulation center.

5. CHANGE IN SHAPE OF THE TORNADO FUNNEL

The technique used for determining the direction of the rotating cloud discussed in the previous section was repeated for the triangulation of the tornado funnel. The result is shown in figure 49. Two dozen pictures were taken within one minute after the appearance of the cone-shaped funnel. This fact indicates that a great number of people with cameras had correctly anticipated the area where the funnel was to drop. Table 2 shows the number of pictures taken during each 2- or 10-minute period after the appearance of the funnel.

It is interesting to find that the number of pictures decreased with time after the appearance of the cone- or rope-shaped funnel. This suggests that

TABLE 2.—*Number of photographs taken during each 2- or 10-minute interval of the Fargo tornado funnel*

Minutes after the tornado	Number of photographs	Remarks
0–2	24	Cone-shaped funnel dropped to the ground.
2–4	9	Funnel appeared like a cylinder.
4–6	15	Huge cone funnel.
6–8	5	Do.
8–10	12	Funnel was over Golden Ridge residential area.
10–12	15	Funnel crossed drain No. 3.
12–14	8	Funnel crossed 13th Street.
14–16	2	Funnel was destroying residential area.
16–18	0	Funnel crossed Red River.
18–20	0	Funnel obscured by rain.
20–30	0	Do.
30–40	9	Rope funnel appeared.
40–50	5	Rope funnel in its dissipating stage.
50–60	1	Rope funnel dissipated.

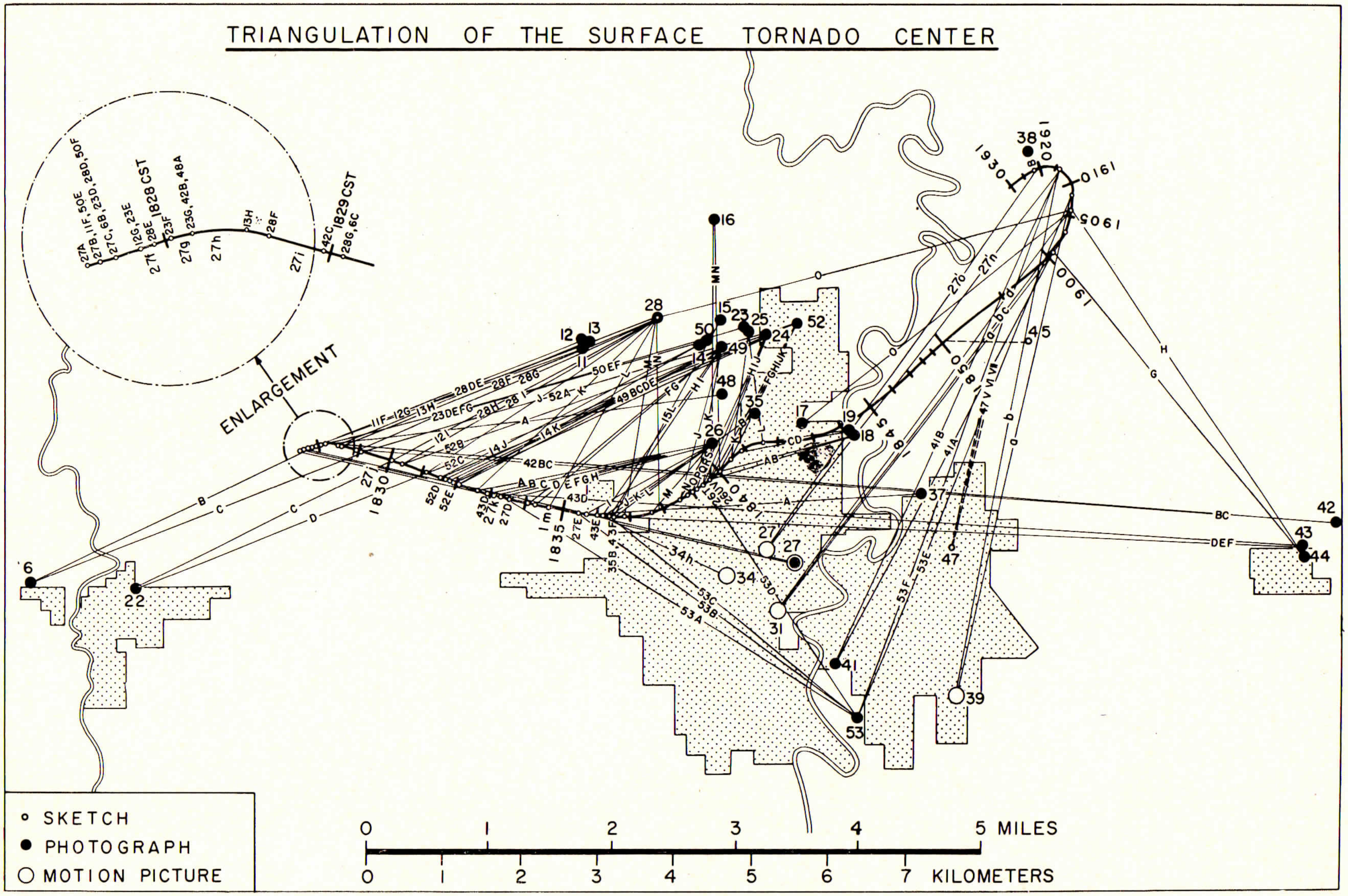


FIGURE 49.—Triangulation of the surface center of the Fargo tornado.

most of the people started taking funnel pictures as soon as they saw a funnel and continued until their film ran out. It would be practically impossible to estimate the correct time intervals for apportioning a given length of film to the life of a tornado. As seen in the figure, the pictures were nevertheless found to be adequate to cover the greater portion of the tornado's life history.

By means of the time-checks made by Weather Bureau observers as the tornado advanced toward the city and other reports concerning the time when the storm crossed certain points, a smoothed time scale was put along the path of the tornado at the surface. Figure 49 indicates the time of each tornado picture as determined from this scale.

CONE-SHAPED FUNNEL

Using the technique described in the previous section, tornado photographs were reduced to the same scale. This reduction seems merited when the various pictures show the storm in stages which can be compared in size and shape with each other. Figures 50–54 give the results of this single-scale representation. It is important to notice that the photographs are arranged in chronological order; thus, successive changes in the funnel can be followed from one picture to the next.

A motion picture with a very short time lapse was made by filming each of these pictures in chronological order. The film, when projected, was found to be capable of representing in a few seconds the entire life cycle of the Fargo tornado.

The change in shape of the Fargo tornado is summarized in figure 55. The top profiles show the schematic features of the funnel in its four stages: (a) dropping stage, (b) rounded bottom stage, (c) shrinking stage, and (d) rope stage.

It will be worthwhile to know how the other tornadoes belonging to the Fargo tornado family went through their life cycles. The following list shows the author's estimate, based upon witnesses' conversation and sketches:

(1)	Wheatland tornado	a–d
(2)	Casselton tornado	a–d–b–?
(3)	Fargo tornado	a–b–c–d
(4)	Glyndon tornado	a–b–c–d
(5)	Dale tornado	a–b–c–d

A detailed analysis of the diameter of the Fargo tornado funnel at its dropping stage was made with the use of still and motion pictures. Since no time checks were made when the photographs were taken, the only indications of the passage of time were the movie strips, 27f (17 seconds), 27g (3 seconds), 27h (13 seconds), 27i (15 seconds), and 27j (10 seconds), from which the rate of increase in funnel diameter was determined.

Figure 56 shows the process of obtaining the times of photographs taken in the dropping funnel stage. The arrows in the figure show the rate of expansion of the average funnel diameters at the surface, 100-meter, and 200-meter levels. The arrow directions coincide with the tangents of a line showing the average funnel diameter. For example, the arrow corresponding to the movie 27f entered the figure first, then was extended to reach the diameter determined by 27h, and again was extrapolated in order to complete the entire mean funnel diameter curve in the figure. Once the mean diameter was determined as a function of time, the time of each still photograph was determined by computing the funnel diameter appearing in the photograph.

Reasonably accurate diameters of the Fargo tornado funnel were thus plotted in figure 57. It can be seen that the funnel dropped at the rate of about 333 m. min.$^{-1}$ or 5 m. sec.$^{-1}$. That is to say, it took only 30 seconds for the funnel to reach the ground after its tip had appeared under the base of the rotating cloud.

ROPE-SHAPED FUNNEL

As shown in the previous sections, most of the tornadoes belonging to the Fargo tornado family went through the rope stage before they dissipated. Unfortunately, no photographic evidence of a rope-type funnel was obtained except from the Fargo-Moorhead area, where the citizens took eight short movie strips and seven still photographs.

The first indication of the transformation from cone to rope-type funnel was witnessed by Mr. Arhart (45I), who observed a grayish white funnel traveling east. His observation point and sketch are shown in figures 40 and 33, respectively. Heavy rain in the area prevented people from observing or photographing the cone funnel as it was redeveloping into a rope funnel.

Soon after, a still (44G) and a motion picture (31a) were made. The three-dimensional triangulation of the funnel shown in figure 58 revealed that the funnel, slender and slightly curved, was tilted at about 45 degrees toward the direction of the rotating cloud center, which had moved east past Dilworth. The top of the funnel was visible up to the 5000-foot level.

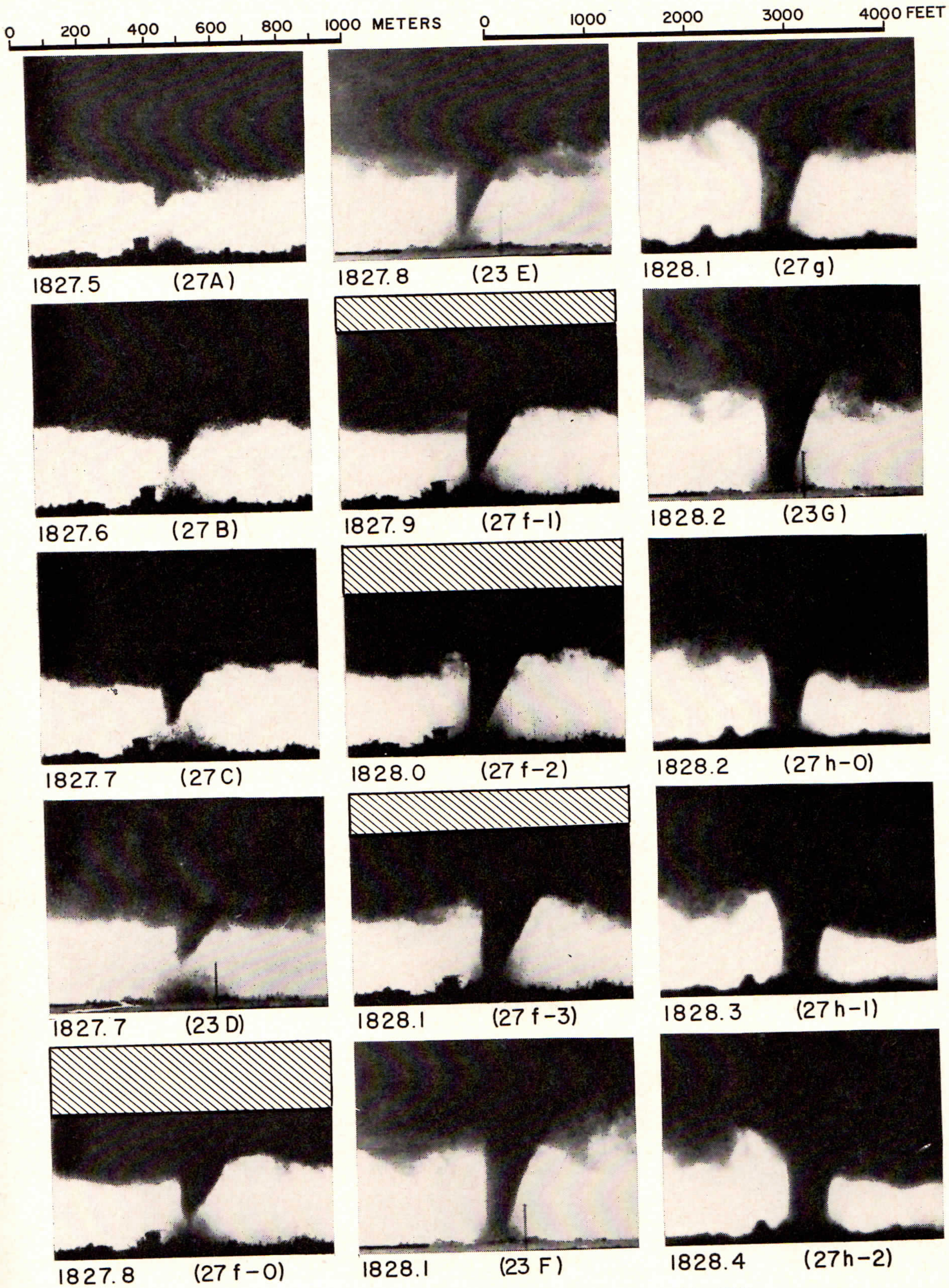


FIGURE 50.—Tornado funnel shown in the same scale, 1827–1828 CST.

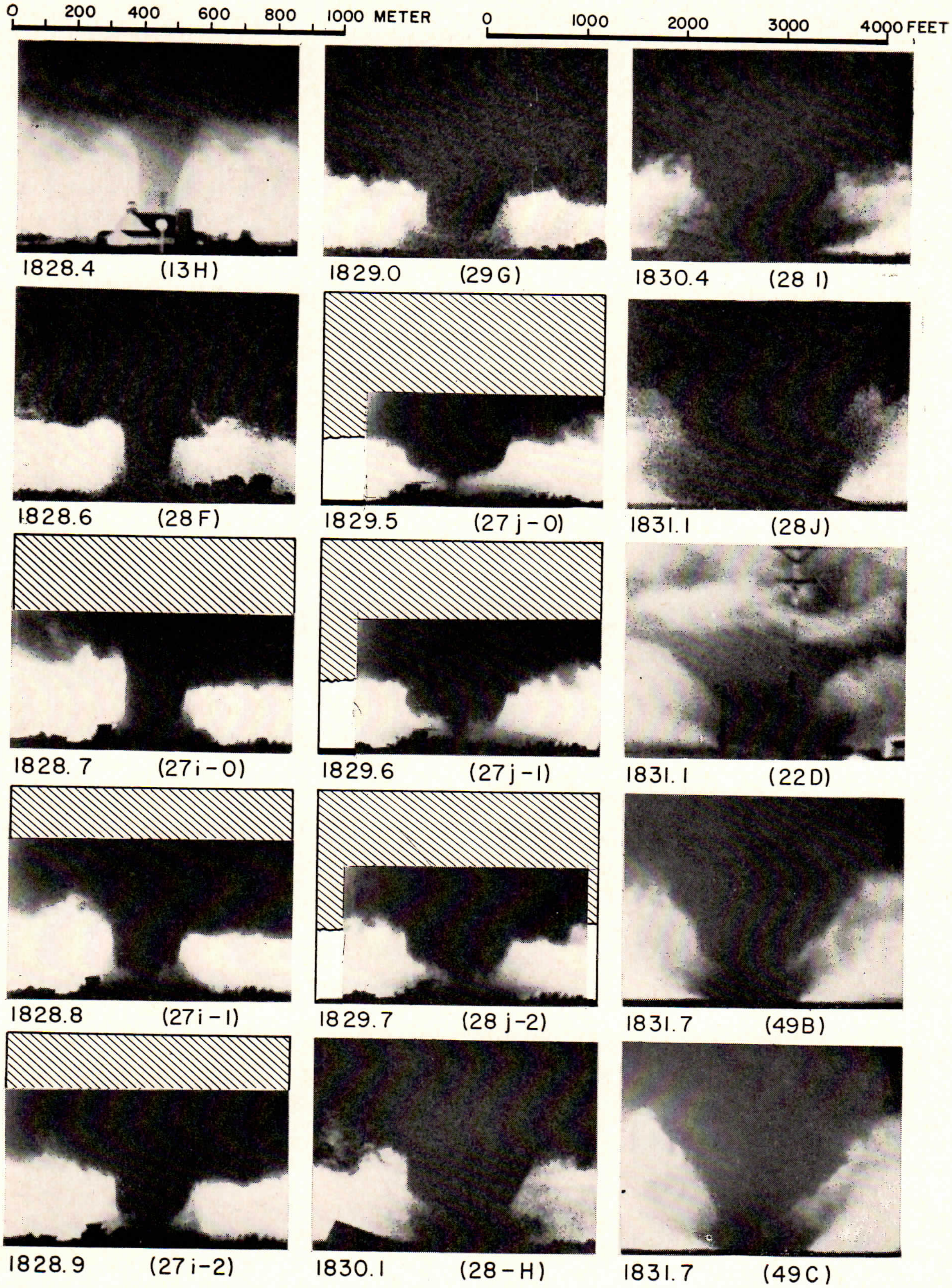


FIGURE 51.—Tornado funnel shown in the same scale, 1828–1831 CST.

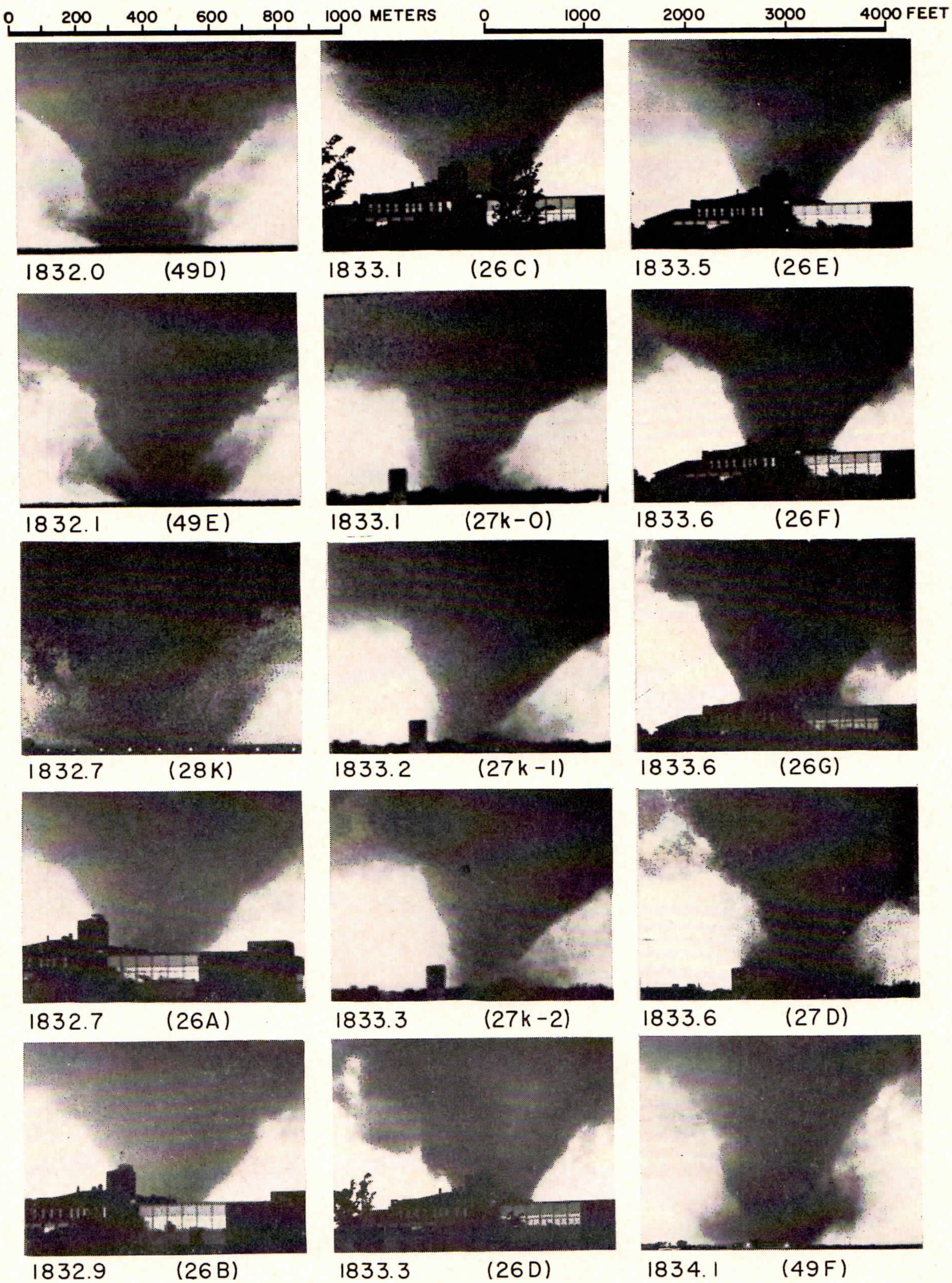


FIGURE 52.—Tornado funnel shown in the same scale, 1832–1834 CST.

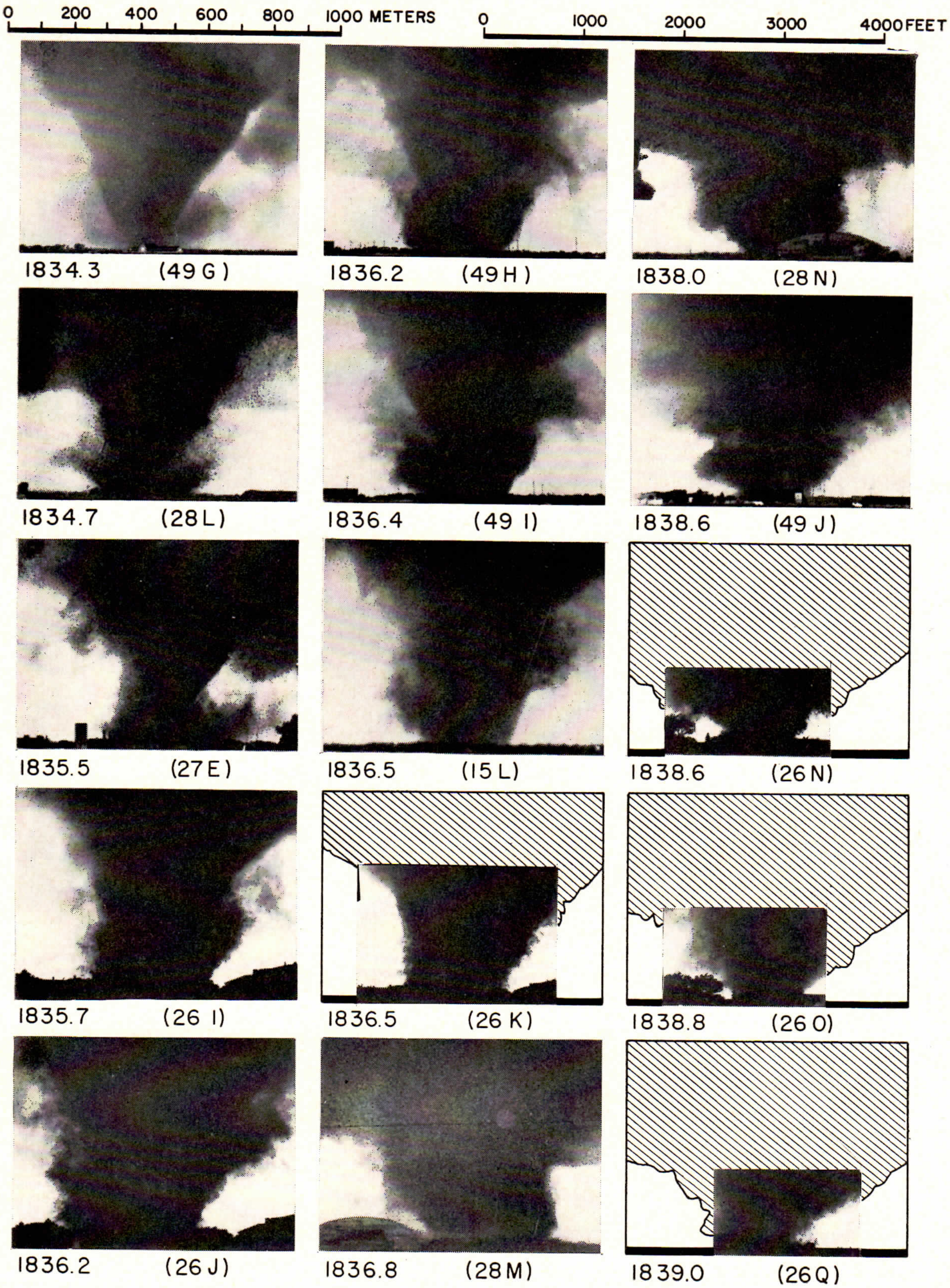


Figure 53.—Tornado funnel shown in the same scale, 1834–1839 cst.

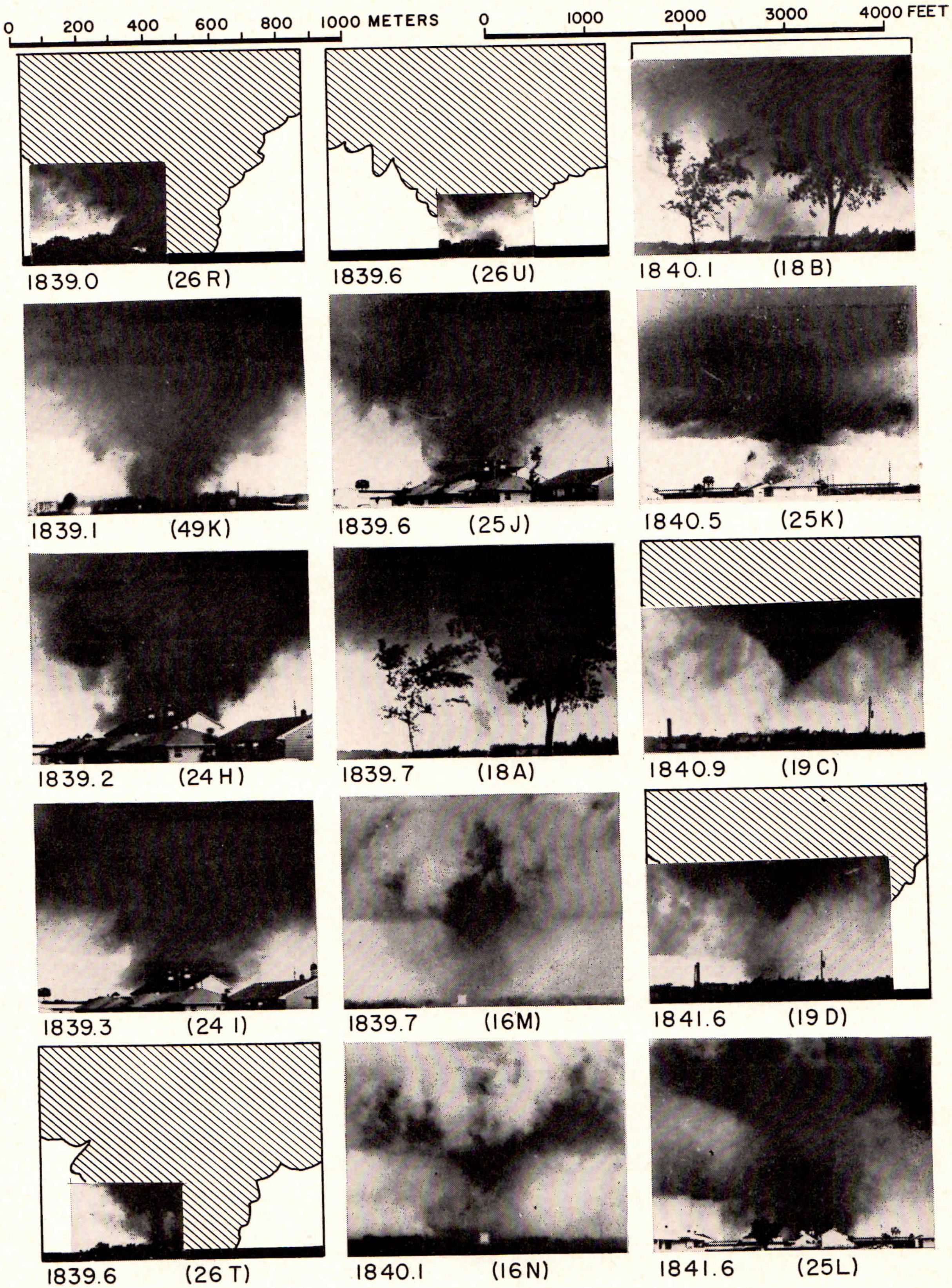


FIGURE 54.—Tornado funnel shown in the same scale, 1839–1841 CST.

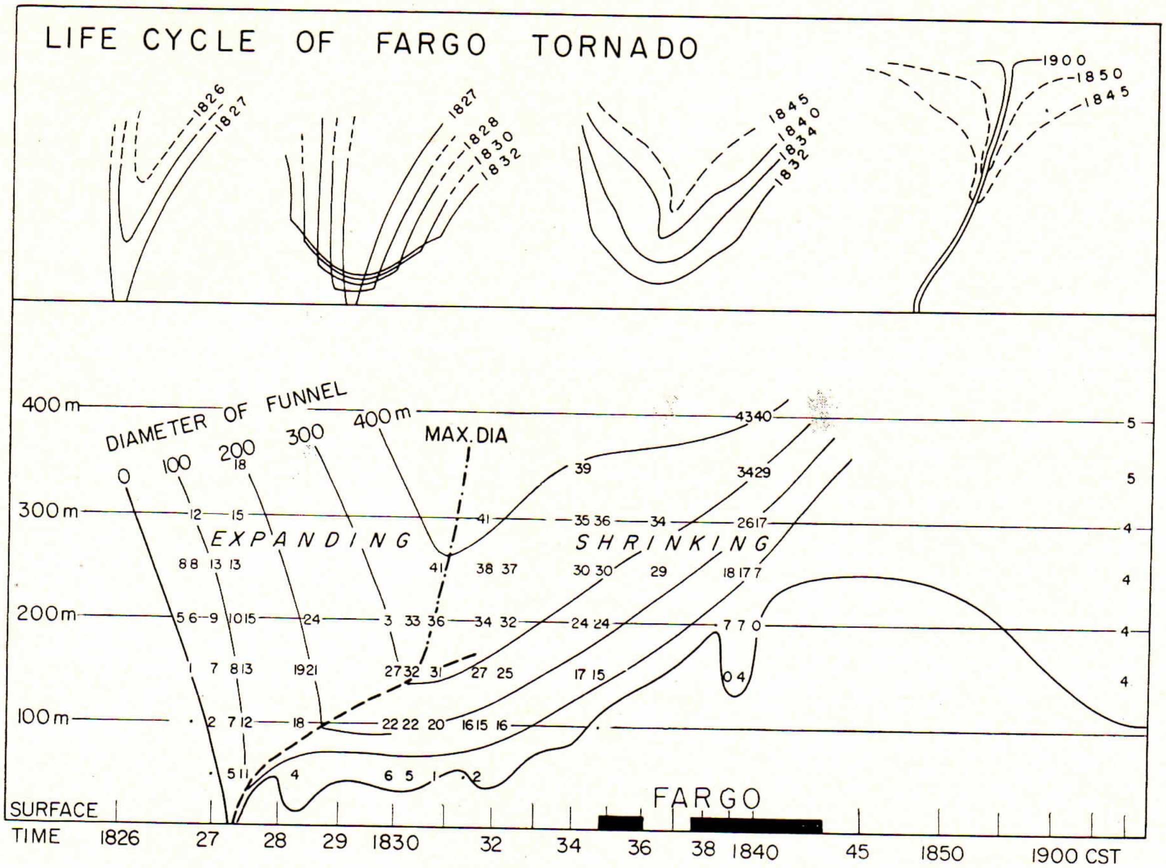


Figure 55.—Change in shape of the Fargo tornado funnel in its entire life history.

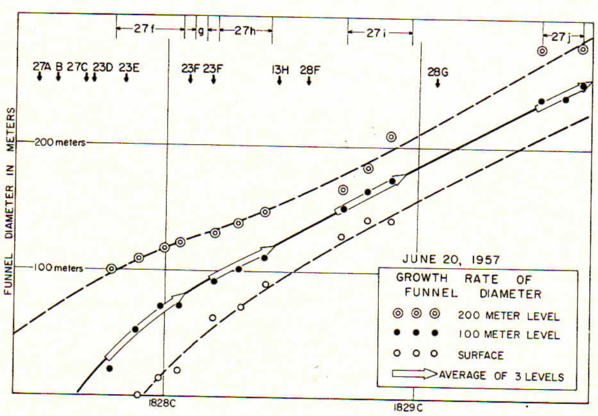


Figure 56.—Funnel diameter-time diagram.

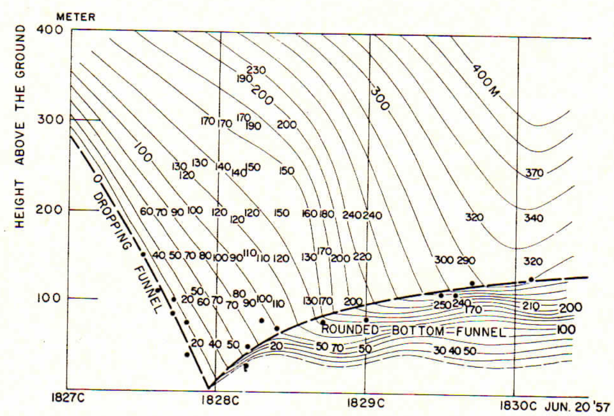


Figure 57.—Diameter (m.) of the Fargo tornado funnel shown in height-time diagram.

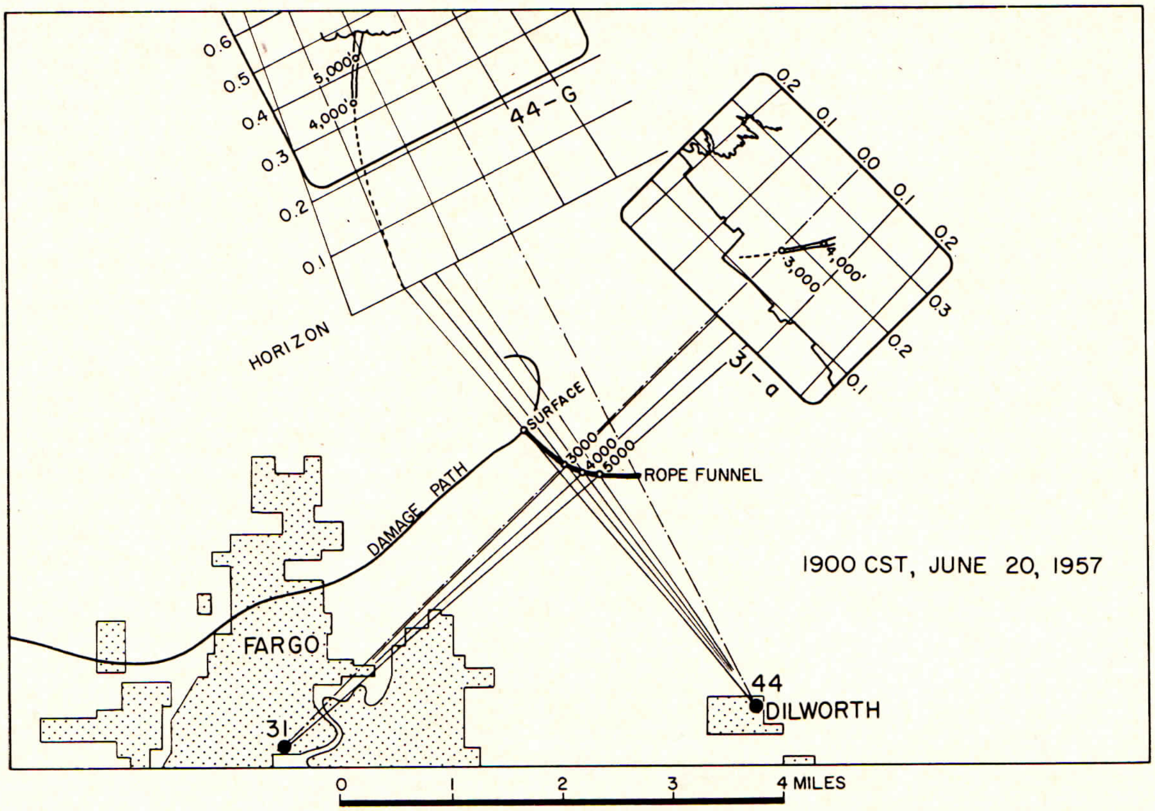


FIGURE 58.—Triangulation of the Fargo tornado funnel in its rope stage.

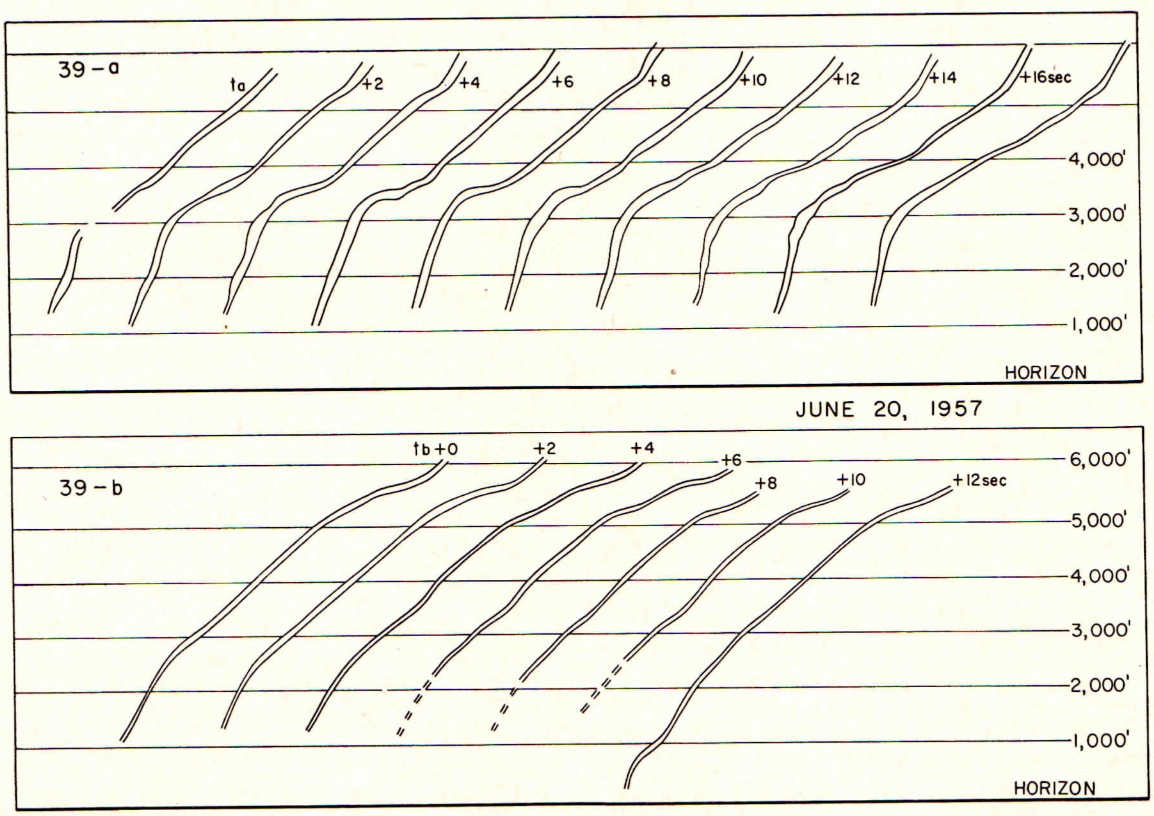


FIGURE 59.—Successive change in shape of the rope funnel appearing in Mickelson's movie 39a and 39b.

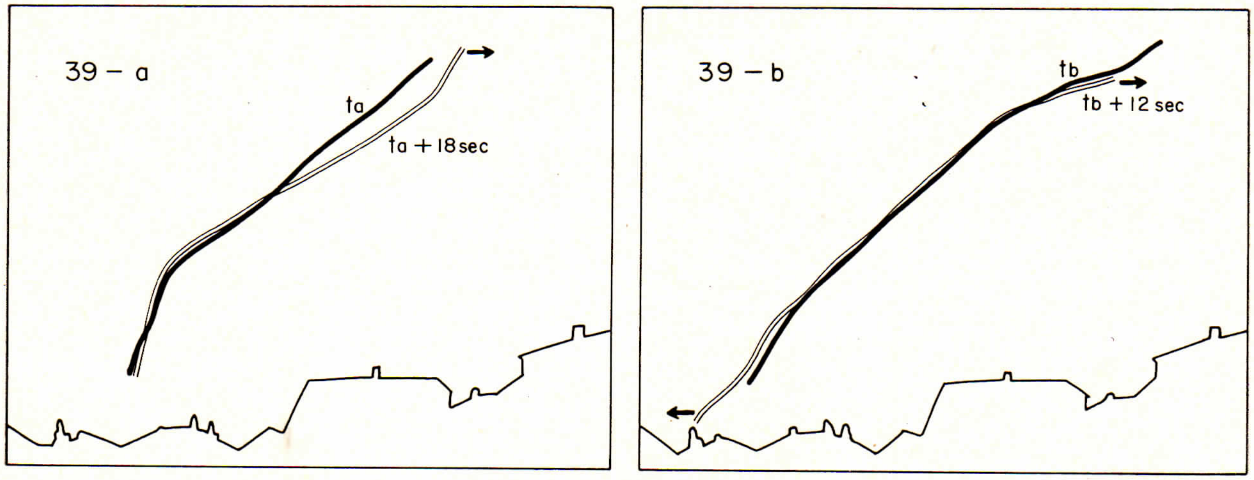


FIGURE 60.—Movement of the rope funnel appearing in 39a and 39b.

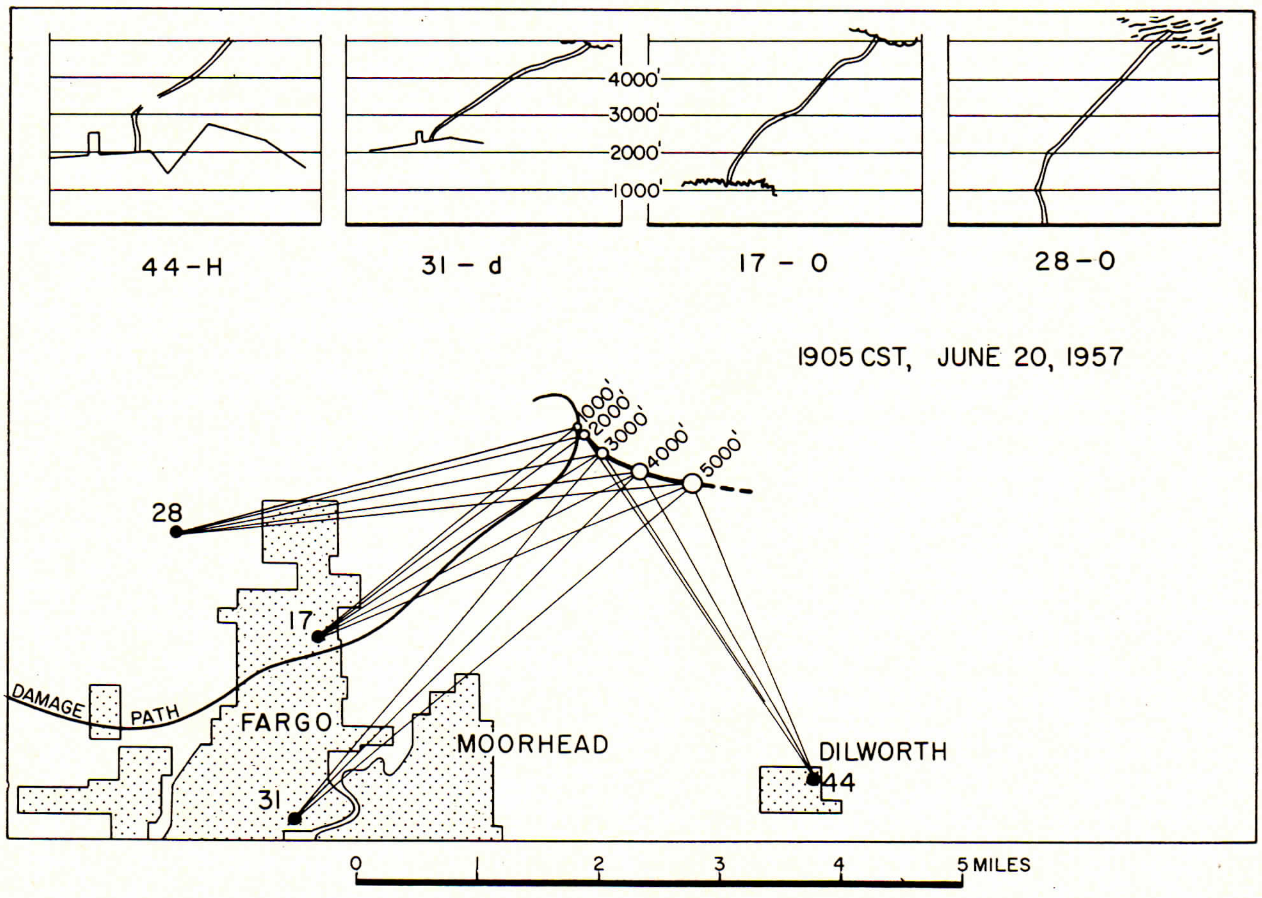


FIGURE 61.—Three-dimensional shape of the rope funnel northeast of Moorhead.

Mr. Mickelson took two movie strips (39 a and b). The shape of the funnel at 2-second intervals appears in figure 59. In spite of attempts to obtain the movement of wide or narrow portions of the rope, no solution has yet been found. Although the time interval between these two movie strips is not known, it is evident that the rope became definitely narrower.

It is of interest to see the superimposed representations of the first and the last frames. Figure 60, with the rope funnel looking north, reveals that the upper portion was moving eastward while the lower portion of the funnel moved westward or remained stationary. According to witnesses, the end of the rope was whipping the ground occasionally.

Photographs 44H, 31d, 17O, and 28O, apparently taken at approximately the same time, were used to construct the three-dimensional picture of the rope funnel slightly before it dissipated. The triangulation is described in figure 61. It should be noted that the funnel was vertically inclined near the ground and tilted almost horizontally near the cloud base.

6. ROTATION OF THE FUNNEL

Attempts were made to compute the rotational speed of the Fargo tornado funnel in its cone stage.

If we assume that the water vapor in rising air parcels condensed at the funnel edge, along which the pressure was constant, the hydrostatic and cyclostrophic assumptions enable us to write:

$$-\frac{1}{\rho}\frac{\Delta p}{\Delta r}=\frac{V^2}{r} \qquad (1)$$

$$\Delta p=-\rho g\Delta z \qquad (2)$$

Therefore we have:

$$\frac{\Delta z}{\Delta r}=\frac{1}{g}\frac{V^2}{r} \qquad (3)$$

where V is the cyclostrophic wind speed; ρ, the density; r, the radius, and p, the pressure. The slope of the funnel, $\Delta z/\Delta r$, is given in figure 62. As shown in equation (3), this slope denotes the centrifugal acceleration in terms of g, the gravity acceleration. The maximum centrifugal acceleration appeared at the 130-meter level shortly before 1829 CST, when the funnel looked like a huge cylinder with a flat bottom.

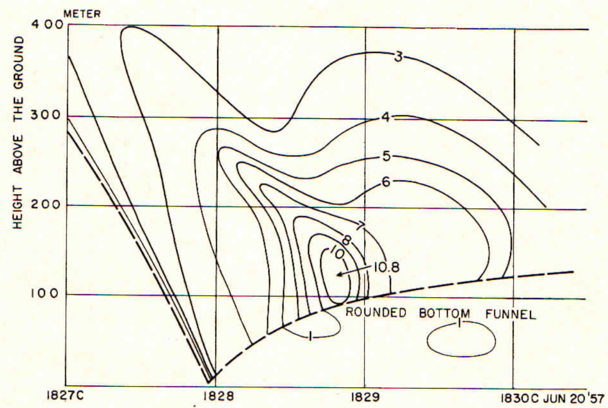


FIGURE 62.—Ratio of centrifugal acceleration to acceleration of gravity at the funnel edge of the Fargo tornado, $\frac{\Delta g}{\Delta r}=\frac{V^2}{r}\Big/g$.

Using the centrifugal acceleration given in figure 62, cyclostrophic wind speeds at the funnel edge were computed (see fig. 63). It should be noted that no cyclostrophic wind speeds were computed for the flat portion of the funnel. The dashed lines in the figure indicate funnel diameter in meters; the full lines, rotation speed in meters per second. The maximum speed obtained was 230 m.p.h.

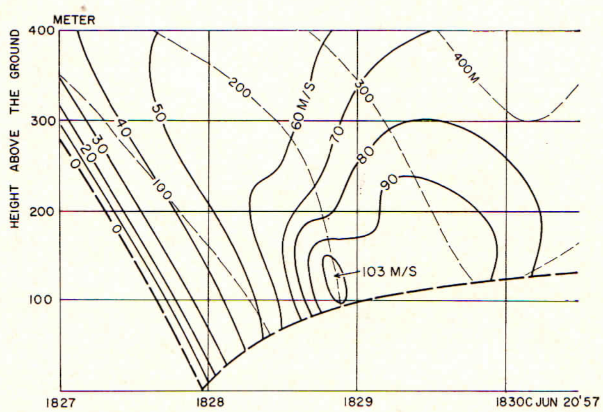


FIGURE 63.—Cyclostrophic wind speed, $V=\sqrt{rg\,\frac{\Delta z}{\Delta r}}$.

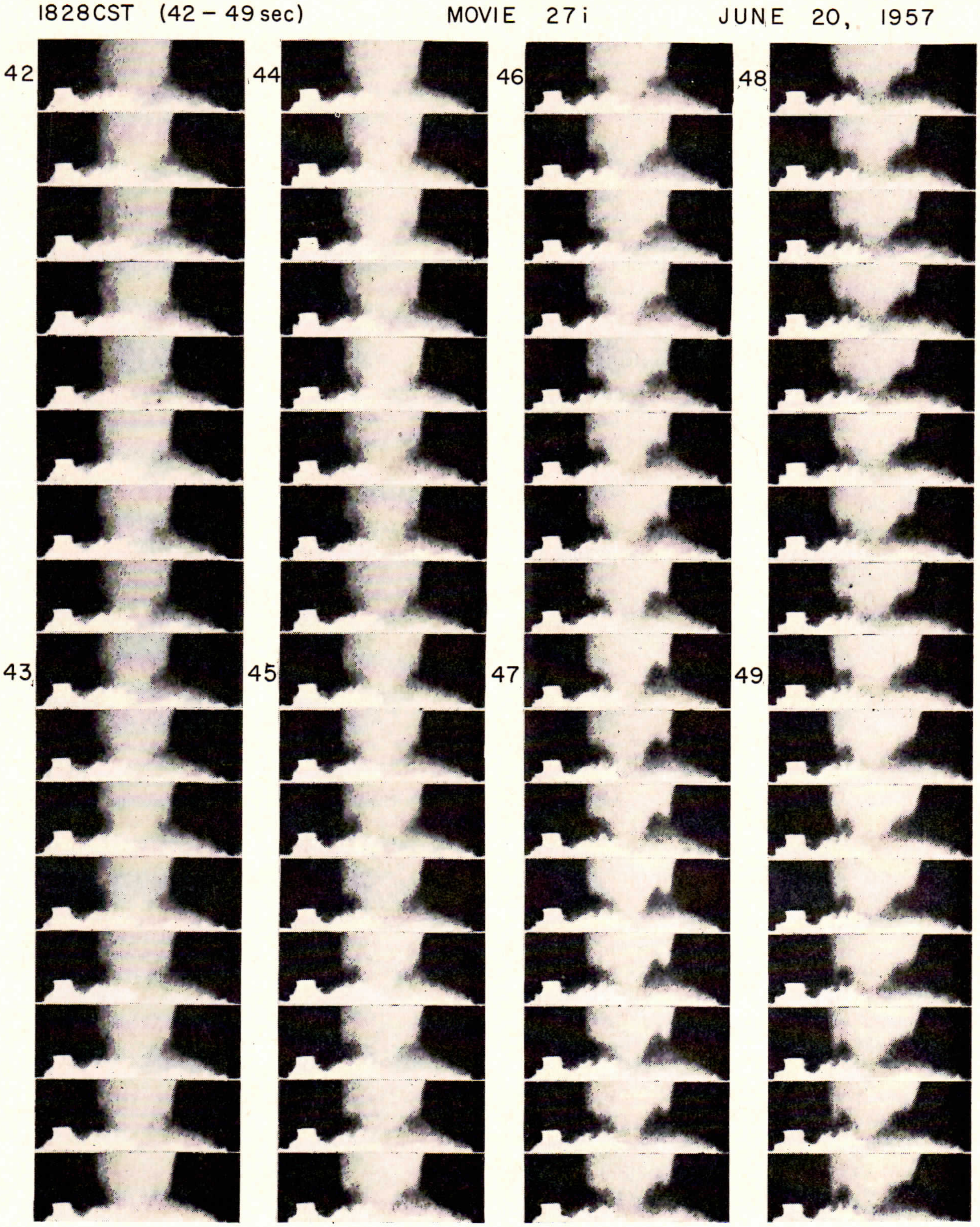


FIGURE 64.—Every third frame of Jennings' movie 27i taken at 24 frames per second (18h28m42s–49s).

FIGURE 65.—Every third frame of Jennings' movie 27i (18h28m50s–57s).

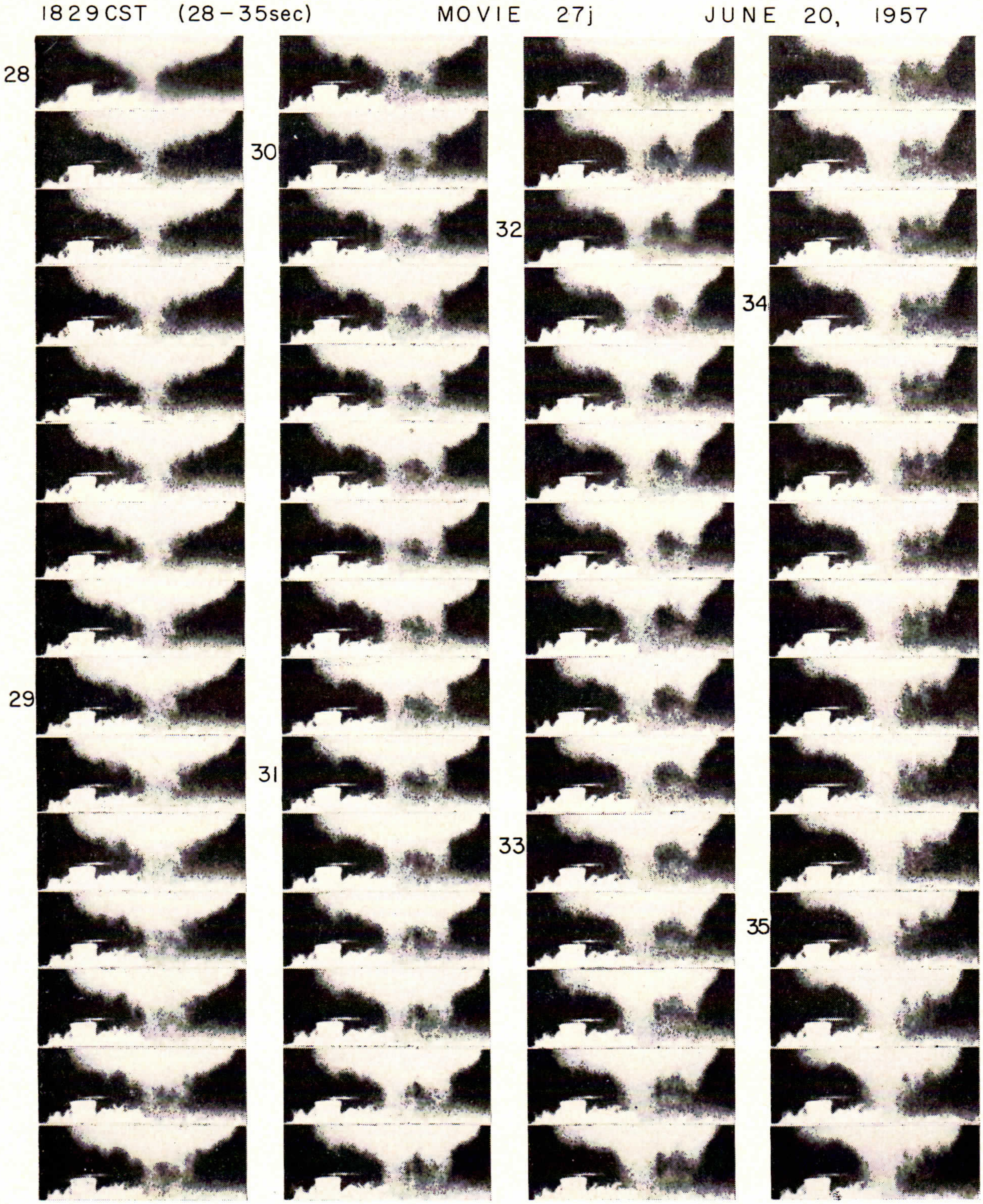


FIGURE 66.—Every third frame of Jennings' movie 27j taken at 24 frames per second (18h29m28s–35s).

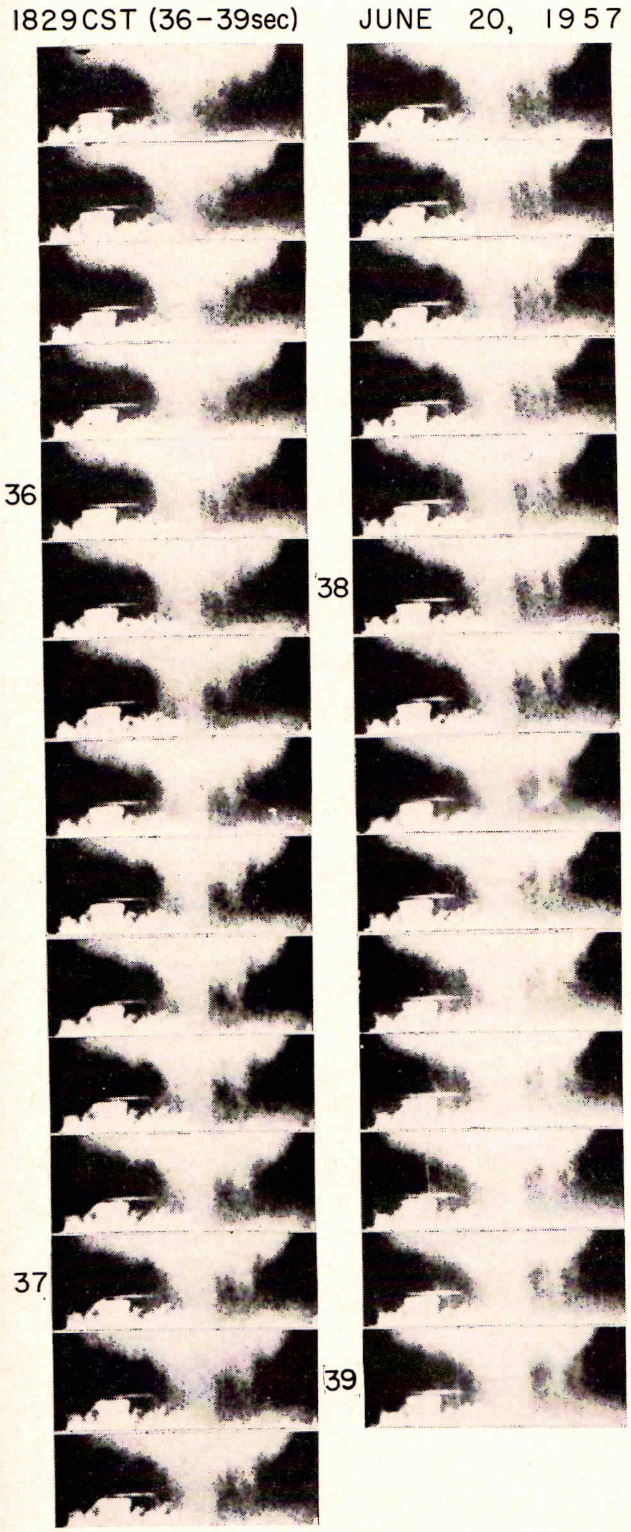


FIGURE 67.—Every third frame of Jennings' movie 27j (18h29m36s–39s).

The second computation method employed the motion picture showing a rotating funnel. For this purpose Jennings' films 27i and 27j were used. Figures 64–67 show enlargements of the cone funnel as it appeared in every third frame of his films. The films were run back and forth on a time-motion study projector so that corresponding features appearing at the bottom of the funnel could be followed carefully.

Only seven pendants at the bottom of the funnel were followed, with the result shown in figure 68. Table 3 summarizes the computation. The rotational speeds of the funnel thus obtained and the profiles of the funnel at the time of the speed computation are both shown in figure 69. The open and solid circles in the figure indicate the speeds measured by the first and the second methods, respectively.

It should be noted that the rotational speeds computed by using these two methods do not fit at the circumference of the flattened or rounded bottom funnel. Unfortunately, it was not possible to follow in the movie a characteristic point on the side of the funnel where the first method was applied in computing the speed. If we assume that the values shown in the figure are correct, there should be an abrupt increase in speed at the circumference of the rounded funnel. It is of interest to see that dust on the ground rose with a sharp boundary. The wind speed at the funnel surface directly above that boundary was between 60 and 70 m. sec.$^{-1}$

TABLE 3.—*Rotational speeds of Fargo tornado funnel computed from movement and duration of seven (A–G) pendants at the bottom of the funnel*

Pendant	Meters from center	Duration of existence	Meters traveled	Average speed
				m./sec.
A	90	18h28m49.7s–55.5s	280	48
B	60	18h28m54.5s–57.8s	160	48
C	30	18h28m54.8s–55.7s	40	40
D	60	18h29m28.1s–30.4s	100	43
E	110	18h29m28.6s–31.1s	120	48
F	100	18h29m35.7s–38.1s	115	43
G	90	18h29m37.4s–39.0s	70	44

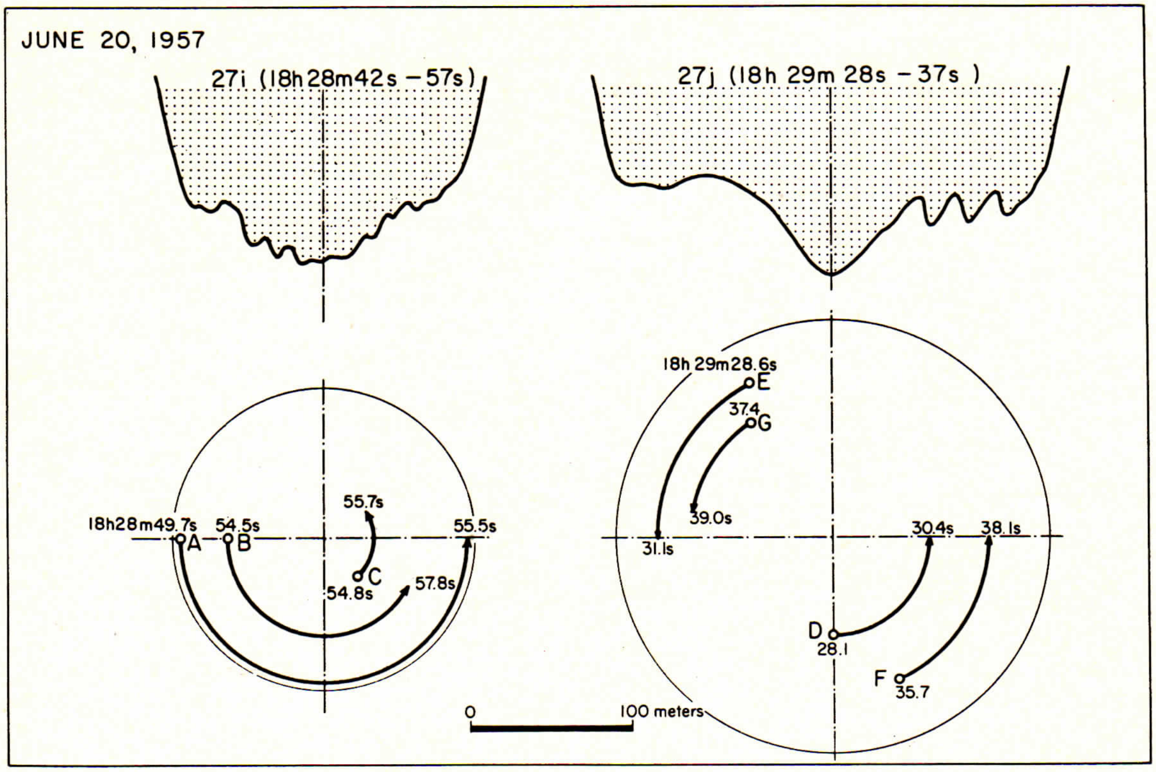


FIGURE 68.—Rotational speed of the funnel obtained from Jennings' movies 27i and 27j.

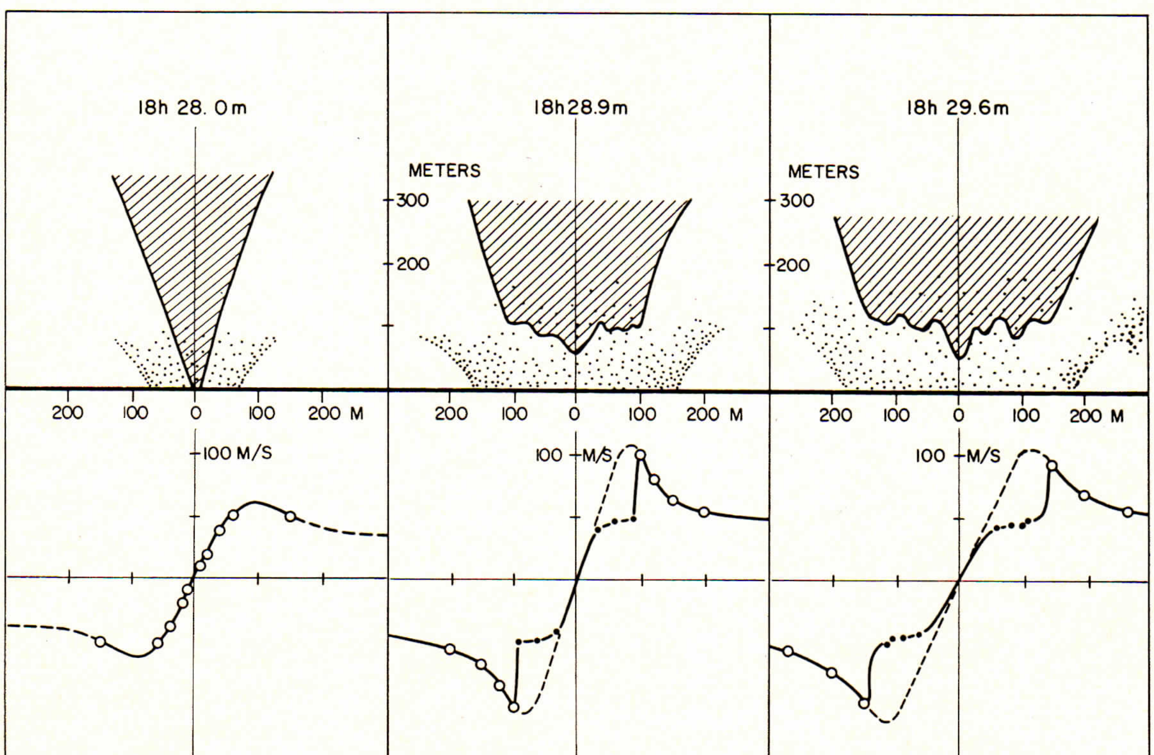


FIGURE 69.—Rotational speed of the funnel. Open and solid circles indicate the speed obtained by the two different methods described in the text.

7. STATEMENT OF THE RESULTS OBTAINED

Through this case study of the Fargo tornadoes of June 20, 1957, important problems concerning tornadoes have become evident. The five tornadoes under discussion appeared one after another at the base of a rotating cloud which moved eastward over the Fargo-Moorhead area. Had a radar station been operating within 50 miles from the storm, it would almost certainly have shown a hook or ring-shaped echo. There are, of course, other types of tornadoes in which funnels appear without relation to any recognizable rotating system as in the Fargo tornado case.

Discussion of the results obtained here should, therefore, be limited to tornadoes associated with a rotating system seen on radar scope as a "hook" or in ordinary photographs as a "rotating cloud."

RELATIVE MOTION OF TORNADOES WITH RESPECT TO THE ROTATING CLOUD

Using the results of the tornado survey and the triangulation of the rotating cloud, it is feasible to locate the relative positions of the tornadoes with respect to the cloud center.

In order to determine the positions of the rotating cloud center at 15-min. intervals, an x–t diagram was constructed in the lower portion of figure 70. The open circles on the path of the rotating cloud center represent the positions thus obtained.

Then the locations of the surface tornadoes were determined or assumed to exist at the arrow points in the figure. The results of the triangulation of the rotating cloud and the tornadoes were fully considered in determining these locations. It can reasonably be concluded that the relative positions of the tornadoes and the rotating cloud centers are represented by the vectors indicated by the arrows.

The relative movement of the five tornadoes summarized in figure 71 reveals several extremely important facts:

(1) Each of the five tornadoes was initiated within 5 miles from the center of the rotating cloud.

(2) The centers of the tornadoes moved cyclonically around the cloud center and dissipated as they moved westward away from the cloud center.

(3) The funnels were cone-shaped when located within about 2 miles from the cloud center. Rope funnels were observed in the region beyond 2 miles from the center.

The Wheatland tornado, which never came close to the rotating cloud center, remained rope-shaped throughout its lifetime. The Casselton tornado was cone-shaped only when it was located 2 miles from the center of the rotating cloud.

AXIS OF TORNADO FUNNEL

Examination of the tornado photographs ap-

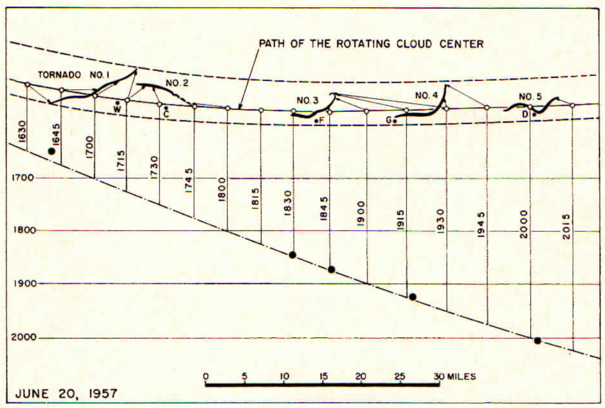


FIGURE 70.—Relative position of the Fargo tornadoes and the center of the rotating cloud.

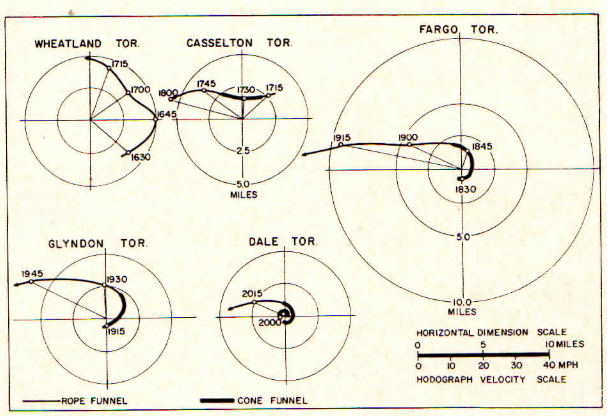


FIGURE 71.—Relative movement of the surface tornado center with respect to the center of the rotating cloud.

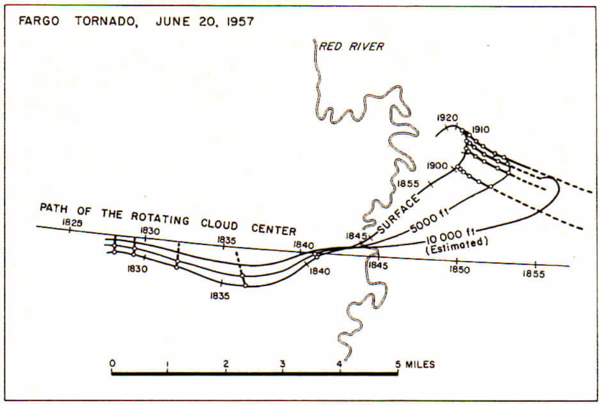


FIGURE 72.—Paths of the Fargo tornado at the surface, 5000-ft., and 10,000-ft. levels.

pearing in this report shows that the cone funnel had a more or less vertical axis, while the funnel in the rope stage was characterized by a long diagonal or horizontal axis.

The three-dimensional shape of the axis of the Fargo tornado was carefully triangulated in order to obtain the paths of the funnel at higher levels. Figure 72 gives the result. It is not possible to obtain directly the upper portion of the cone-shaped funnel because it was hidden at the 1,000–3,000-foot level by the base of the cloud. The axis of the rope funnel was triangulated up to the 6,000-foot level, where it entered the stratus-type cloud.

It can be seen in the figure that the higher the level, the more the funnel was displaced toward the center of the rotating cloud. Extrapolated positions of the funnel suggest that the axis of the tornado coincided with that of the rotating cloud at the level between 10,000 and 20,000 feet. The rope-type funnel, standing at its latest stage in the rural area north of Moorhead, probably extended almost 10 miles to the east-southeast as far as the rotating cloud system.

PRESSURE FIELD BENEATH THE ROTATING CLOUD AND THE LIQUID WATER STORAGE

Two barograph traces, one from the U.S. Weather Bureau station at Hector Airport and the other from the North Dakota Agricultural College, both in Fargo, indicated the existence of a high pressure ring surrounding the surface center of the rotating cloud.

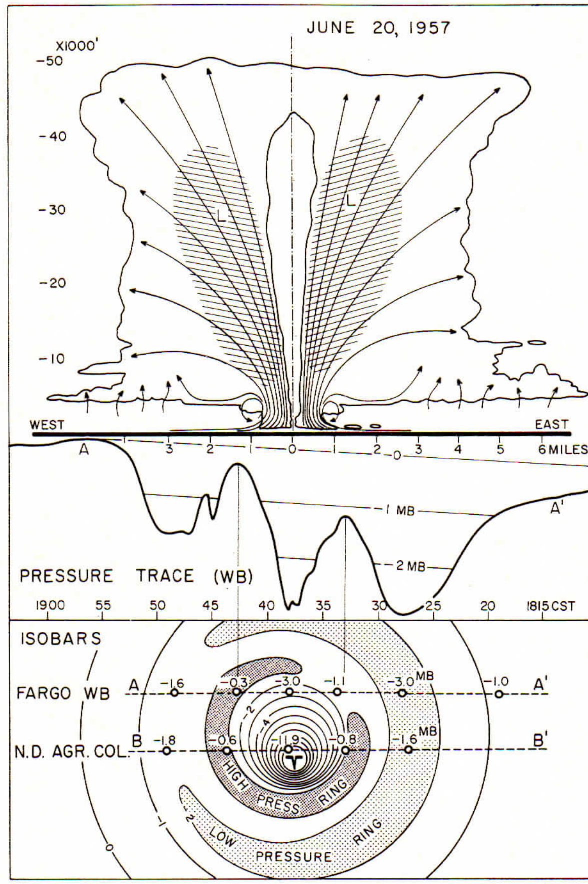


FIGURE 73.—Pressure field beneath the rotating cloud.

As shown in figure 73, the relative positions of these barograph stations A–A′ and B–B′ were obtained by converting the time change into space change. The 16 m.p.h. speed of the rotating system was used. A schematical drawing of the cloud was made for the purpose of finding the dimensions of the high pressure ring in relation to the extent of the rotating cloud. The figure shows that the diameter of the high pressure ring was about 3 miles, which was much larger than that of the collar cloud surrounding the ring-shaped wall cloud.

It is proposed that the rotating cloud under discussion had a liquid water storage above the high pressure ring on the ground. The hatched areas in the cloud indicate this storage. The amount of the pressure rise, as high as 3 mb., permits us to assume that the amount of liquid water contributing to the excessive weight of the

TABLE 4.—*Depth of liquid water storage in cloud for various liquid water contents*

Liquid water content	Depth of the storage	
g.m.$^{-3}$	*Meters*	*Feet*
1	30,000	99,000
2	15,000	50,000
3	10,000	33,000
4	7,500	25,000
5	6,000	20,000
10	3,000	10,000

air column would be about 3 $g.cm^{-2}$. The depths of the storage corresponding to the possible liquid water content are given in table 4. It will be reasonable to assume the depth of the storage to be about 25,000 feet; consequently, the liquid water content may be estimated at about 4 $g.m^{-3}$.

Another evidence of the presence of the high pressure ring was seen in the surface winds recorded at Hector Airport. Wind speed plotted in figure 74 showed a definite drop as the converging air blew through the pressure gradient L_1H_1. However, the surface wind possessed an inflow speed of about 25 m.p.h. as it reached H_1, the point of highest pressure along the ring.

The precipitation which accompanied the rotating cloud fell between 1842 and 1845 CST, when the surface pressure was falling from H_2 to L_2 as recorded in the figure. A small rise, h, appeared when precipitation, mostly hail, occurred around 1843 CST.

The total amount of liquid water estimated by areal integration of the excess pressure of the high pressure ring was about 10^9 kg. The radial wind speed roughly estimated was about 10 m. $sec.^{-1}$ at a 1-mile radius, with the depth of the inflow layer being up to 400 meters above the ground. These figures give us a rough idea of how much condensation was taking place inside the cloud. The amount of inflow

$$(2\pi)\times(1 \text{ mile})\times(400 \text{ m.})\times(10 \text{ m. sec.}^{-1}) \doteqdot 4\times10^7 \text{m.}^3 \text{ sec.}^{-1}$$

multiplied by the absolute humidity, 15 g. $m.^{-3}$, in existence on the ground at the time of the storm indicates the rate of condensation if there were no water vapor escaping from the sides of the cloud. Thus the condensation obtained is

$$(4\times10^7 \text{m.}^3 \text{ sec.}^{-1})\times(15 \text{ g. m.}^{-3}) \doteqdot 6\times10^5 \text{ kg. sec.}^{-1}$$

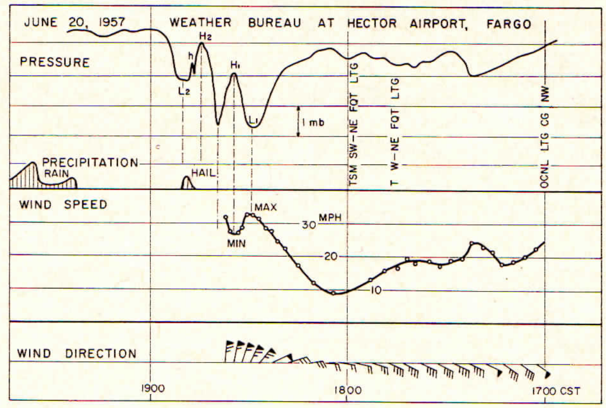


FIGURE 74.—Pressure, wind, and precipitation traces from the U.S. Weather Bureau Station at Hector Airport, Fargo.

In order to charge 10^9 kg., the total amount of the liquid water in the cloud, at the rate of 6×10^5 kg. $sec.^{-1}$, it would take 2×10^3 sec. $\doteqdot$ 30 min. The rotating cloud traveled at least a few hours before arriving at Fargo, where the pressure traces were recorded. If the computed period of 30 minutes is correct, the rotating cloud would have been discharging the liquid water in the form of precipitation. There are, however, several reasons to believe that 30 minutes would be too short a period for this to occur. First, the convergence beneath the cloud would have been very small in the early stage of the development of the rotating cloud. Second, the escape of moisture from the sides of the cloud would also have prolonged the charge period of the liquid water. Taking these points into consideration, it is reasonable to assume that the rotating cloud was in its mature stage when it traveled over the Fargo-Moorhead area. It is probable that the liquid water stored in the cloud was discharged as it moved inside Minnesota.

WINDS INSIDE THE ROTATING CLOUD AND THE FARGO TORNADO

The tangential wind speed shown in figure 75 summarizes the computation presented in figures 47 and 48. If a velocity profile were made through the center of the tornado funnel, the peak speed would be over 200 m.p.h. as described in figure 69.

The estimation of the vertical wind speed given in figure 46 reveals that the vertical motion at the edge of the cylindrical wall cloud was about 50 mph

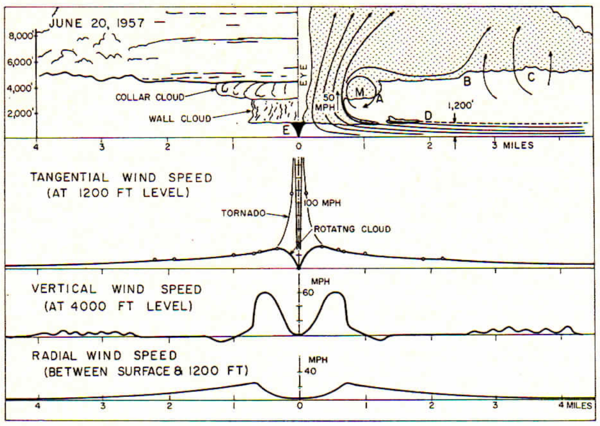


FIGURE 75.—Schematical diagram showing the wind distribution beneath the rotating cloud.

m.p.h. and was still increasing upward. Based upon this result, a mechanically driven ring vortex (M in fig. 75) is assumed. The vortex is continuously enforced by rising air which makes contact with the vortex at its inner side. Forced circulation would result in condensation of the air existing above the convergence layer, which extends up to 1200 feet above the ground; and the condensed moisture would evaporate at point A along the circular stream line. The vertical wind speed at the 4000-foot level thus estimated appears in the figure.

The radial wind speed inside the convergent layer below 1200 feet was also computed from the vertical wind speed by assuming that the thickness of the convergent layer was the same throughout except beneath the wall cloud.

It will be worthwhile to study the shape of the cloud of dust picked up by the Fargo tornado. Figure 76 represents three drawings of the dust clouds in the same scale as the surface debris patterns left by the storm. The circles in the debris chart give the outer boundary of the dust cloud on the ground. The clearness of the boundary near the ground enables us to determine its exact

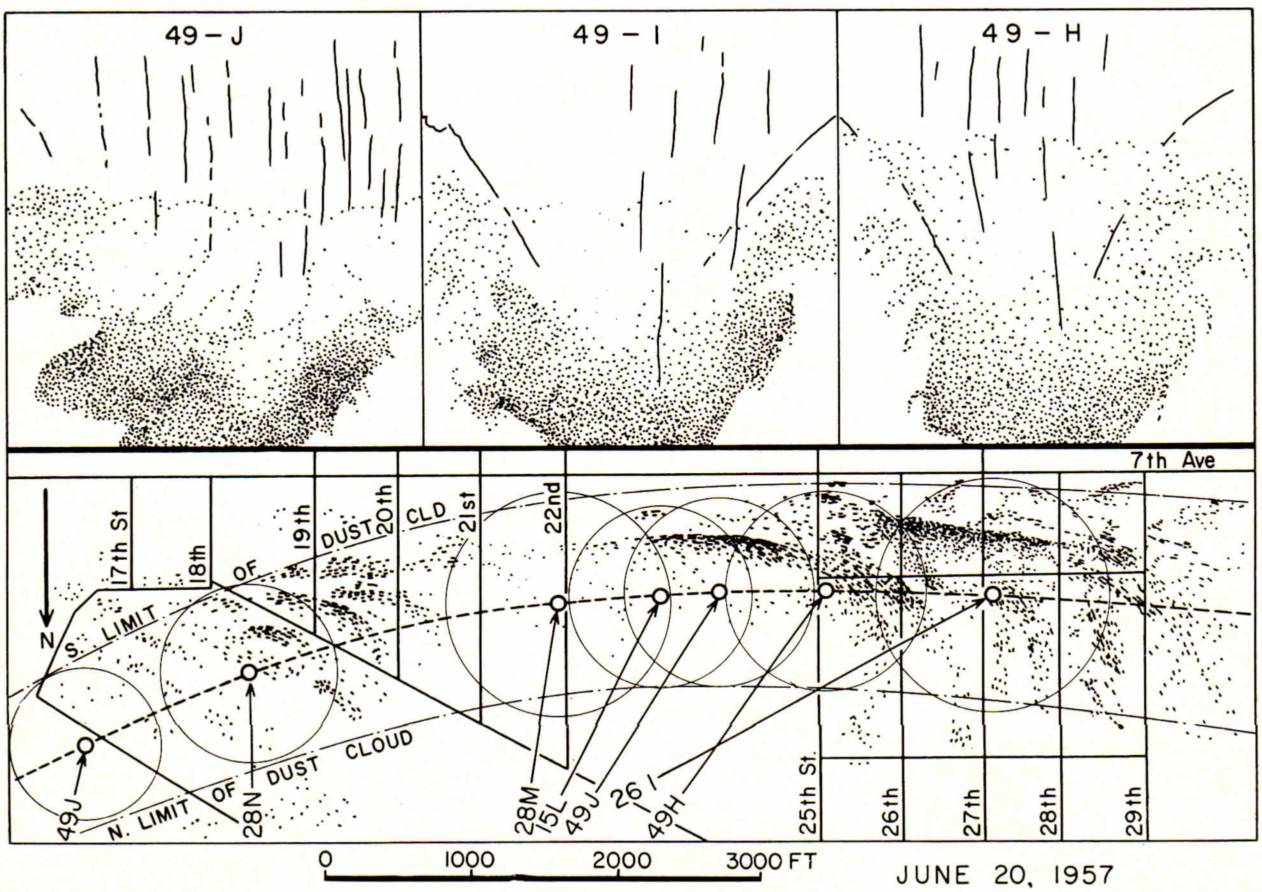


FIGURE 76.—Comparison of dimensions of debris pattern and the dust cloud of the Fargo tornado.

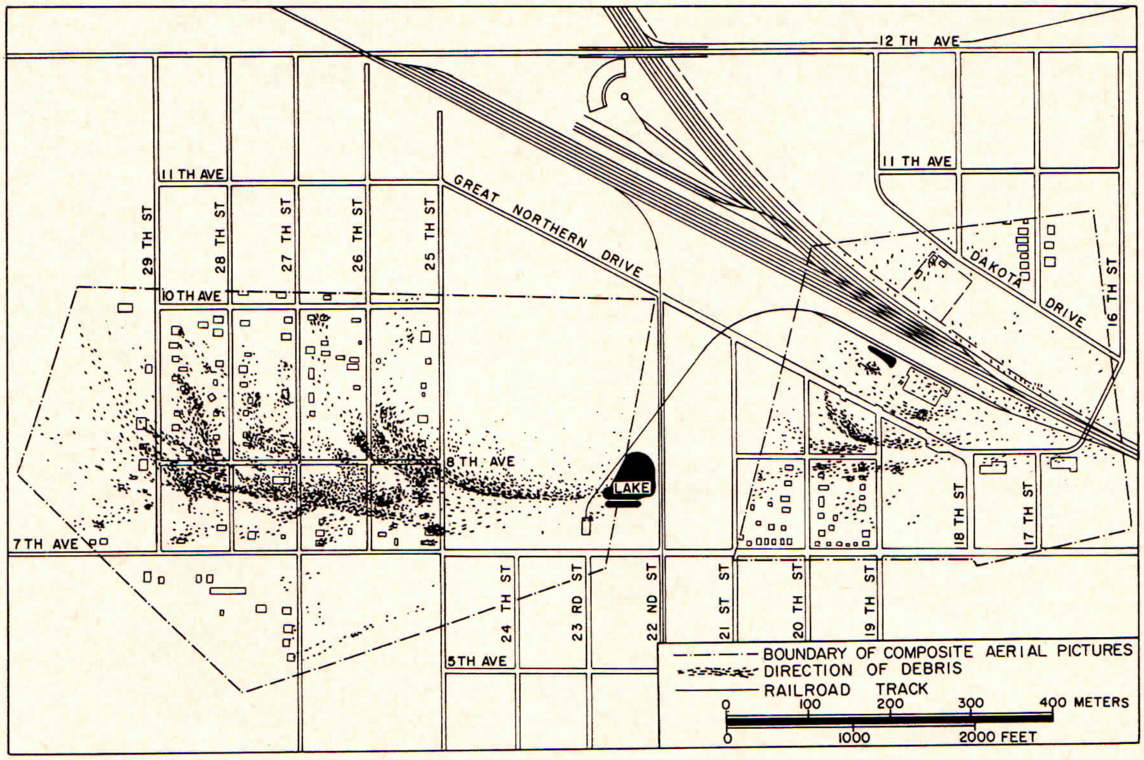


FIGURE 77.—Damage path in the western suburb of Fargo.

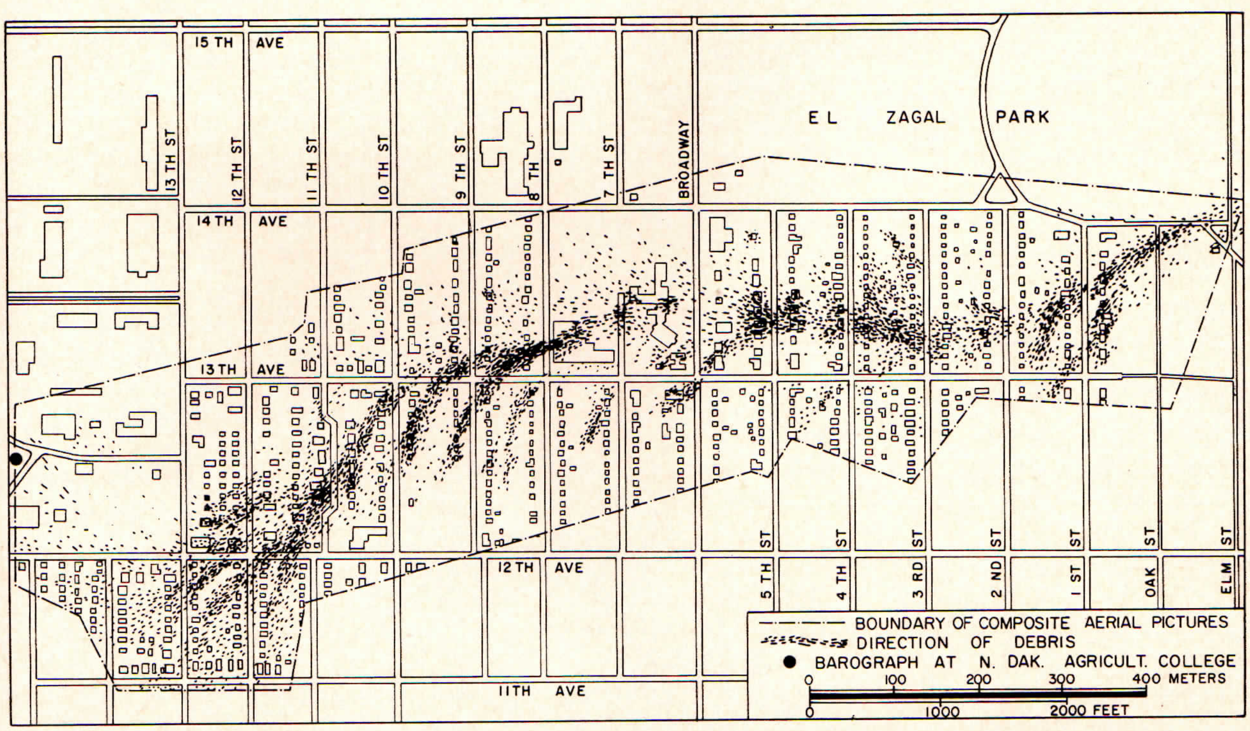


FIGURE 78.—Damage path in the residential area north of downtown Fargo.

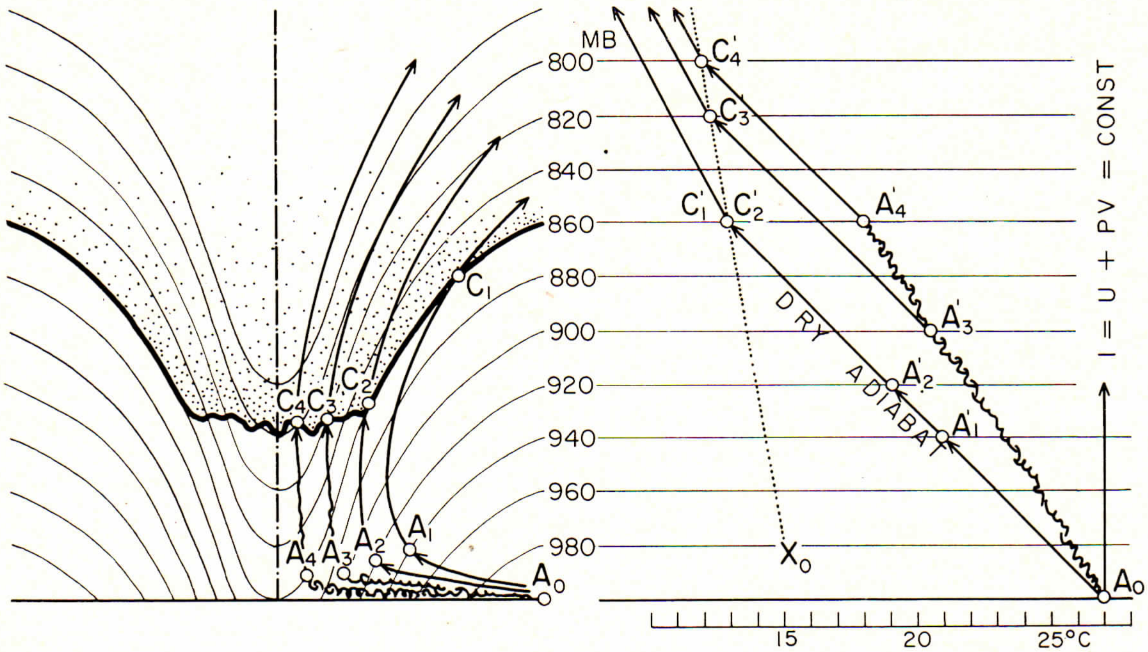


FIGURE 79.—Explanation of irreversible processes taking place beneath a tornado funnel. Heavy and thin lines represent stream lines and isobars, respectively.

diameter on each photograph. Figures 77 and 78 are detailed debris charts made by using the aerial photographs taken immediately after the storm.

The three drawings of the Fargo tornado in its very early stage shown in figure 69 consistently reveal that the edge of the dust cloud corresponded to the circle of 60 m. sec.$^{-1}$ tangential wind speed. The destruction outside these lines was very minor, indicating that most of the damage took place inside the clouds of dust.

IRREVERSIBLE PROCESS TAKING PLACE IN AIR FLOWING INTO THE TORNADO

One of the most interesting features of the shape of the Fargo tornado funnel was its rounded portion. The cyclostrophic wind speed computed from the slope of the rounded portion of the funnel was negligible compared to the rotational speed computed by using Jennings' movie (see fig. 68). That is, the slope of the rounded funnel would have to be much steeper than it actually was if the surface of the rounded portion of the funnel is to denote a surface of constant pressure. This fact suggests that the constant pressure surface should cut through the bottom of the funnel.

The left diagram in figure 79 shows the vertical cross section of constant pressure surfaces which intersect the rounded portion of the tornado funnel; thus the surfaces give the observed cyclostrophic wind speed at that portion of the funnel.

A question arises, however, as to why the condensation pressure near the center of the funnel bottom is lower than that along the outer edge of the funnel. Certainly the difference in the moisture content of atmosphere beneath the funnel does change the condensation pressure. This difference, however, still fails to explain why the mixing ratio drops toward the axis of the funnel. It seems more natural to assume that the subfunnel moisture field either is uniform or varies at random along the funnel path.

The first law of thermodynamics is probably not sufficient to explain this phenomenon. The second law of thermodynamics may be expressed by

$$dS \geqq \frac{dQ}{T}$$

where dS is the entropy increment and dQ, the amount of heat added to the system at temperature T. This inequality denotes that the increase in entropy is equal (reversible process) or larger (irreversible process) than the amount of given heat divided by temperature.

A typical example of such an irreversible process is Joule-Thomson's "porous plug" experiment, which was done by compressing a gas through a porous plug in an adiabatic cylinder. As is well known, the gas conserves its enthalpy through the irreversible adiabatic process, namely,

$$U_0+P_0V_0=U+PV$$

where U, P, and V are respectively the internal energy, pressure, and volume of the gas. If we assume Joule-Thomson's coefficient $\left(\frac{\partial T}{\partial P}\right)_I$, where $I=U+PV$, is zero, it follows that a gas may expand adiabatically through a porous plug without changing its temperature. This process may be called adiabatic isothermal expansion.

The right diagram in figure 79 demonstrates an expansion process of air whose cooling rate lies between the isentrope and isenthalp originating from A_0, the point farthest away from the funnel sub-point. Such a process will take place when the air parcel immediately above the ground flows more or less toward the funnel sub-point while converting its pressure energy into internal heat energy through friction and turbulence. Such an internal production of heat will increase the parcel's entropy, namely, its potential temperature, adiabatically. It should also be noted that flying debris and dust particles around the funnel axis near the ground will help to increase irreversibility. The rate of cooling under this condition appears in the figure as A_0–A'_3–A'_4.

As soon as the air parcel starts climbing vertically, the internal heat production becomes less appreciable, resulting in a process of isentropic cooling. The figure thus schematically shows how the condensation pressures are obtained for different parcels. It is of importance to see that the slight entropy increase due to irreversible heat production is extremely effective in lowering the condensation pressure.

It is evident that the second law of thermodynamics is indispensable in solving tornadic circulation problems. In studies of future cases, a more complete survey and photogrammetric analysis of tornado funnels will be mandatory.

REFERENCE

1. T. Fujita, H. Newstein, and M. Tepper, "Mesoanalysis—An Important Scale in the Analysis of Weather Data," U.S. Weather Bureau *Research Paper* No. 39, Washington, D.C., Jan. 1956, 83 pp.

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