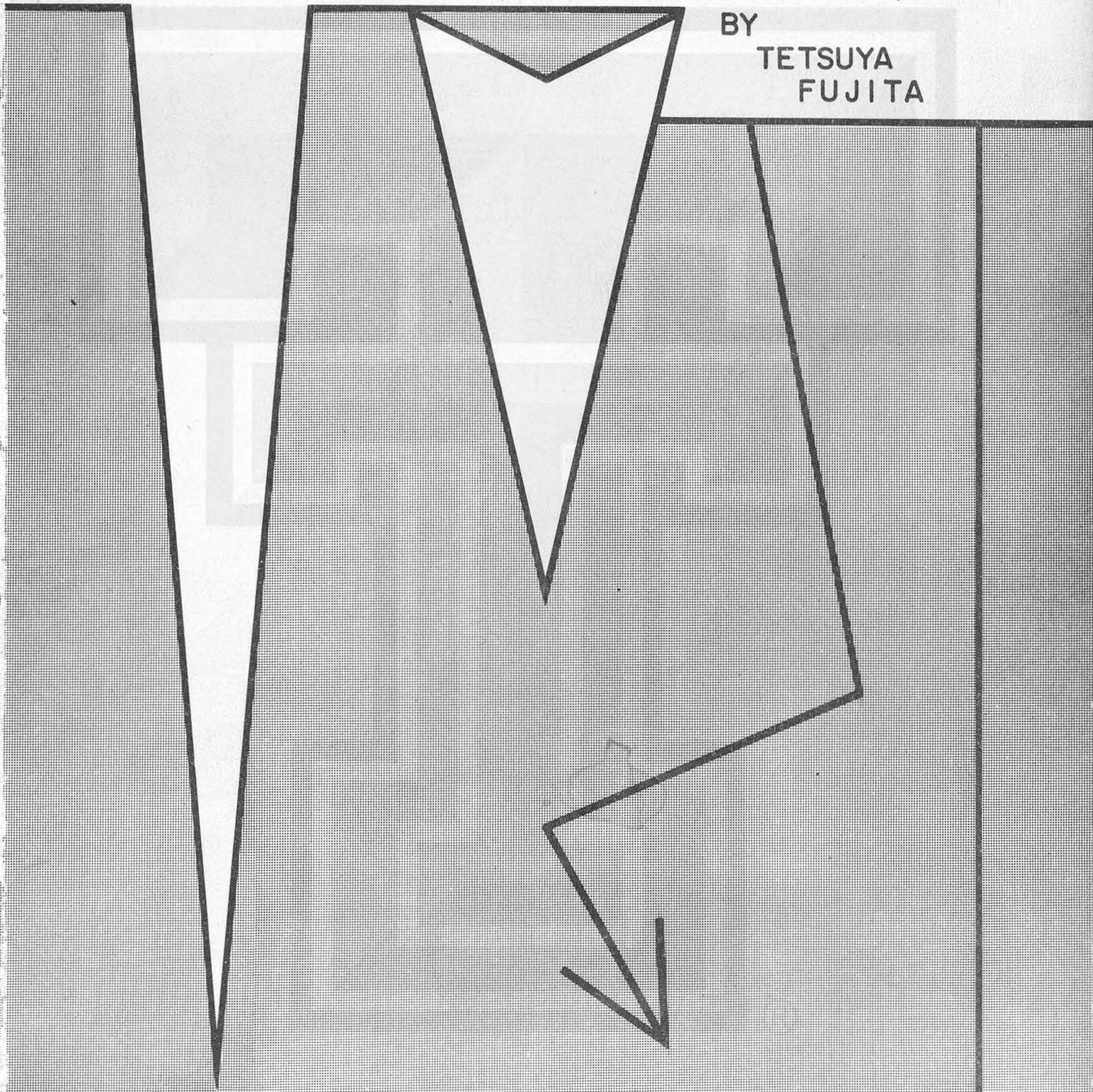
DETAILED ANALYSIS OF THE FARGO TORNADOES OF JUNE 20, 1957



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A DETAILED ANALYSIS OF THE FARGO TORNADOES OF JUNE 20, 1957

by

Tetsuya Fujita

Technical Report Number 5

to

United States Weather Bureau
(Contract Number Cwb 9530)

June 1959

CONTENTS

FOREWARD

A few weeks after one of the tornadoes of June 20, 1957 leveled a part of the residential area of Fargo, 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 a 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 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} per second. 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.

ACKNOWLEDGEMENTS

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 Chapter Three. Throughout the time of this research, 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, Mr. Yukio Omoto, Miss Charlotte Ridinger, and other members of the staff of the Severe Local Storms Project, Department of Meteorology, University of Chicago.

CHAPTER I: GENERAL WEATHER SITUATION

On the afternoon of June 20, 1957, a cone-shaped funnel dropped over the rural area west of Fargo, North Dakota. 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 Fig. 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 will lead 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 Fig. 3 reveals further a rather complicated structure of dry and moist layers overrunning the lowest moist 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 upper air networks in the area of the northern Great Plain 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 Figs. 4, 5, and 6. In analysing these charts, time-section sheets including traces obtained from each weather station were prepared beforehand; then the standard mesoanalysis techniques developed in the Severe Local Storms Project, University of Chicago, were applied.

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

The chart at 1800 shows that the tornado was very close to Fargo when a mesoscale high began filling up a low pressure center. In one hour the tornado moved into Minnesota, where the boundary of the mesohigh almost caught up with the tornado, which was moving at about 16 mph. After the next hour or so, the mesohigh 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 Gray, 205 miles SSE of Fargo
1900 CST: Tops of echoes near Fargo were 65,000-75,000 feet.

ADC Station Origin, 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.

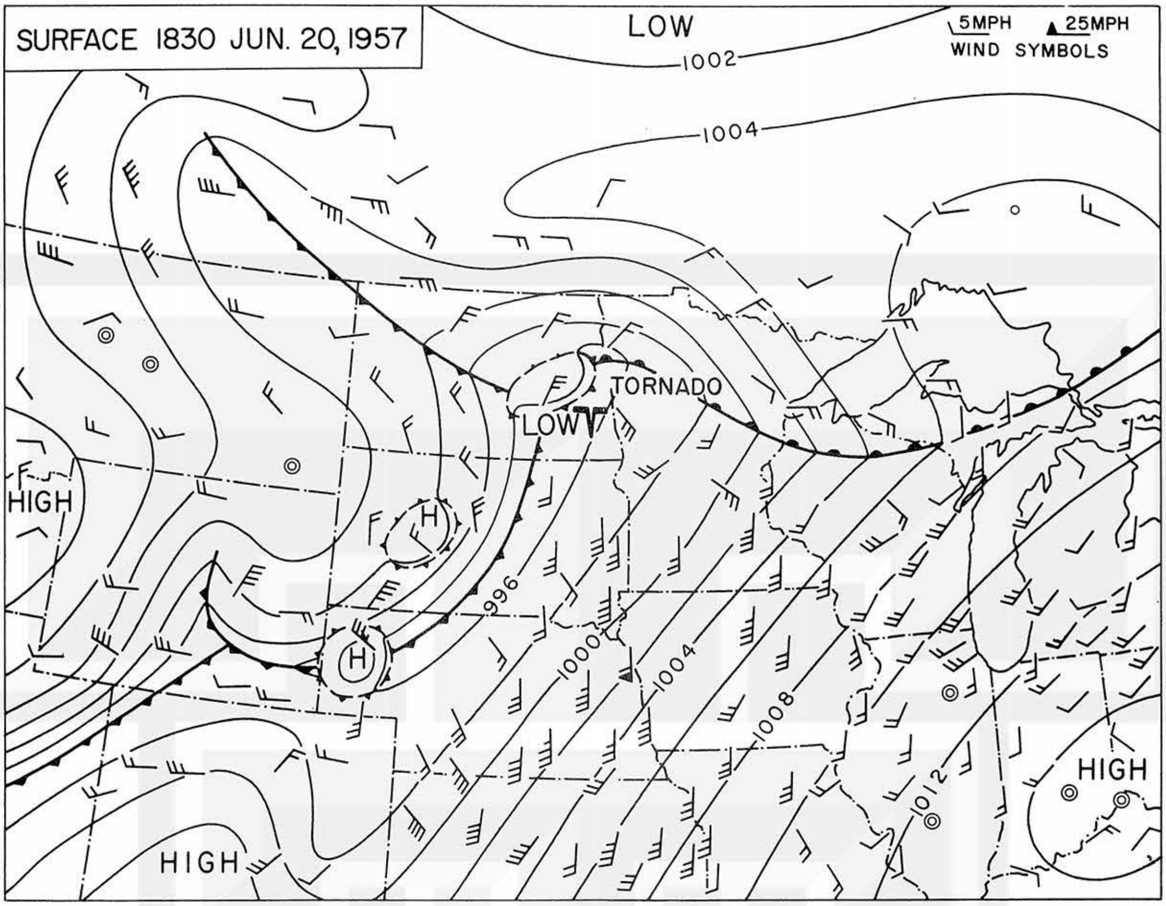

SURFACE 1830 JUN. 20, 1957
LOW
1002
1004
5MPH 25MPH
WIND SYMBOLS
TORNADO
LOW
HIGH
H
H
996
1000
1004
1008
1012
HIGH
HIGH

FIG. 1

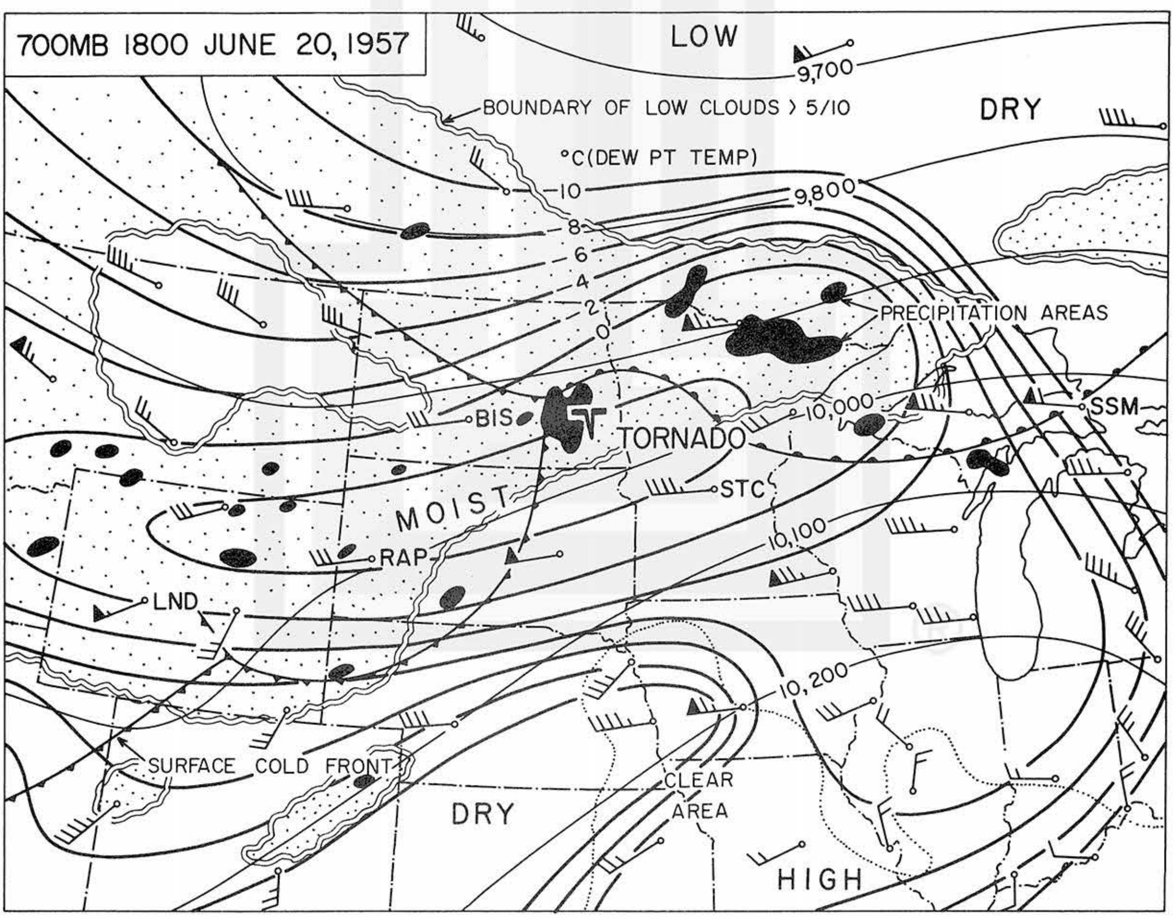

700MB 1800 JUNE 20, 1957
LOW
9,700
BOUNDARY OF LOW CLOUDS > 5/10
DRY
°C (DEW PT TEMP)
10
8
6
4
2
0
9,800
PRECIPITATION AREAS
BIS
TORNADO
10,000
SSM
STC
MOIST
RAP
10,100
LND
10,200
SURFACE COLD FRONT
CLEAR
AREA
DRY
HIGH

FIG. 2

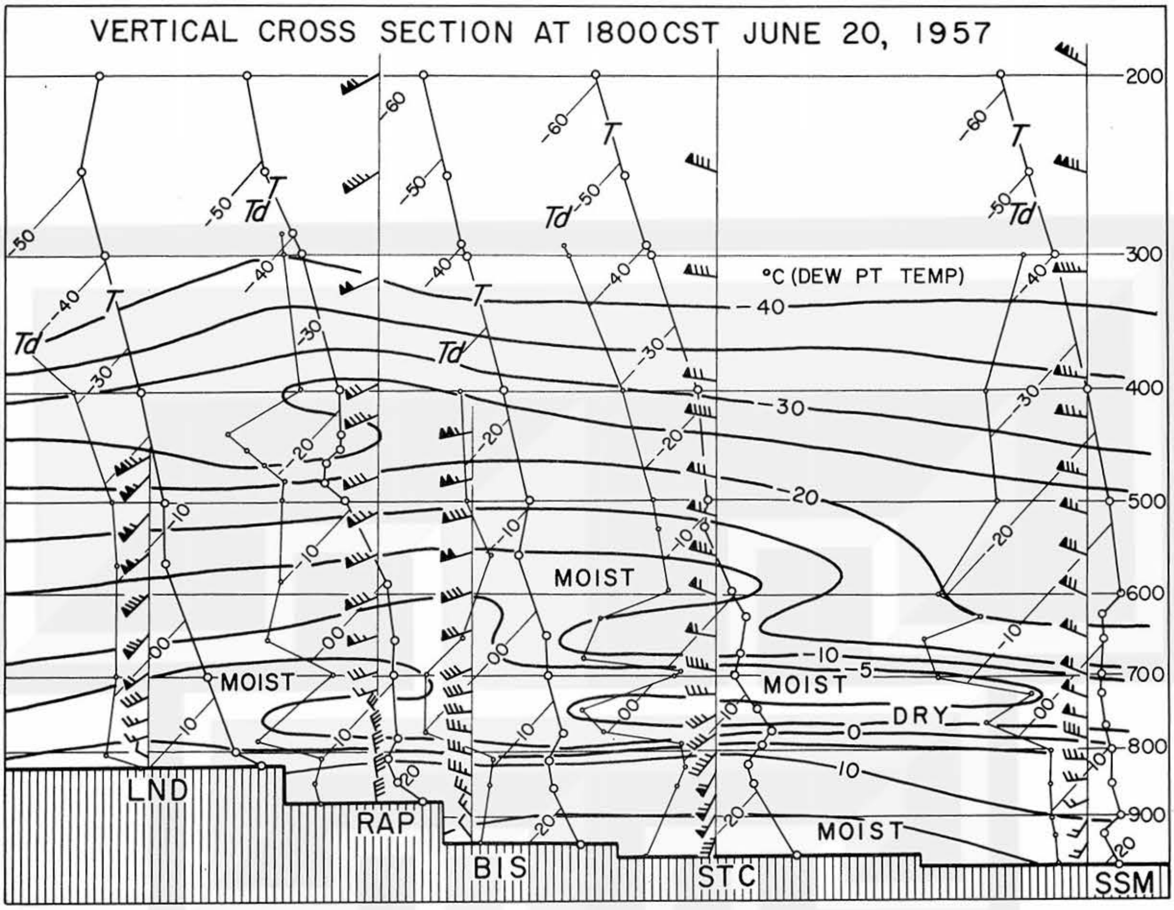

VERTICAL CROSS SECTION AT 1800CST JUNE 20, 1957
°C (DEW PT TEMP)
MOIST
MOIST
MOIST
DRY
MOIST
LND
RAP
BIS
STC
SSM
200
300
400
500
600
700
800
900

FIG. 3

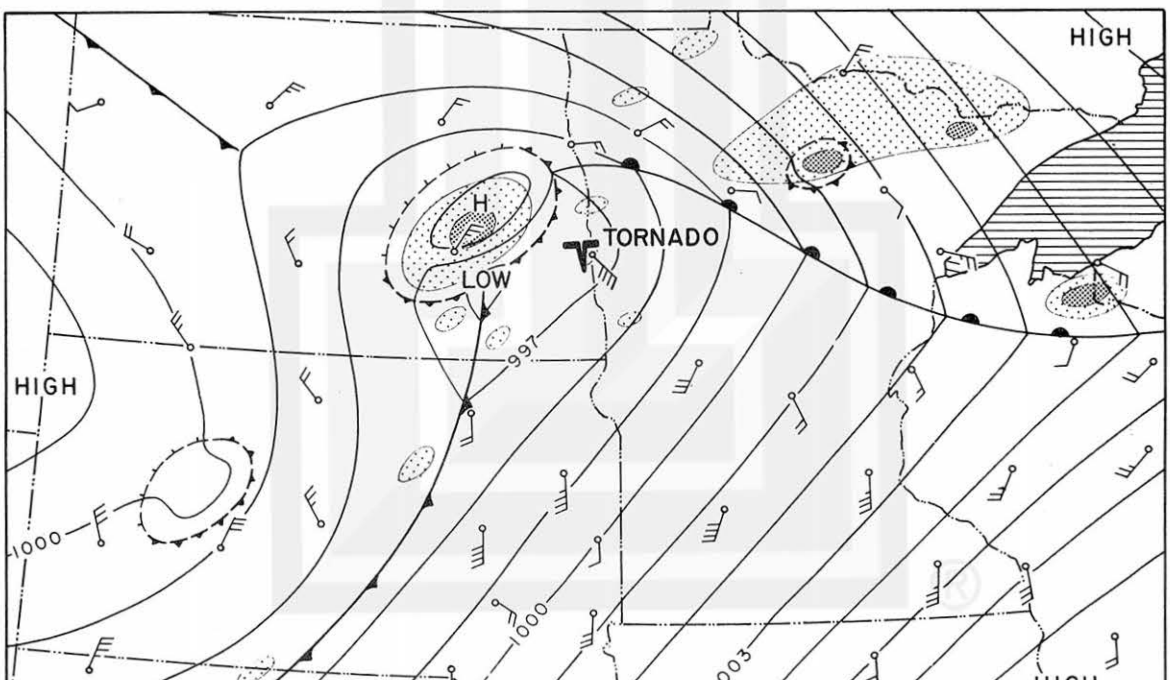

HIGH
TORNADO
H
LOW
997
HIGH
1000
1000
1003
HIGH
1800C JUNE 20, 1957

FIG. 4

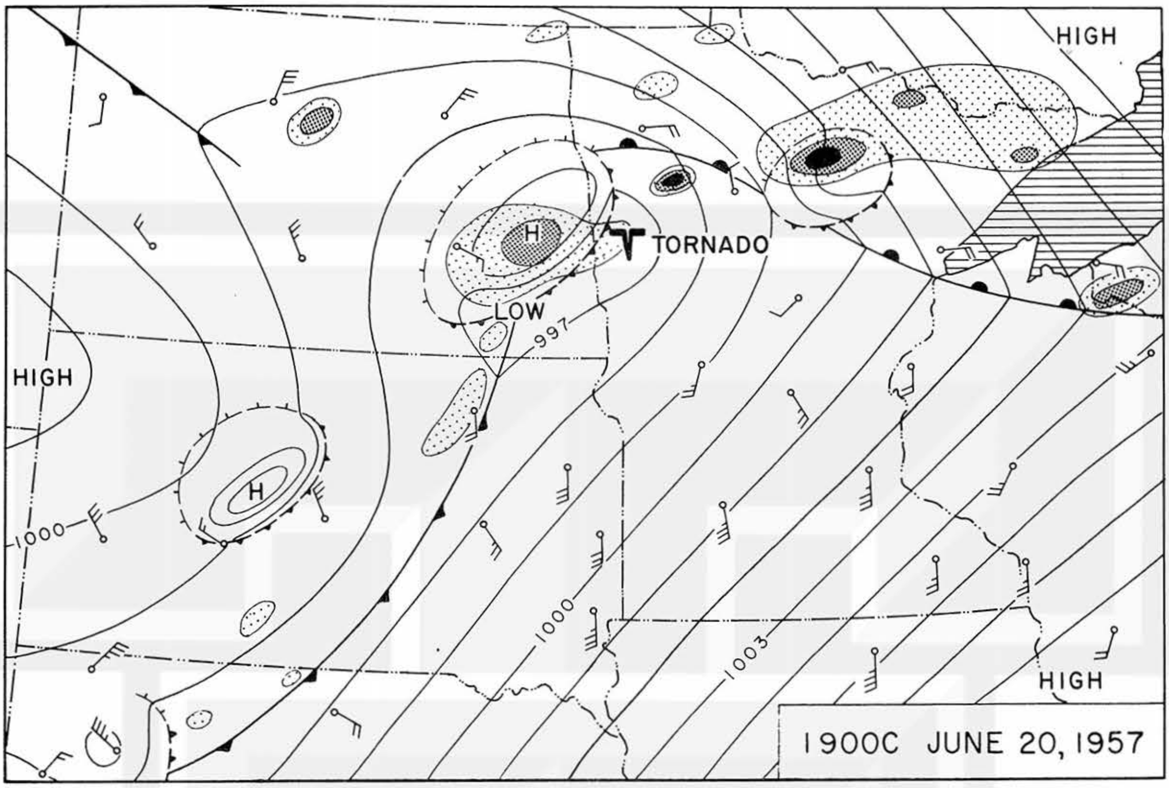

HIGH
TORNADO
LOW
997
HIGH
H
H
1000
1000
1003
HIGH
1900C JUNE 20, 1957

FIG. 5

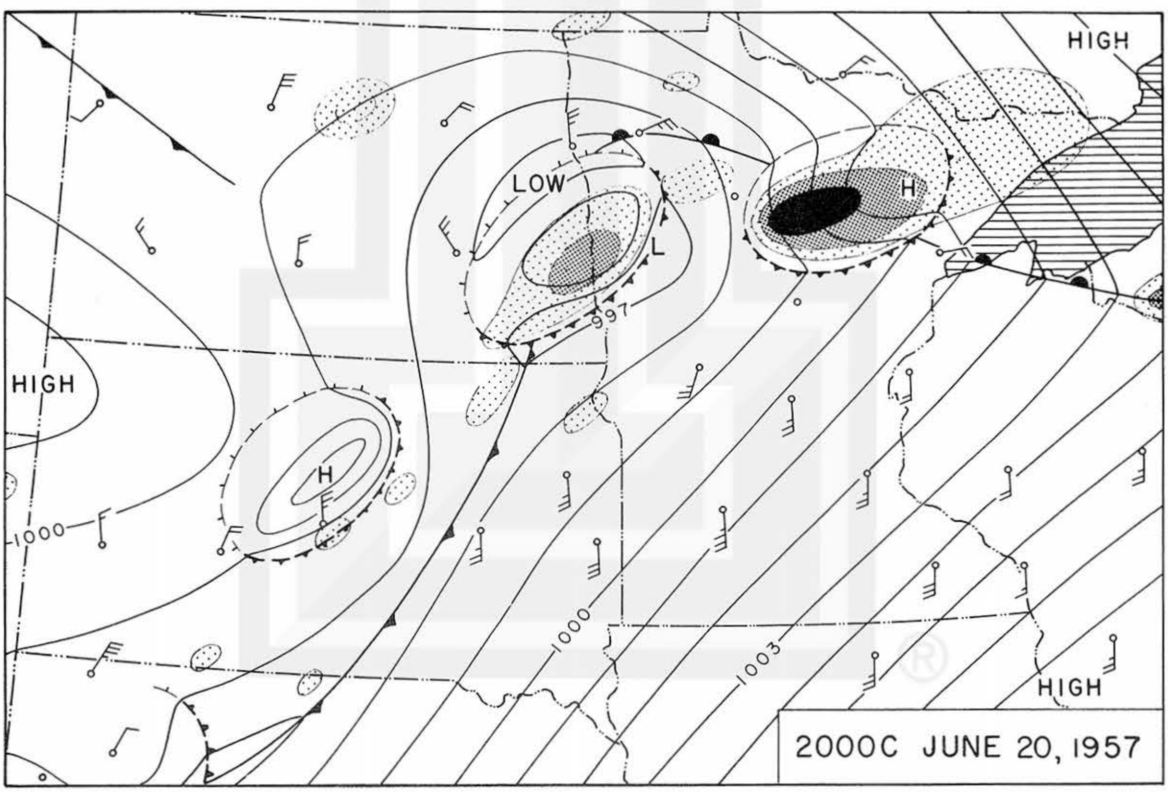

HIGH
LOW
H
L
997
HIGH
H
1000
1000
1003
HIGH
2000C JUNE 20, 1957

FIG. 6

CHAPTER I: GENERAL WEATHER SITUATION

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

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

Fig. 3 Vertical cross section of wind, temperature, and moisture along Lander, Wyoming; Rapid City, South Dakota; Bismarck, North Dakota; St. Cloud, Minnesota; Sault Ste. Marie, Michigan.

Fig. 4 Surface chart for 1800 CST June 20, 1957.

Fig. 5 " " " 1900 " " " "

Fig. 6 " " " 2000 " " " "

Three stippled areas show the area of precipitation amounts 0.01", 0.1", and 1" occurring in the one-hour period ending at the map time.

CHAPTER II: 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.

A. 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 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. 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 one hundred 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.

B. 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 Fig. 9, she (γ) reported that the storm was picking up quite a lot of dust while moving east in a direction southeast of the Madsen farm. People on the farms south of the storm observed a funnel moving east.

The outlines of the funnel appearing in every tenth frame of the movie film 3a are reproduced in Fig. 10. The movie was taken at an estimated distance of 2 1/4 miles from the funnel. 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, 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 ten 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 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 1 1/2 miles west-northwest of the Byram farm, where a garage was picked up and trees were badly damaged.

Observers from two spots seven miles east-southeast of Casselton reported a cone funnel moving east 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, which was made about five minutes after 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 four 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.

<u>Summary</u>:

This tornado, appearing approximately when the first one disappeared, left a path of five miles in the 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 five miles, but the system aloft would have drifted at least a few miles toward the east-southeast.

<u>C. Fargo Tornado</u>.

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 Fig. 11.

Summary:

This was the third tornado to drop in the rural area some 2 1/2 miles west of the Fargo city limits. The total damage path was nine miles, extending into Minnesota. This storm will be fully discussed in the following chapters.

D. 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 east, 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 ten 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 northeast was observed from the Wyland and Ackerson farms after the passage of the storm. Sketches δ and ε are shown in Fig. 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 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 ten miles in length and two blocks in maximum width. Before it dissipated, the storm resembled a huge rope.

E. Dale Tornado.

The last tornado of the Fargo tornado family started disturbing the surface in Section 32 of the Highland Grove Township. As shown in Fig. 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 northeast, damaging the Carson 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 the last tornado left a surface damage path of as much as seven 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.

F. Characteristics of Fargo Tornadoes.

Five tornadoes occurring in the afternoon of June 20, 1957 are summarized in Fig. 14. Although the shape of the funnel of the Wheatland tornado in its early stage and the Casselton tornado in the dissipating stage necessarily remains 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 or an ocean. It might be stated that many tornadoes characterized by majestic cone-shaped funnels change into waterspouts 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 rope or waterspout 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 eight miles, 11 miles being the longest and four 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 the diagram of Fig. 14, we may postulate the existence of one or two small tornadoes next to the Dale tornado.

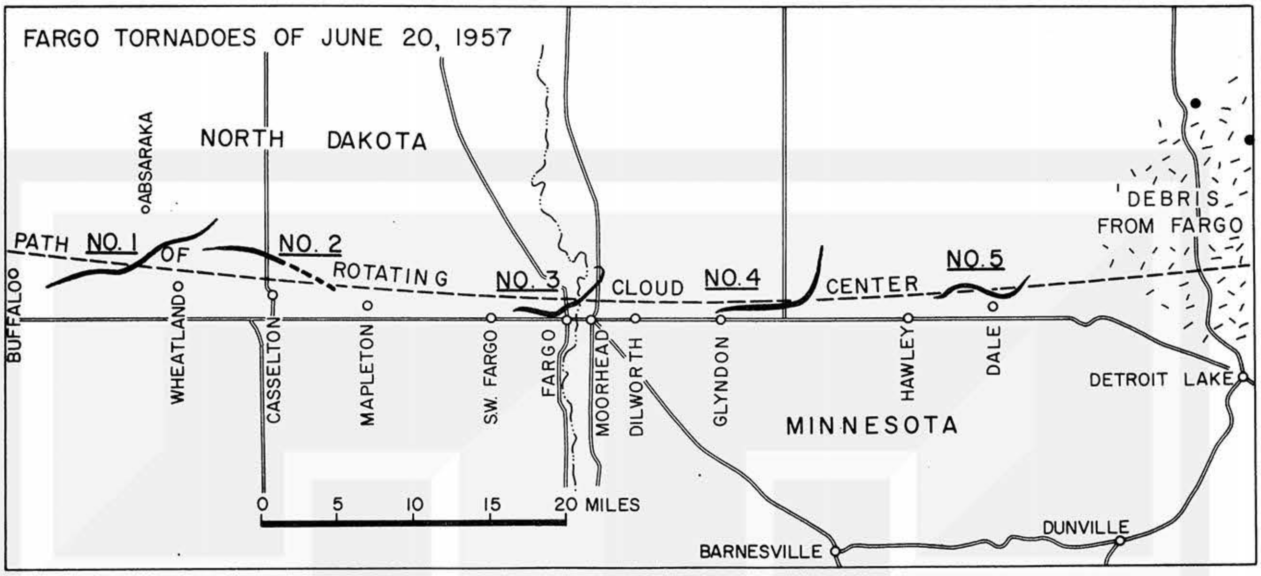

FARGO TORNADOES OF JUNE 20, 1957
NORTH DAKOTA
MINNESOTA
ABSARAKA
PATH NO. 1 OF NO. 2 ROTATING NO. 3 CLOUD NO. 4 CENTER NO. 5
DEBRIS FROM FARGO
BUFFALO
WHEATLAND
CASSELTON
MAPLETON
SW. FARGO
FARGO
MOORHEAD
DILWORTH
GLYNDON
HAWLEY
DALE
DETROIT LAKE
BARNESVILLE
DUNVILLE
0 5 10 15 20 MILES

FIG. 7

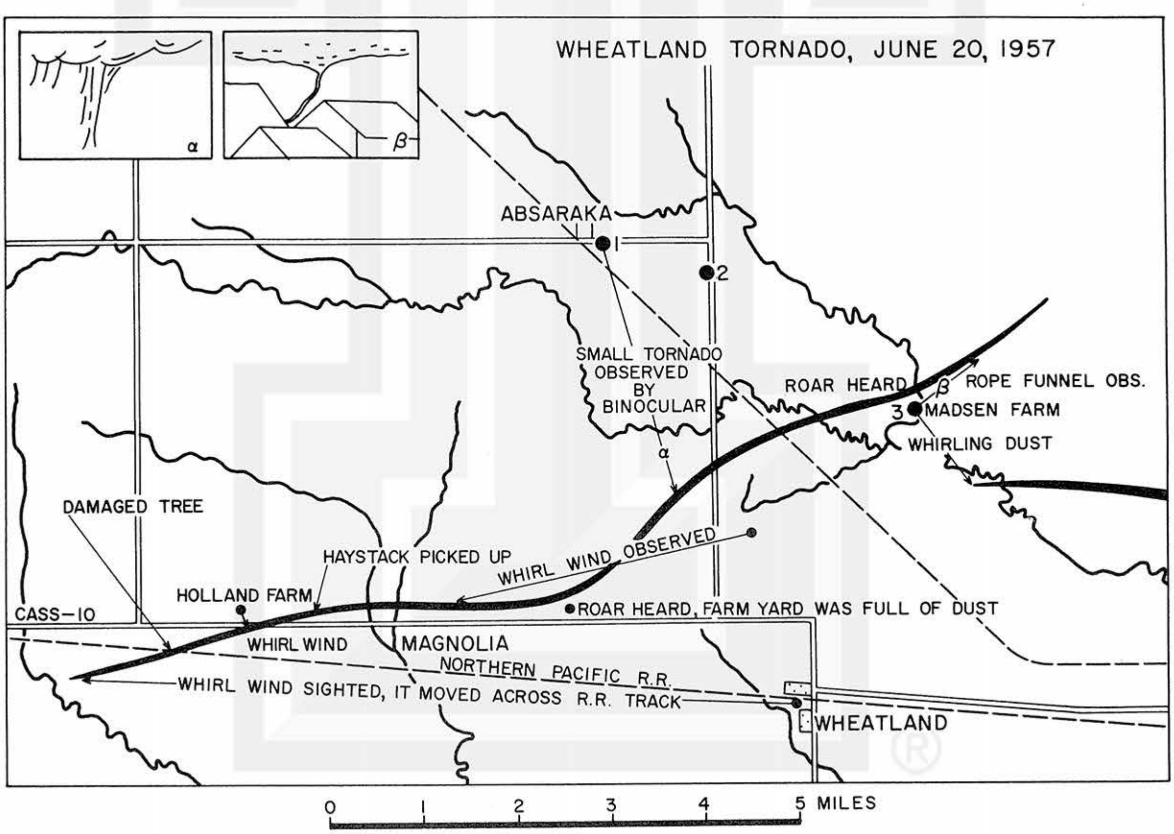

WHEATLAND TORNADO, JUNE 20, 1957
α
β
ABSARAKA
1
2
3
SMALL TORNADO OBSERVED BY BINOCULAR
ROAR HEARD
ROPE FUNNEL OBS.
MADSEN FARM
WHIRLING DUST
DAMAGED TREE
HAYSTACK PICKED UP
WHIRL WIND OBSERVED
HOLLAND FARM
CASS-10
ROAR HEARD, FARM YARD WAS FULL OF DUST
WHIRL WIND
MAGNOLIA
NORTHERN PACIFIC R.R.
WHIRL WIND SIGHTED, IT MOVED ACROSS R.R. TRACK
WHEATLAND
0 1 2 3 4 5 MILES

FIG. 8

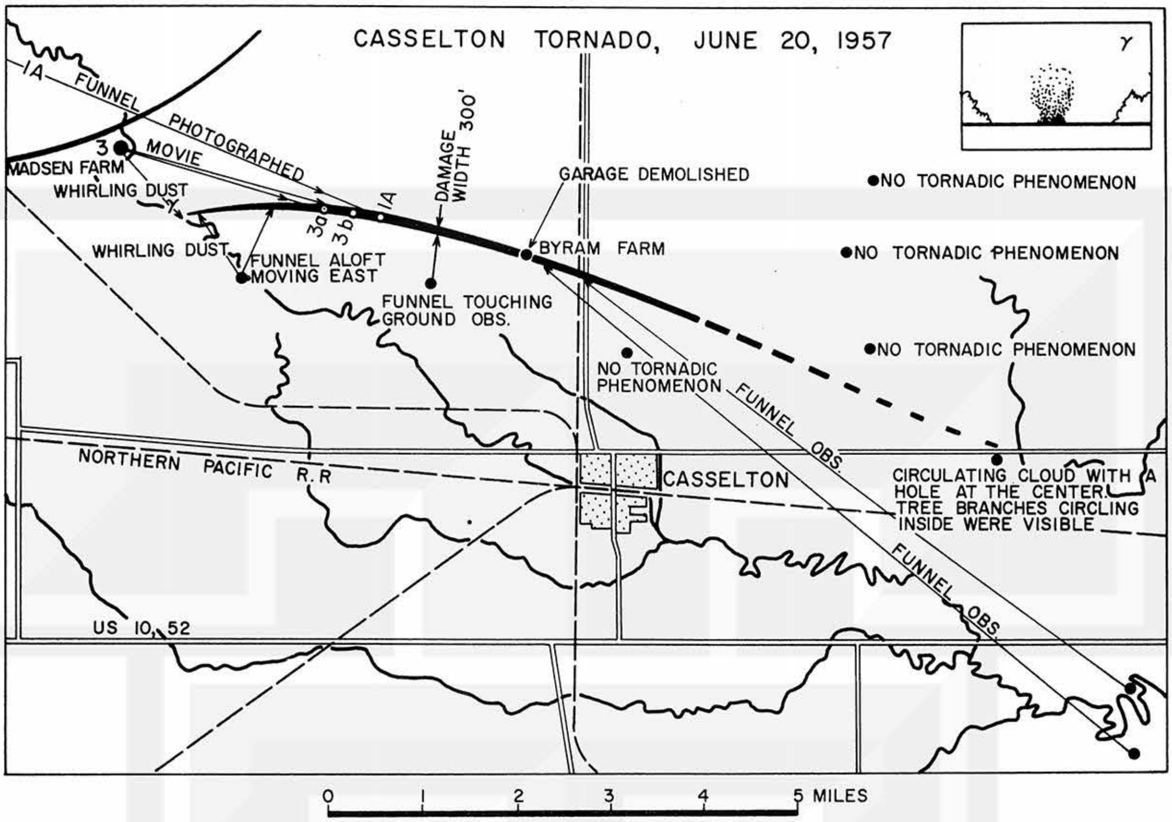

CASSELTON TORNADO, JUNE 20, 1957
γ
1A FUNNEL PHOTOGRAPHED
3 MOVIE
MADSEN FARM
WHIRLING DUST
3a
3b
1A
DAMAGE WIDTH 300'
GARAGE DEMOLISHED
NO TORNADIC PHENOMENON
BYRAM FARM
NO TORNADIC PHENOMENON
WHIRLING DUST
FUNNEL ALOFT MOVING EAST
FUNNEL TOUCHING GROUND OBS.
NO TORNADIC PHENOMENON
NO TORNADIC PHENOMENON
FUNNEL OBS.
NORTHERN PACIFIC R.R
CASSELTON
CIRCULATING CLOUD WITH A HOLE AT THE CENTER. TREE BRANCHES CIRCLING INSIDE WERE VISIBLE
FUNNEL OBS.
US 10, 52
0 1 2 3 4 5 MILES

FIG. 9

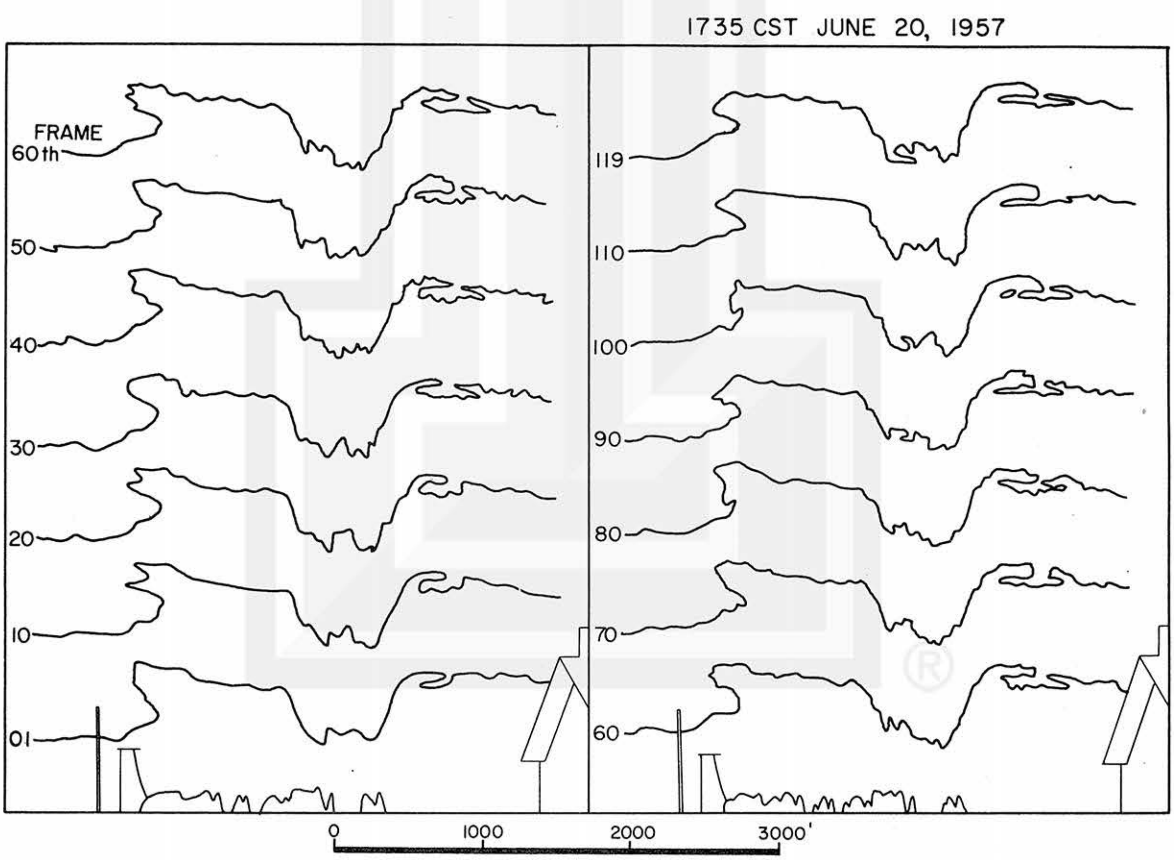

1735 CST JUNE 20, 1957
FRAME 60th
50
40
30
20
10
01
119
110
100
90
80
70
60
0 1000 2000 3000'

FIG. 10

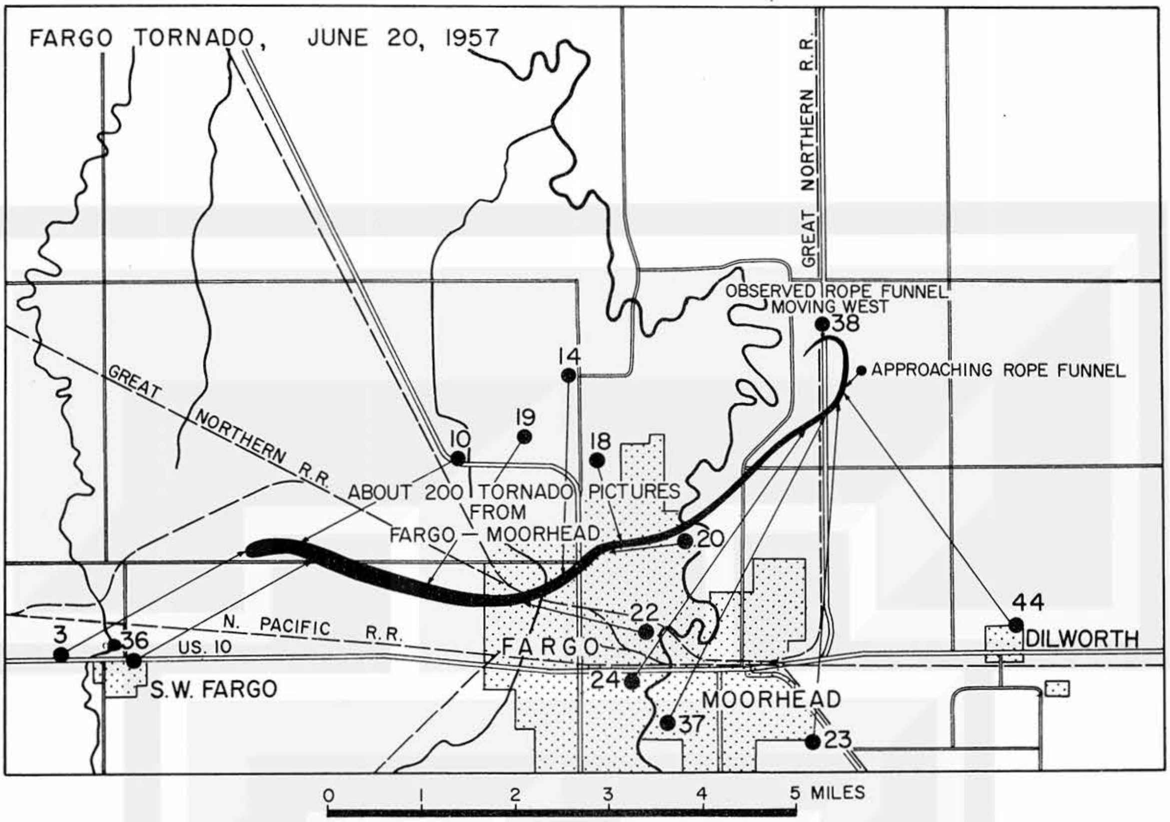

FARGO TORNADO, JUNE 20, 1957
GREAT NORTHERN R.R.
OBSERVED ROPE FUNNEL MOVING WEST
38
APPROACHING ROPE FUNNEL
14
19
10
18
ABOUT 200 TORNADO PICTURES FROM FARGO — MOODHEAD
20
22
44
DILWORTH
3
36
N. PACIFIC R.R.
US. 10
FARGO
S.W. FARGO
24
MOORHEAD
37
23
0 1 2 3 4 5 MILES

FIG. 11

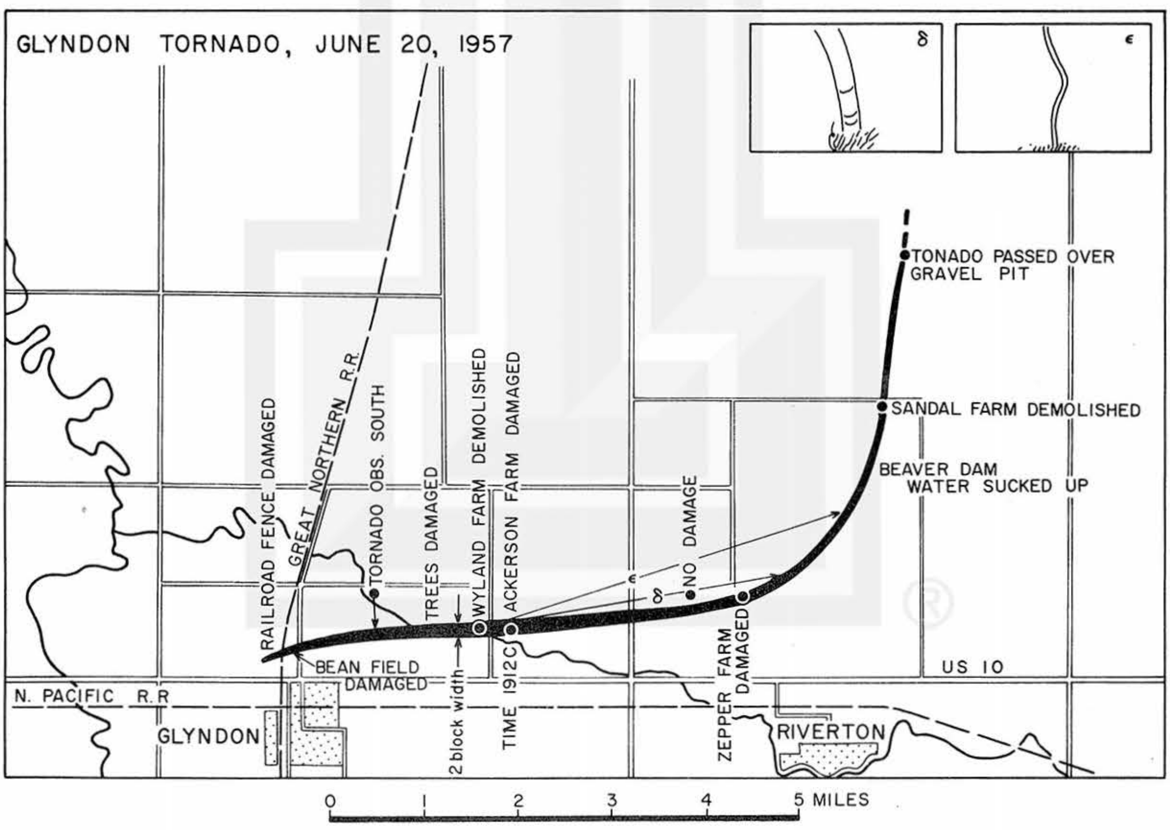

GLYNDON TORNADO, JUNE 20, 1957
δ
ϵ
TONADO PASSED OVER GRAVEL PIT
SANDAL FARM DEMOLISHED
BEAVER DAM WATER SUCKED UP
RAILROAD FENCE DAMAGED
GREAT NORTHERN R.R.
TORNADO OBS. SOUTH
TREES DAMAGED
WYLAND FARM DEMOLISHED
ACKERSON FARM DAMAGED
NO DAMAGE
BEAN FIELD DAMAGED
2 block width
TIME 1912C
ZEPPER FARM DAMAGED
US 10
N. PACIFIC R.R
GLYNDON
RIVERTON
0 1 2 3 4 5 MILES

FIG. 12

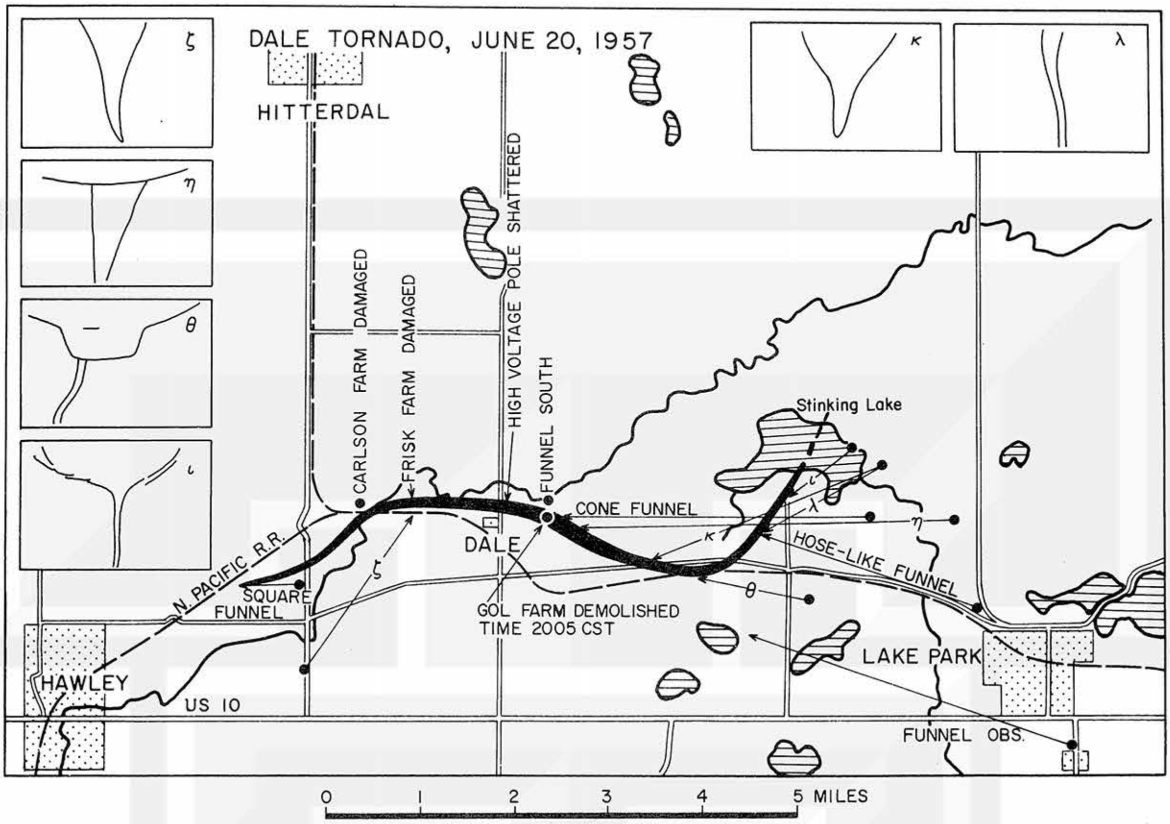

DALE TORNADO, JUNE 20, 1957
HITTERDAL
HIGH VOLTAGE POLE SHATTERED
CARLSON FARM DAMAGED
FRISK FARM DAMAGED
FUNNEL SOUTH
Stinking Lake
CONE FUNNEL
DALE
HOSE-LIKE FUNNEL
N. PACIFIC R.R.
SQUARE FUNNEL
GOL FARM DEMOLISHED
TIME 2005 CST
LAKE PARK
HAWLEY
US 10
FUNNEL OBS.
0 1 2 3 4 5 MILES

FIG. 13

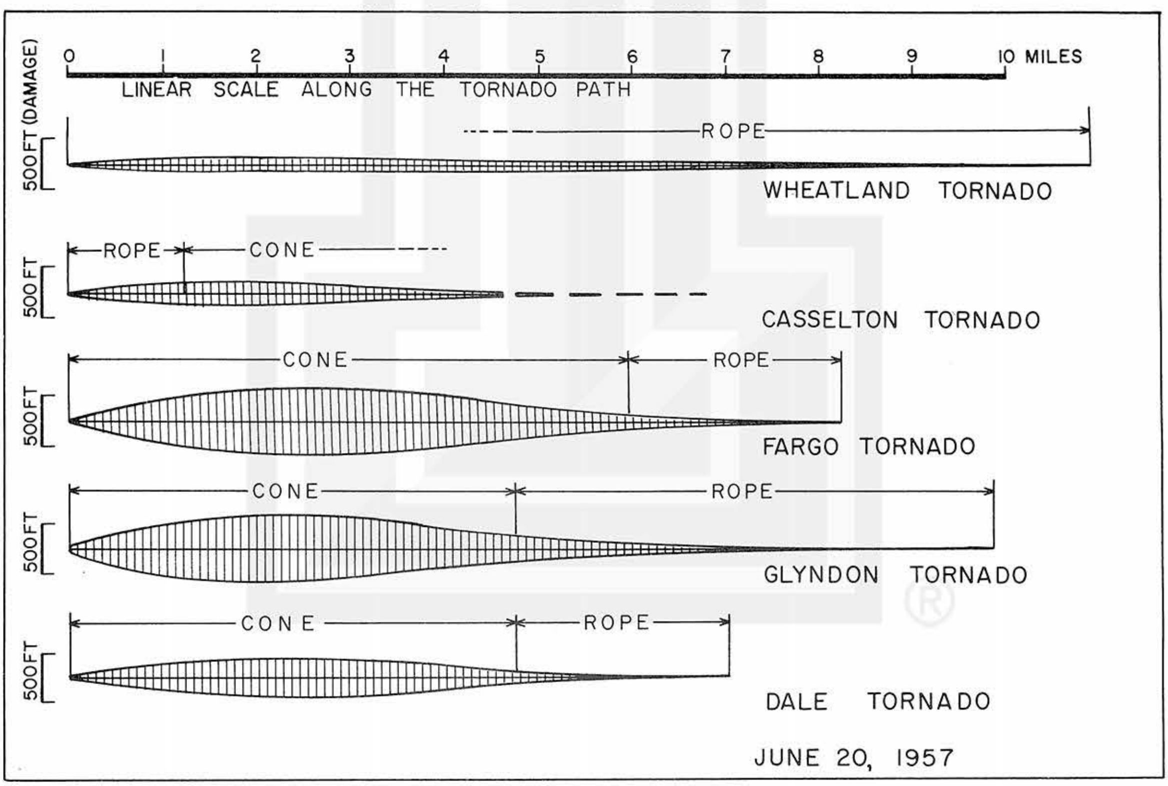

0 1 2 3 4 5 6 7 8 9 10 MILES
LINEAR SCALE ALONG THE TORNADO PATH
500 FT (DAMAGE)
ROPE
WHEATLAND TORNADO
500 FT
ROPE
CONE
CASSELTON TORNADO
500 FT
CONE
ROPE
FARGO TORNADO
500 FT
CONE
ROPE
GLYNDON TORNADO
500 FT
CONE
ROPE
DALE TORNADO
JUNE 20, 1957

FIG. 14

CHAPTER II: FIVE TORNADOES OF JUNE 20, 1957

CHAPTER III: TORNADO PICTURES COLLECTED

An unusual number and quality of photographs were collected from citizens in 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 ten times larger than a tornado in horizontal dimensions, for the tornado itself and began taking pictures of the cloud.

Following is the list of the photographers who made the excellent observations used in completing this report:

Town	Obs. Pt.	Observer	Type of Obs.	Frame
Absaraka	1	Faught	35 mm color	A
"	2	"	"	B
Wheatland	3	Madsen	8 mm color	a, b
West Fargo	4	Fradet	35 mm color	A, B, C, D, E
"	5	Payne	35 mm b & w	A
"	6	"	"	B, C
"	7	Stensrud	"	A, B, C
Fargo	8	Beaton	120 b & w	A, B, C
"	9	Bergquist	4 x 5 b & w	A, B
"	10	"	"	C, D
"	11	"	"	E, F
"	12	"	"	G, I
"	13	"	"	H
"	14	"	"	J, K
"	15	"	"	L
"	16	"	"	M, N
"	17	"	"	O
"	18	Byers	120 b & w	A, B
"	19	"	"	C, D

Town	Obs. Pt.	Observer	Type of Obs.	Frame
Fargo	20	Frank	35 mm color	A
"	21	"	"	B
"	22	"	"	C, D
"	23	Gebert	120 b & w	A-H
"	24	"	4 x 5 b & w	I, J
"	25	"	120 b & w	K, L
"	26	Hutchinson	35 mm b & w	A-H
"	26	"	4 x 5 b & w	I-M
"	26	"	35 mm b & w	N-V
"	27	Jennings	"	A-E
"	27	"	16 mm b & w	a-m, p-s
"	27'	Dooley	"	n, o
"	28	Kittelsrud	35 mm color	A-O
"	28	Jensen	sketches	I, II, III
"	29	Olsen	120 b & w	A, B
"	30	"	"	C, D
"	31	Pilato	8 mm color	a-d
"	32	Schrader	16 mm b & w	a-f
"	33	"	"	g
"	34	"	"	h
"	35	Wild	35 mm color	A, B
Moorhead	36	Arhart	polaroid	A
"	37	Helmeke	35 mm b & w	A
"	38	"	"	B, C
"	39	Mickelson	8 mm color	a, b
"	40	Stenerson	35 mm color	A
"	41	Tenold	"	A, B
Dilworth	42	Littke	"	A, B, C
"	43	"	"	D, E, F
"	44	"	"	G, H
Moorhead	45	Arhart	sketch	I
"	46	Oksendahl	"	I

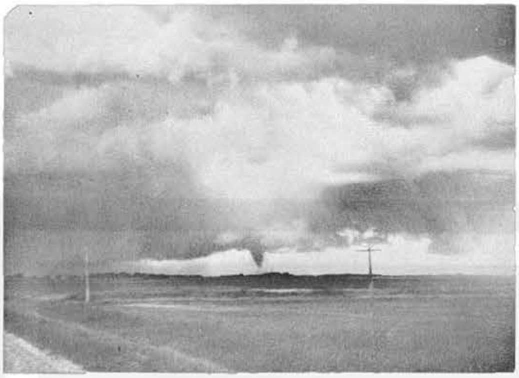
Town	Obs. Pt.	Observer	Type of Obs.	Frame
Moorhead	47	Wilson	sketch	I-VII
Fargo	48	Hagen	120 b & w	A
"	49	"	"	B-K
"	50	Frahm	35 mm color	A-F
West Fargo	51	Payne	35 mm b & w	D, E

This list includes the township where each observation was made, point of observation designated by number, name of observer, 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.

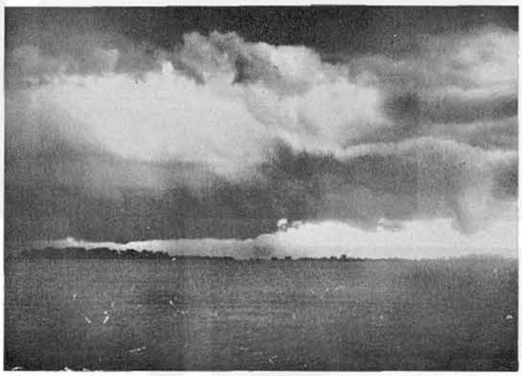
Figures 15-37 show reduced reproductions of all the photographs and sketches available for the study of the Fargo tornadoes.

Figure 38 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 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.

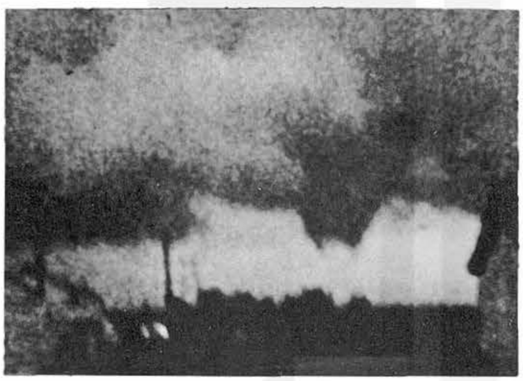
In the upper left section of the figure are shown the points where the early activities of the Fargo tornadoes were photographed.



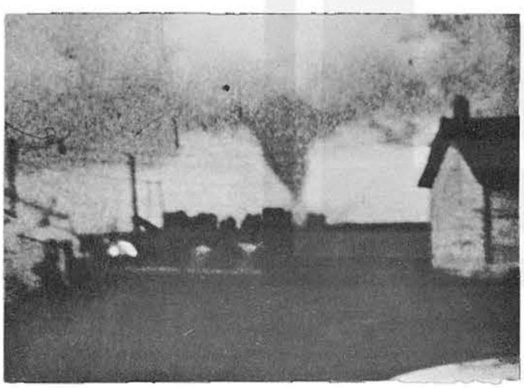
01 A FAUGHT



02 B FAUGHT



03 a MADSEN

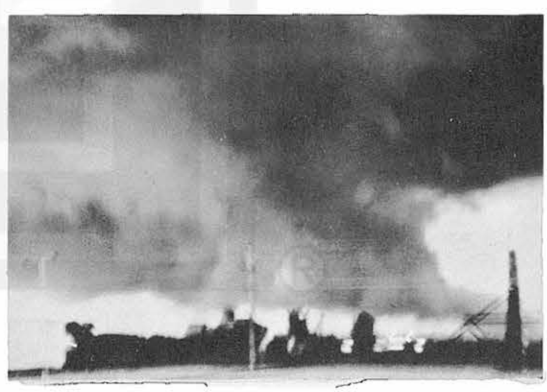


03 b MADSEN

04 A FRADET

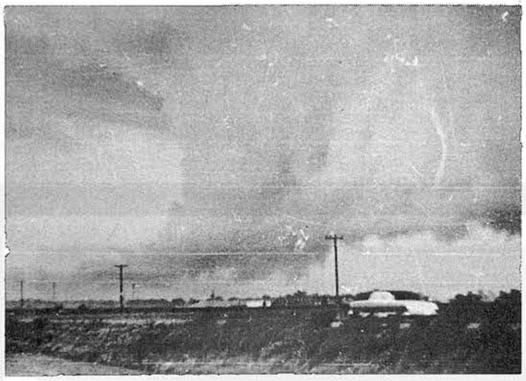
04 B FRADET

04 C FRADET



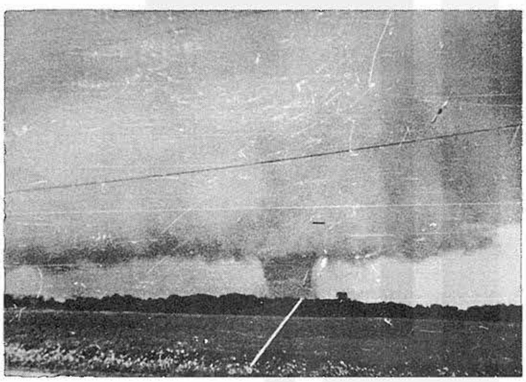
04 D FRADET

FIG. 15



05 A PAYNE

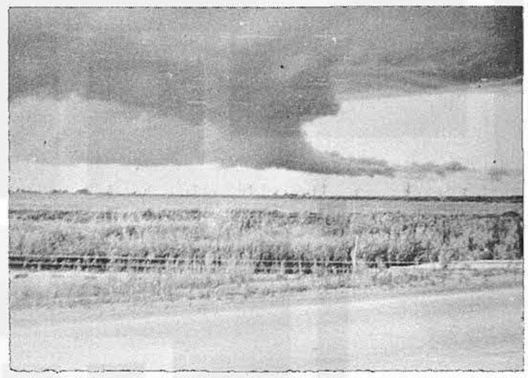
06 B PAYNE



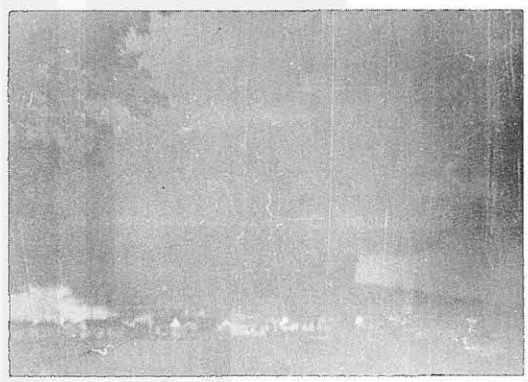
06 C PAYNE

07 A STENSRUD

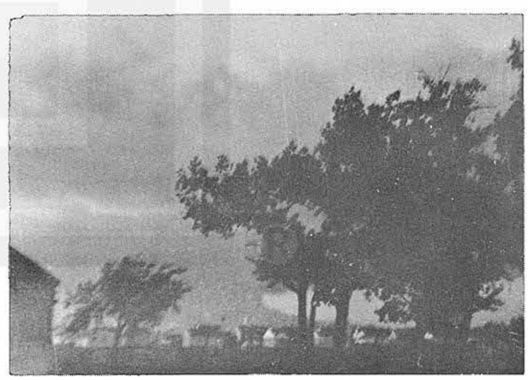
07 B STENSRUD



07 C STENSRUD



08 A BEATON



08 B BEATON

FIG. 16

08 C BEATON

10 D BERGQUIST

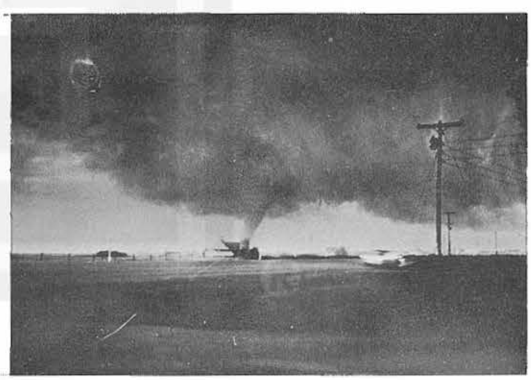
09 A BERGQUIST

11 E BERGQUIST

09 B BERGQUIST

11 F BERGQUIST

10 C BERGQUIST

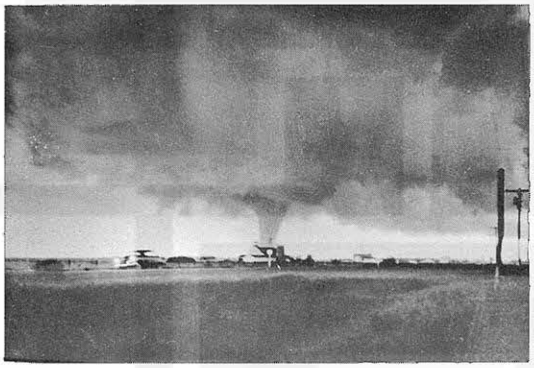


12 G BERGQUIST

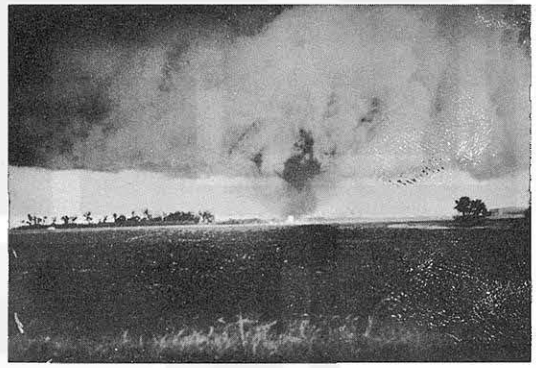
FIG. 17

12 I BERGQUIST

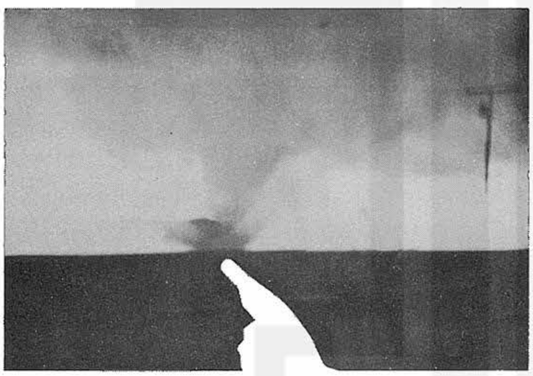
15 L BERGQUIST



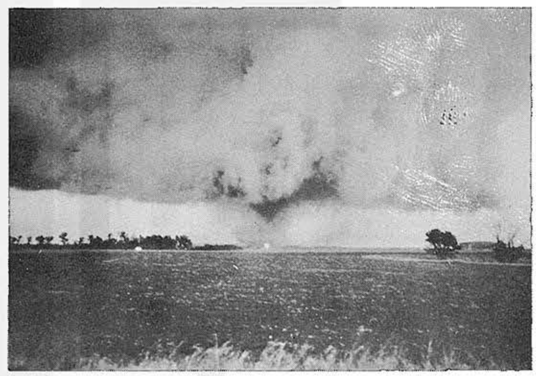
13 H BERGQUIST



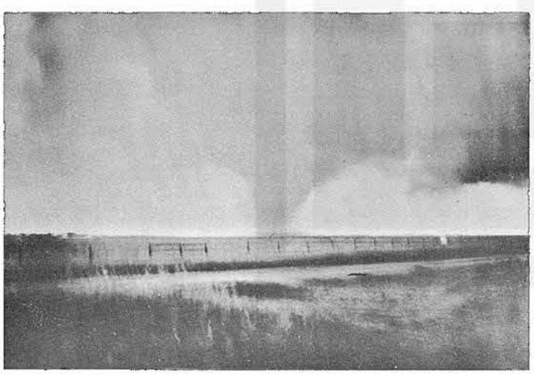
16 M BERGQUIST



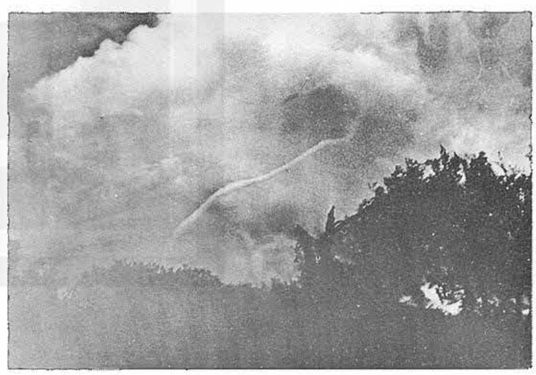
14 J BERGQUIST



16 N BERGQUIST

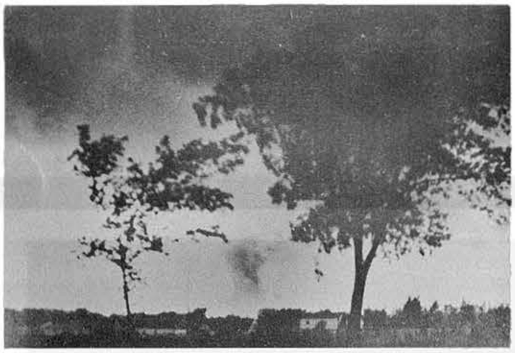


14 K BERGQUIST



17 O BERGQUIST

FIG. 18



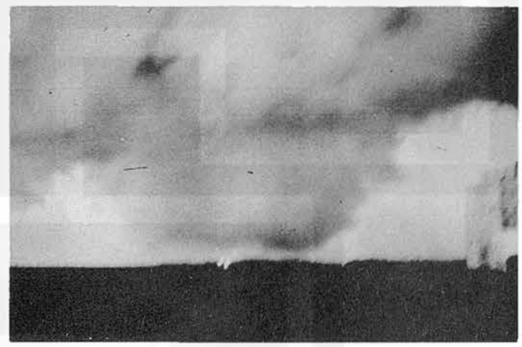
18 A BYERS

18 B BYERS

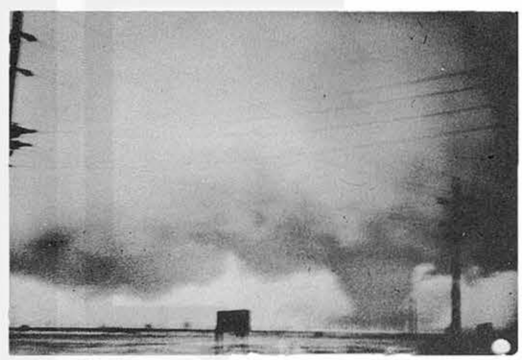
19 C BYERS

19 D BYERS

20 A FRANK



21 B FRANK

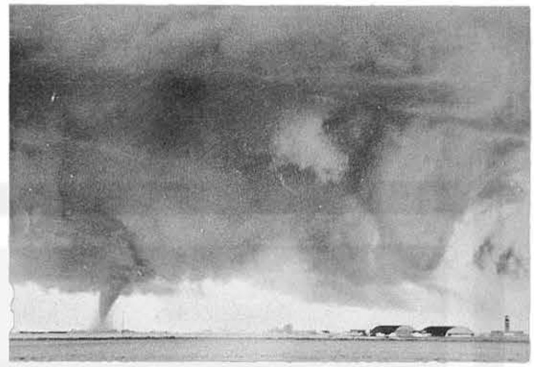


22 C FRANK

22 D FRANK

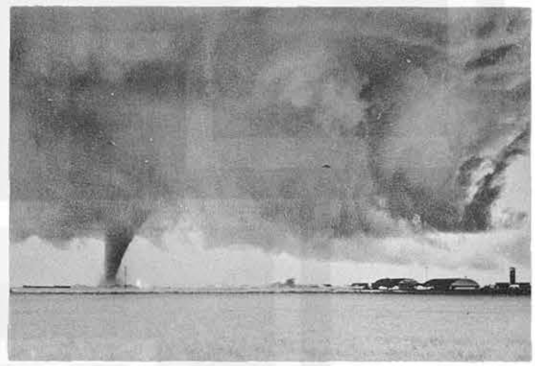
FIG. 19

23 A GEBERT



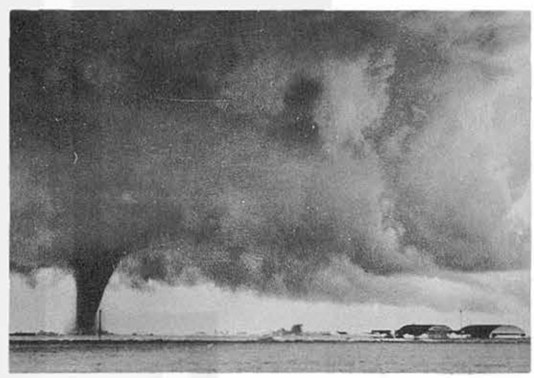
23 E GEBERT

23 B GEBERT



23 F GEBERT

23 C GEBERT



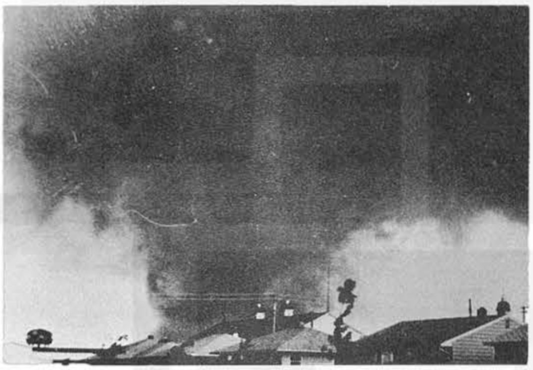
23 G GEBERT

23 D GEBERT

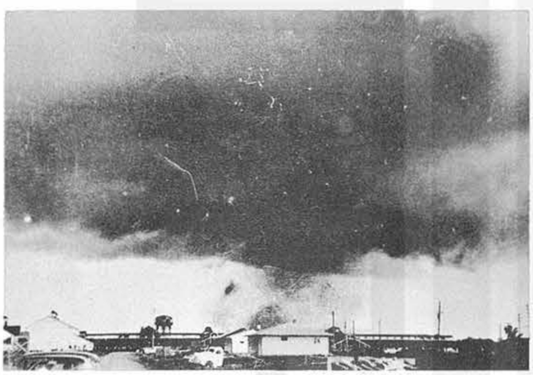
24 H GEBERT

FIG. 20

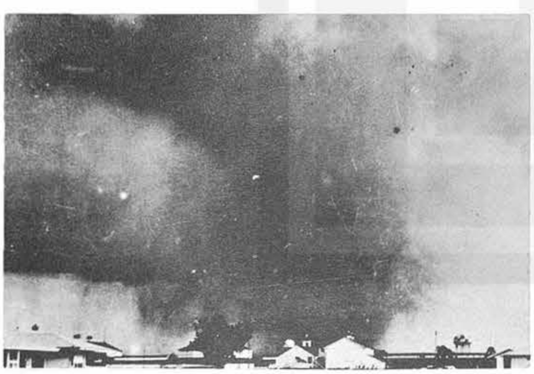
24 I GEBERT



24 J GEBERT



25 K GEBERT

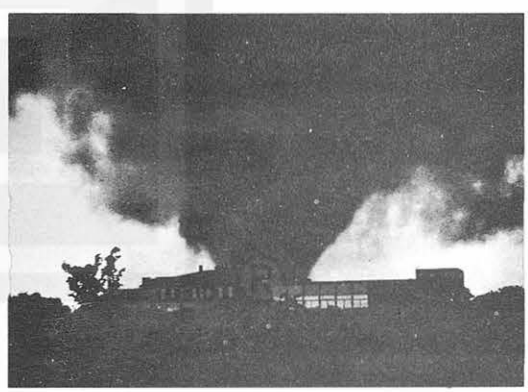


25 L GEBERT

26 A HUTCHINSON

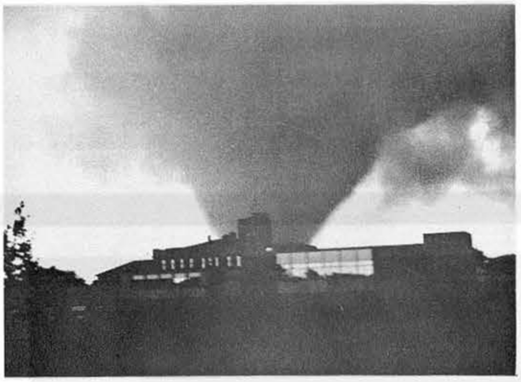
26 B HUTCHINSON

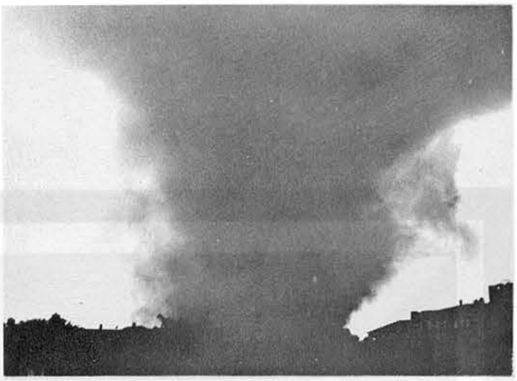
26 C HUTCHINSON



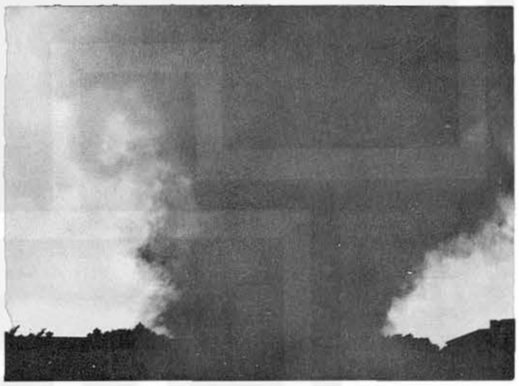
26 D HUTCHINSON

FIG. 21


26 E HUTCHINSON

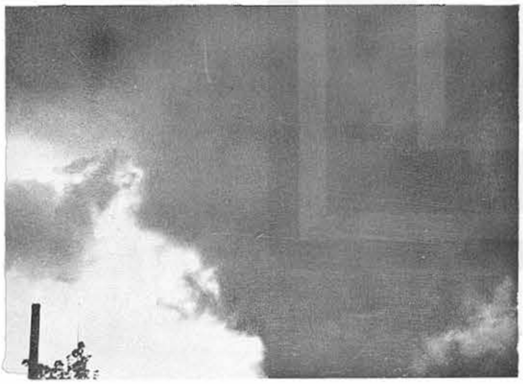

26 I HUTCHINSON


26 F HUTCHINSON


26 J HUTCHINSON


26 G HUTCHINSON


26 K HUTCHINSON


26 H HUTCHINSON

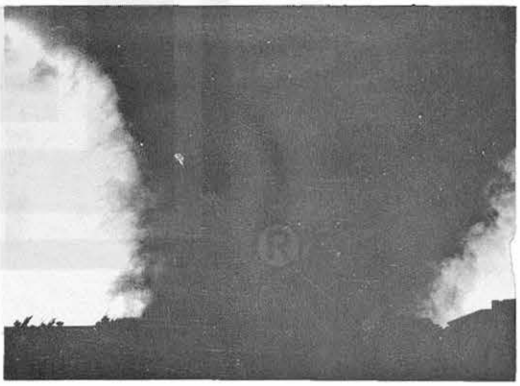
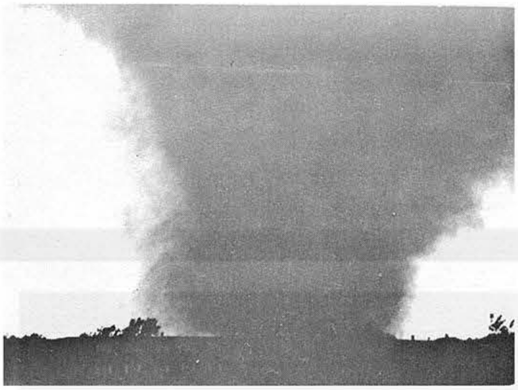
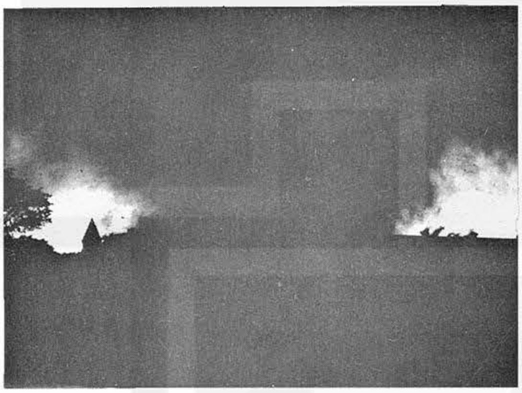

26 L HUTCHINSON

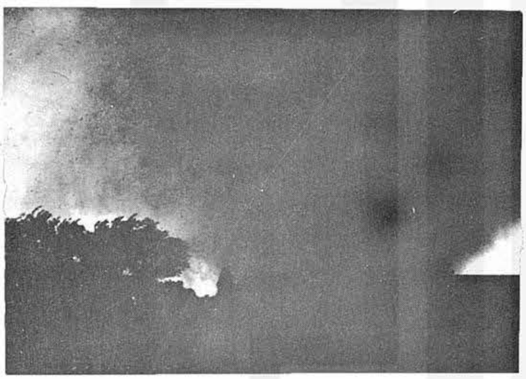
FIG. 22



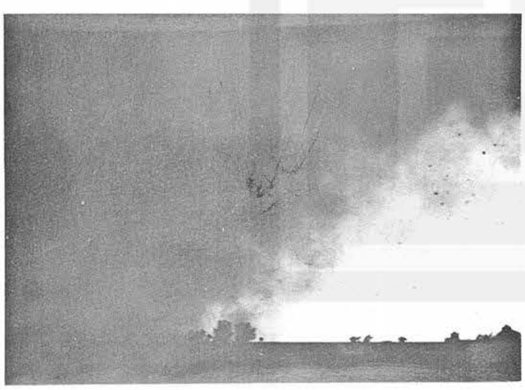
26 M HUTCHINSON



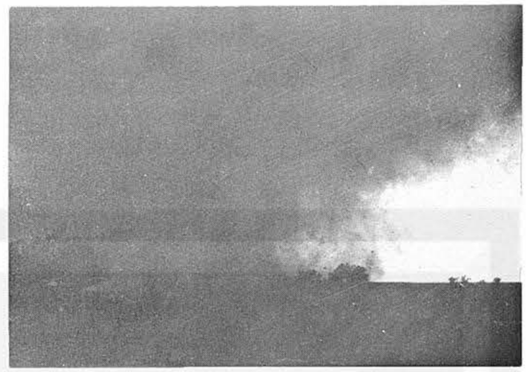
26 N HUTCHINSON



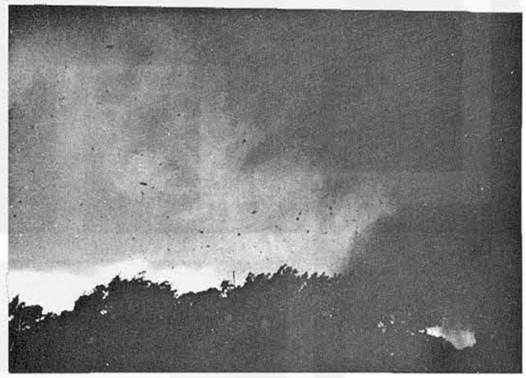
26 O HUTCHINSON



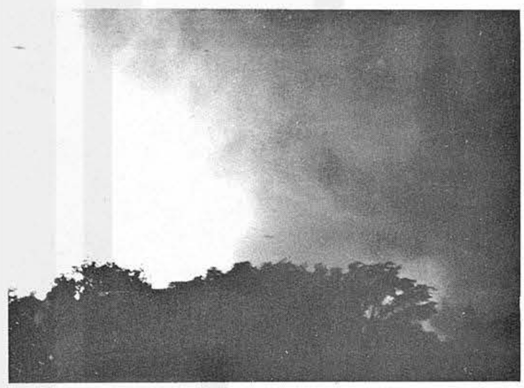
26 P HUTCHINSON



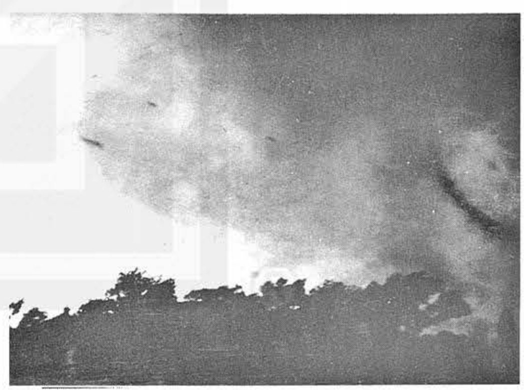
26 Q HUTCHINSON



26 R HUTCHINSON



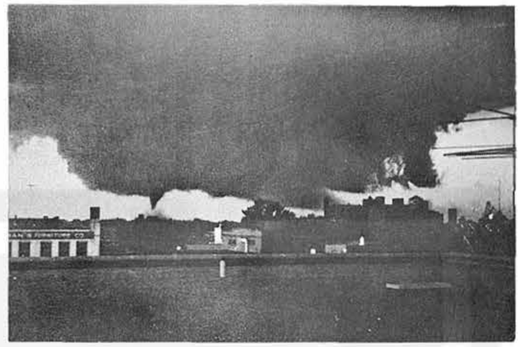
26 S HUTCHINSON



26 T HUTCHINSON

FIG. 23

26 U HUTCHINSON



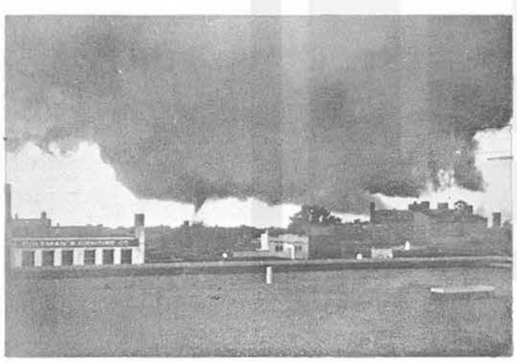
27 C JENNINGS

26 V HUTCHINSON

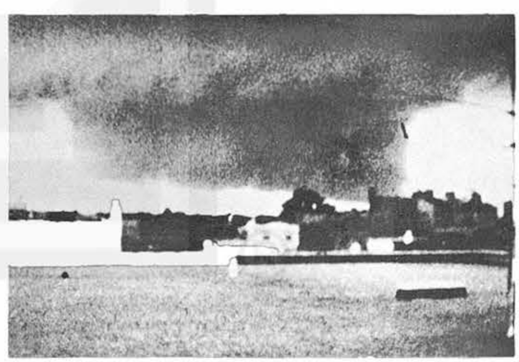
27 D JENNINGS

27 A JENNINGS

27 E JENNINGS

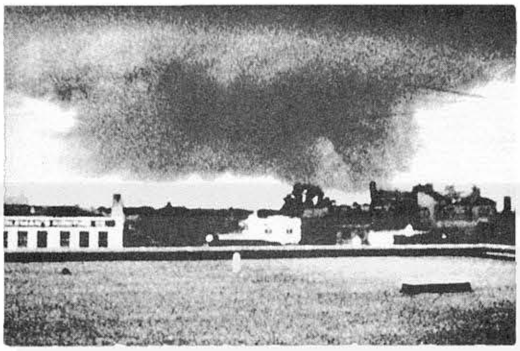


27 B JENNINGS



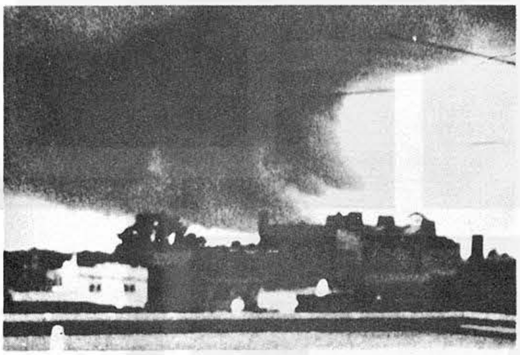
27 a JENNINGS

FIG. 24

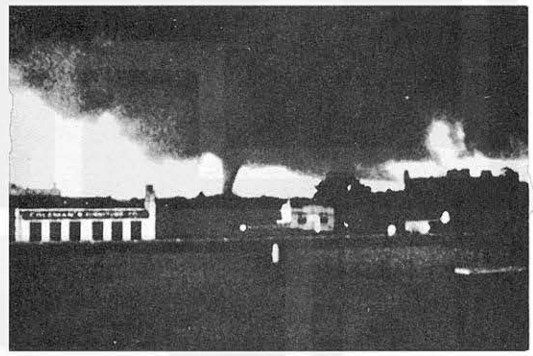


27 b JENNINGS

27 f JENNINGS



27 c JENNINGS

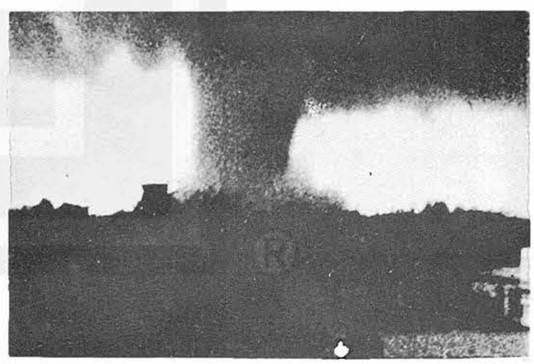


27 g JENNINGS

27 d JENNINGS

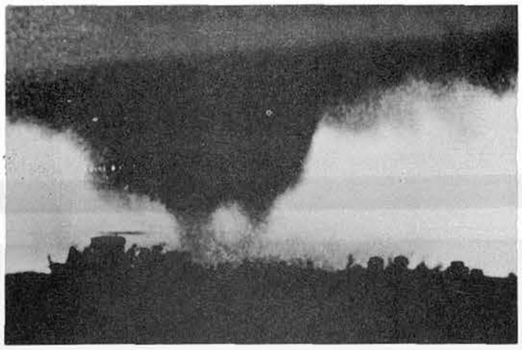
27 h JENNINGS

27 e JENNINGS



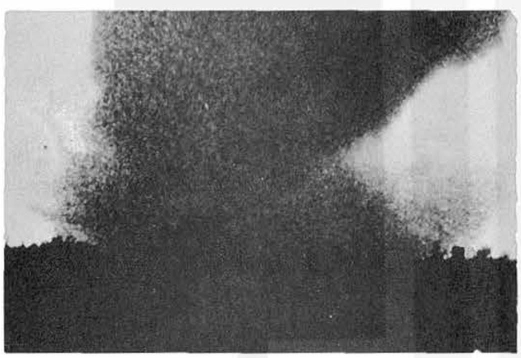
27 i JENNINGS

FIG. 25

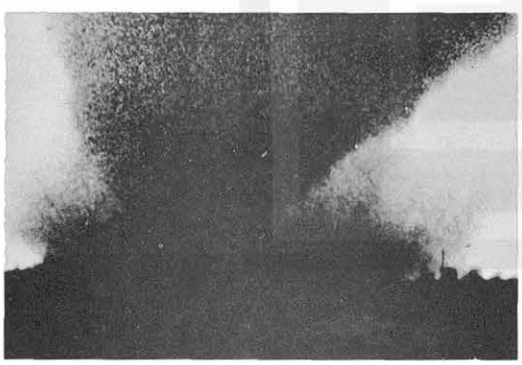


27 j JENNINGS

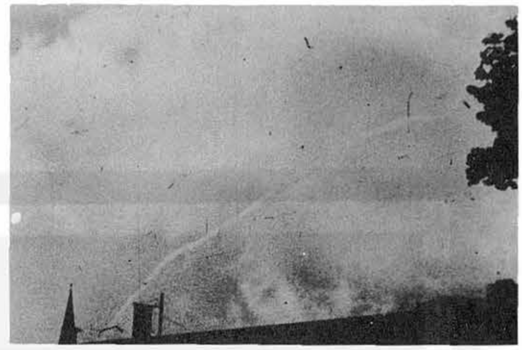
27 k JENNINGS



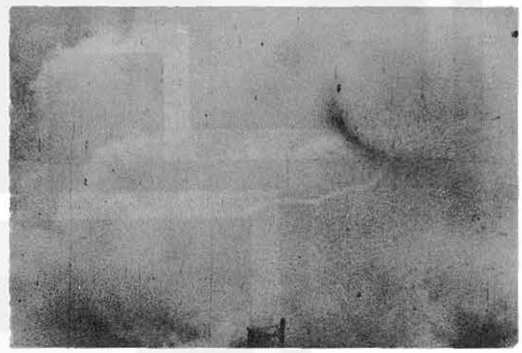
27 l JENNINGS



27 m JENNINGS



27' n DOOLEY



27' o DOOLEY

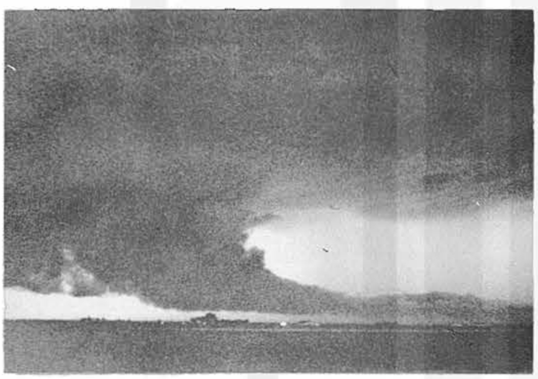
27 p JENNINGS

27 q JENNINGS

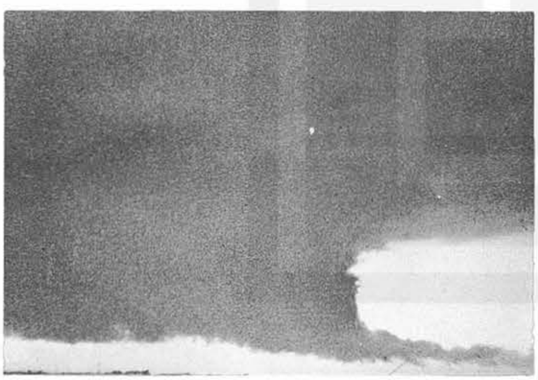
FIG. 26

27 r JENNINGS

27 s JENNINGS

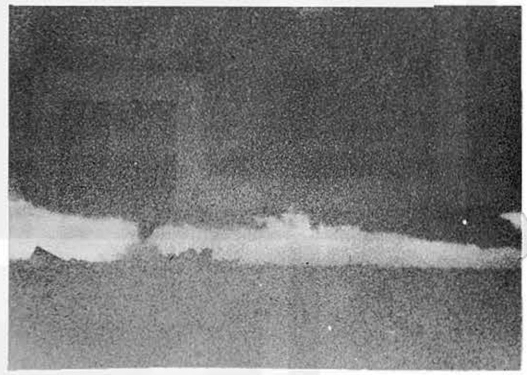


28 A KITTELSRUD

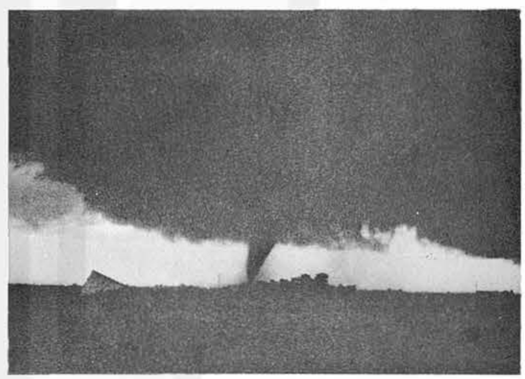


28 B KITTELSRUD

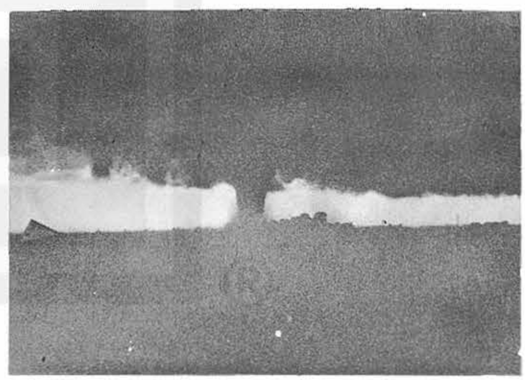
28 C KITTELSRUD



28 D KITTELSRUD

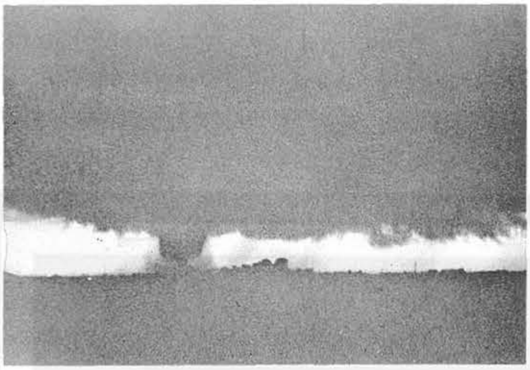


28 E KITTELSRUD

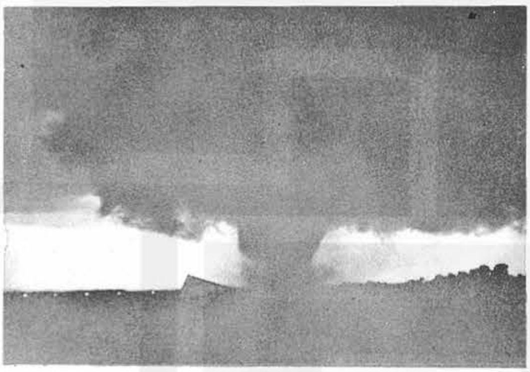


28. F KITTELSRUD

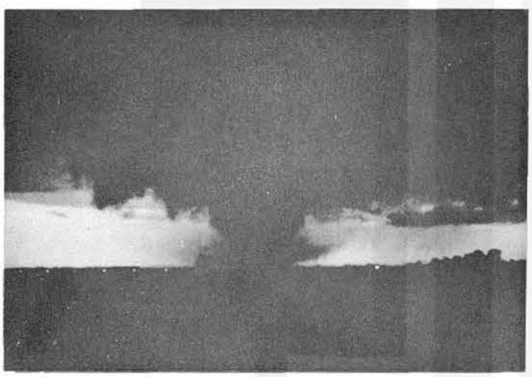
FIG. 27



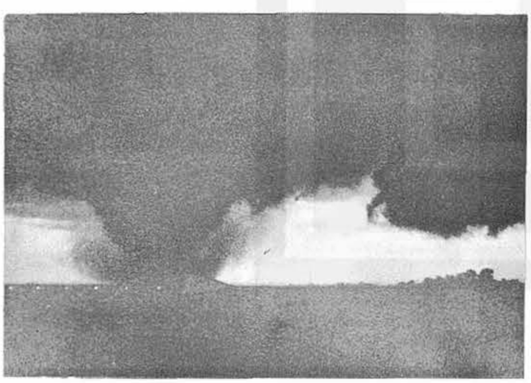
28 G KITTELSRUD



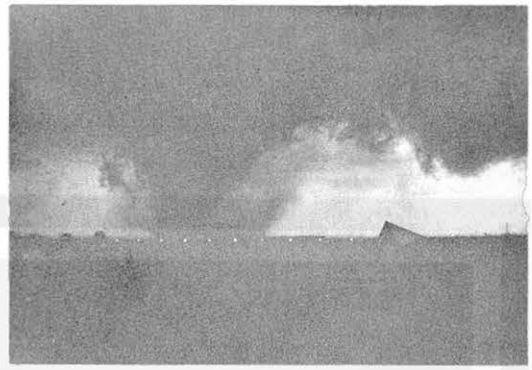
28 H KITTELSRUD



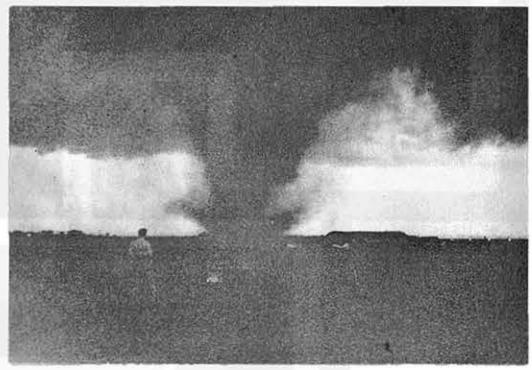
28 I KITTELSRUD



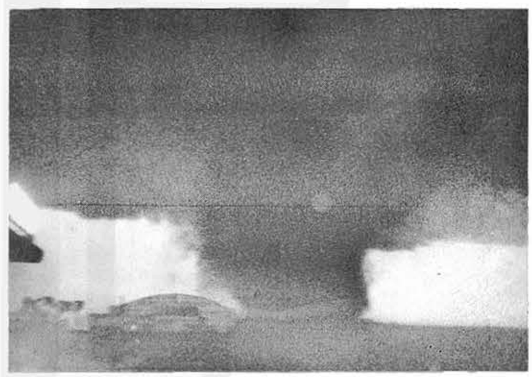
28 J KITTELSRUD



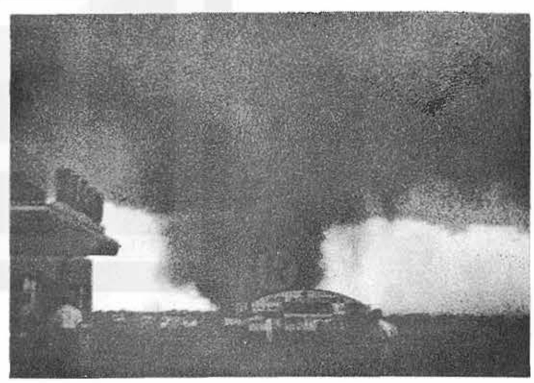
28 K KITTELSRUD



28 L KITTELSRUD



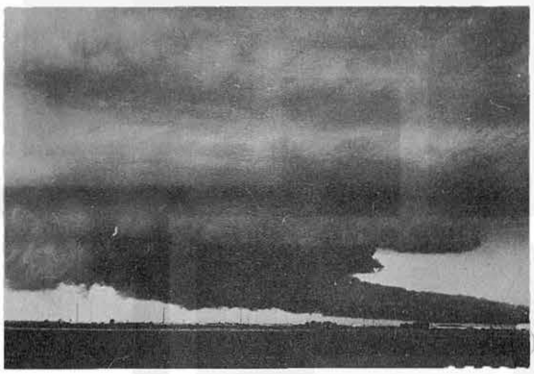
28 M KITTELSRUD



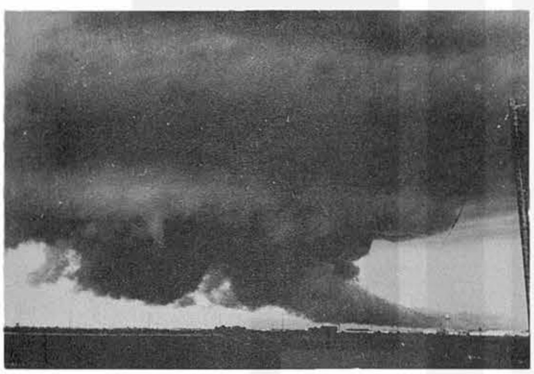
28 N KITTELSRUD

FIG. 28

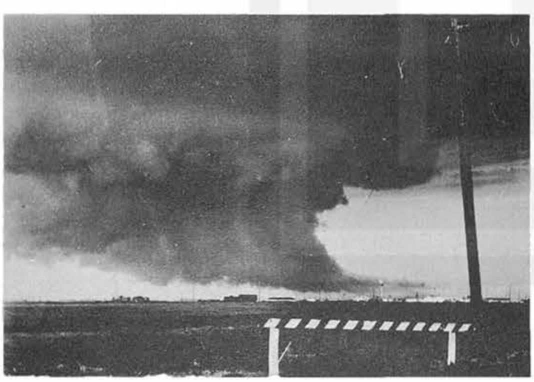
28 O KITTELSRUD



29 A OLSEN



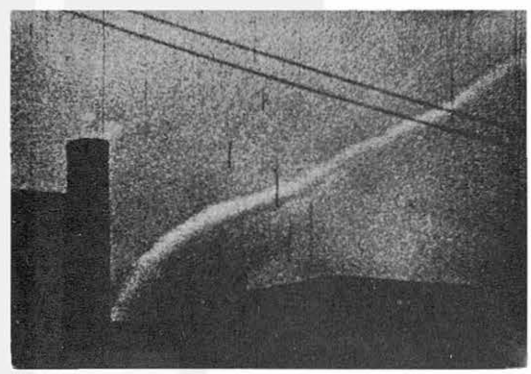
29 B OLSEN



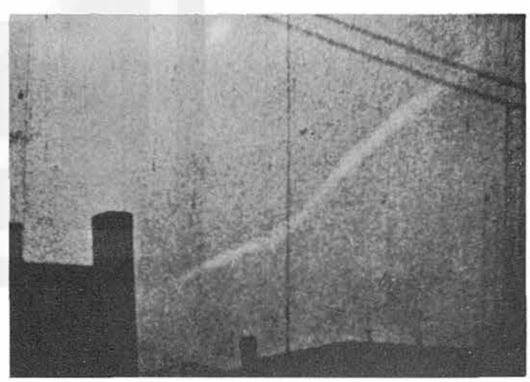
30 C OLSEN

30 D OLSEN

31 a PILATO

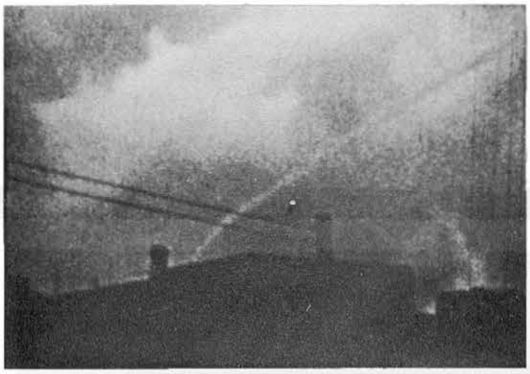


31 b PILATO

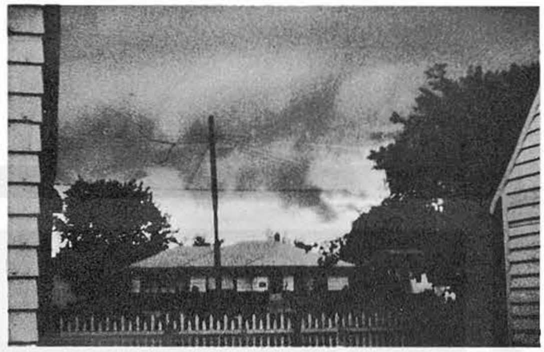


31 c PILATO

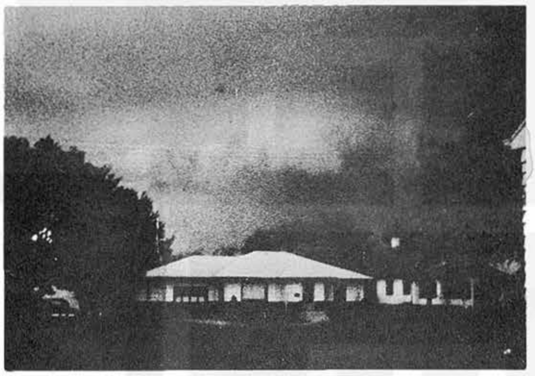
FIG. 29



31 d PILATO

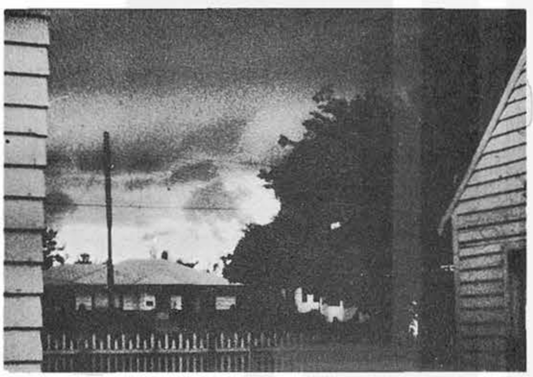


32 d SCHRADER



32 a SCHRADER

32 e SCHRADER



32 b SCHRADER

32 f SCHRADER

32 c SCHRADER

33 g SCHRADER

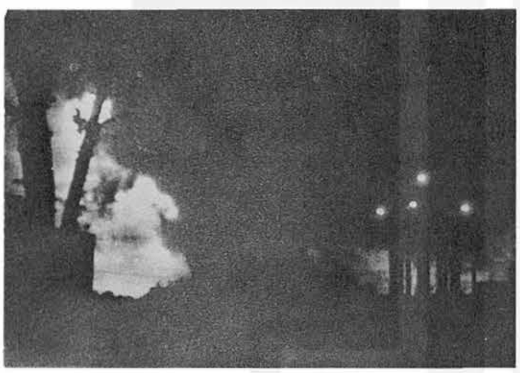
FIG. 30

34 h SCHRADER

37 A HELMEKE

35 A WILD

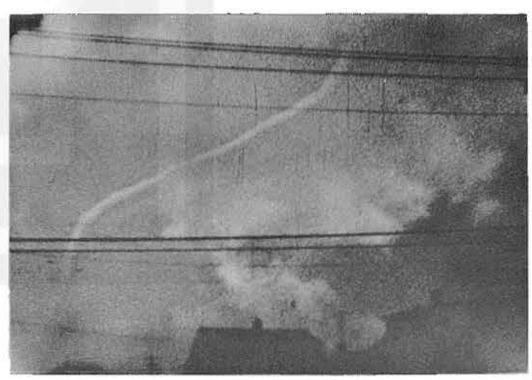
38 B HELMEKE



35 B WILD

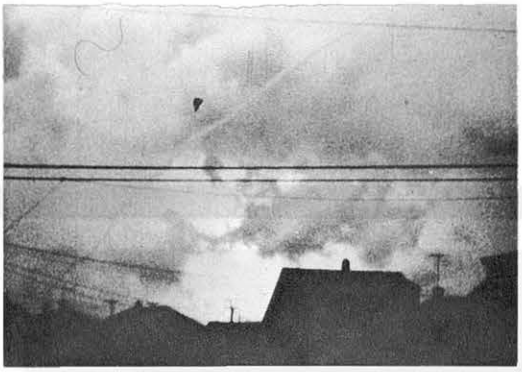
38 C HELMEKE

36 A ARHART

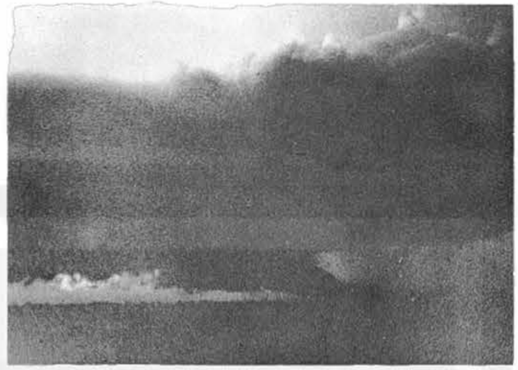


39 a MICKELSON

FIG. 31

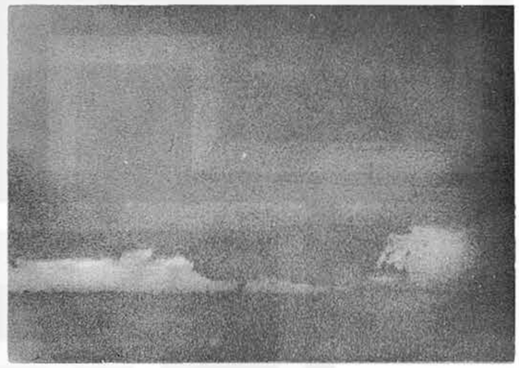


39 b MICKELSON



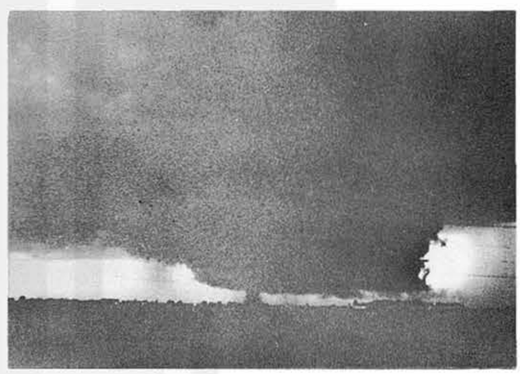
42 A LITTKE

40 A STENERSON

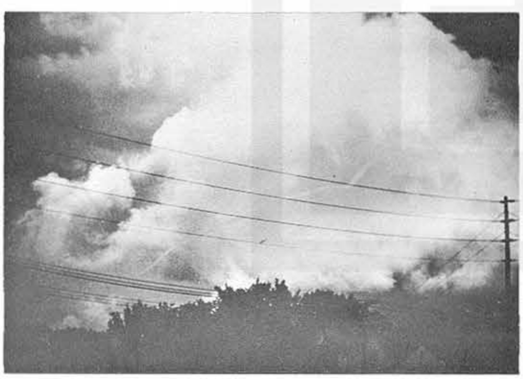


42 B LITTKE

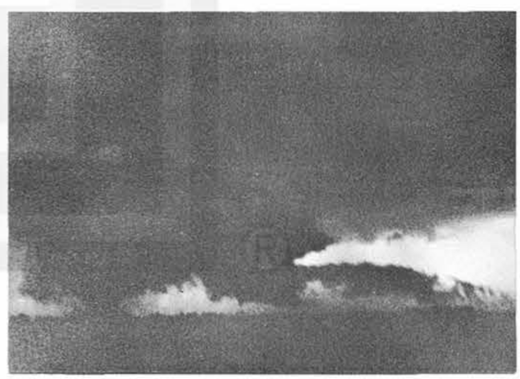
41 A TENOLD



42 C LITTKE

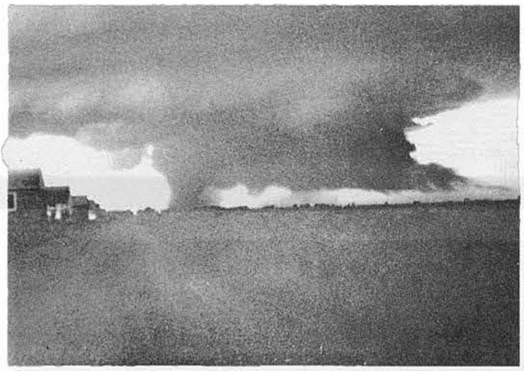


41 B TENOLD

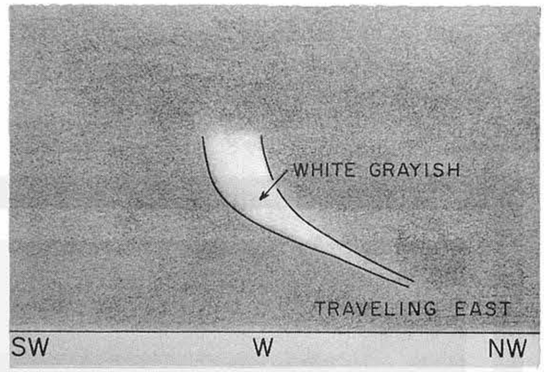


43 D LITTKE

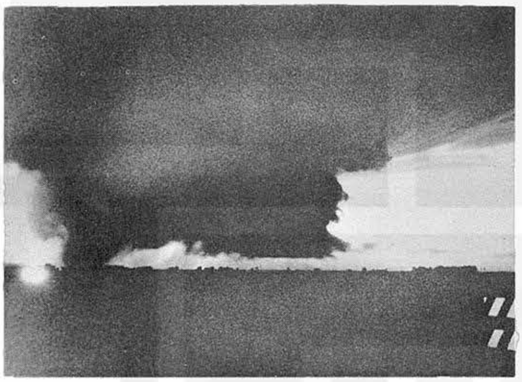
FIG. 32



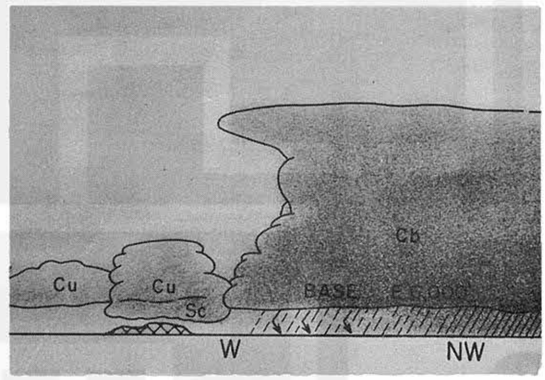
43 E LITTKE



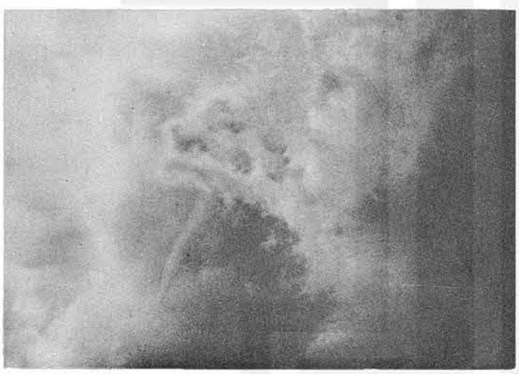
45 I ARHART



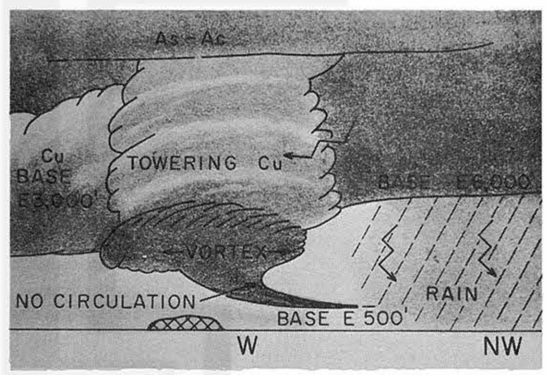
43 F LITTKE



28 I JENSEN

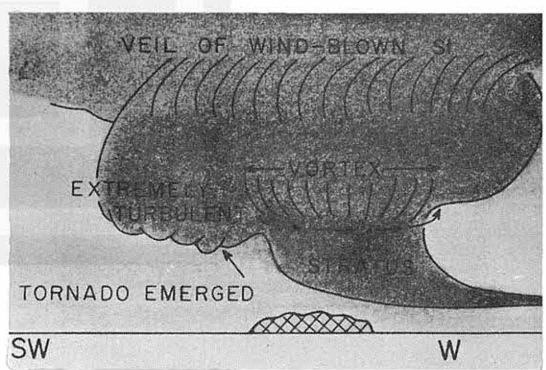


44 G LITTKE



28 II JENSEN

44 H LITTKE



28 III JENSEN

FIG. 33

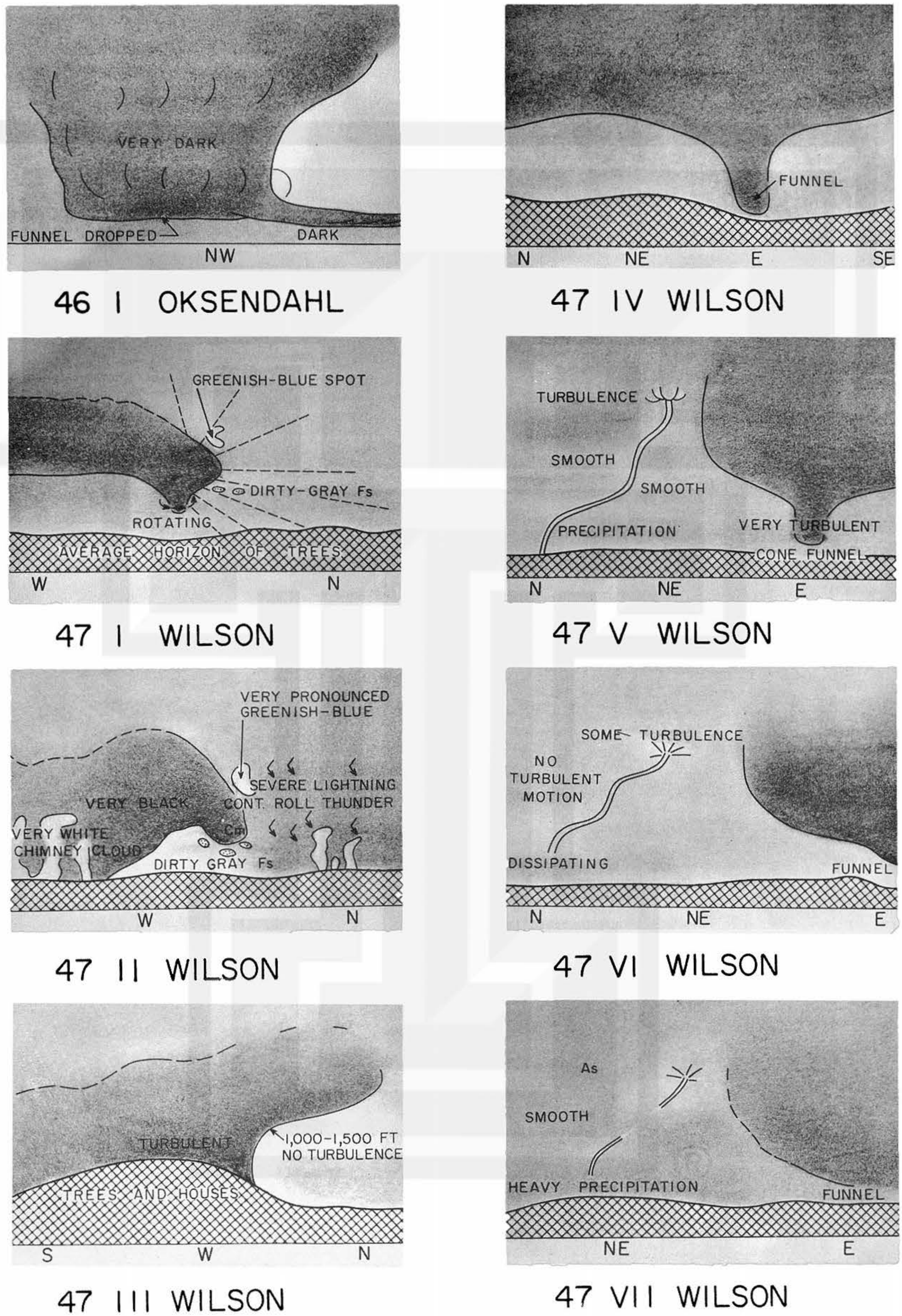
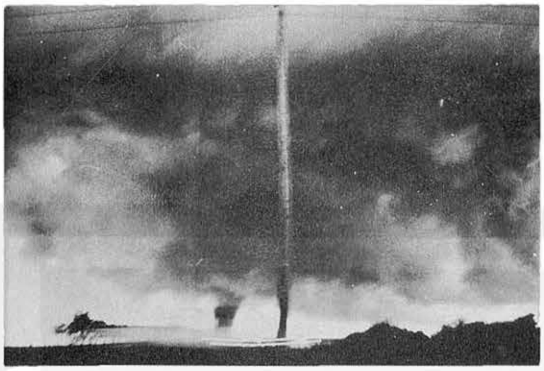
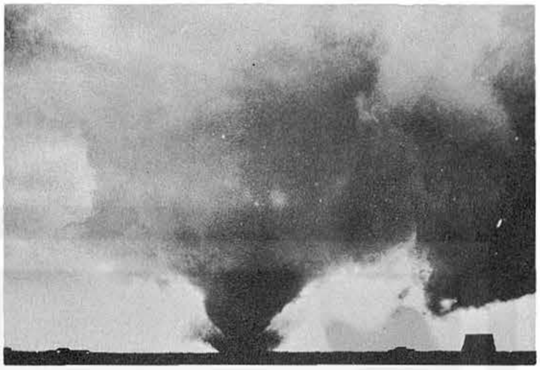

VERY DARK
FUNNEL DROPPED
DARK
NW
46 I OKSENDAHL
FUNNEL
N
NE
E
SE
47 IV WILSON
GREENISH-BLUE SPOT
DIRTY-GRAY Fs
ROTATING
AVERAGE HORIZON OF TREES
W
N
47 I WILSON
TURBULENCE
SMOOTH
SMOOTH
PRECIPITATION
VERY TURBULENT
CONE FUNNEL
N
NE
E
47 V WILSON
VERY PRONOUNCED
GREENISH-BLUE
SEVERE LIGHTNING
CONT. ROLL THUNDER
VERY BLACK
Cm
VERY WHITE
CHIMNEY CLOUD
DIRTY GRAY Fs
W
N
47 II WILSON
SOME TURBULENCE
NO
TURBULENT
MOTION
DISSIPATING
FUNNEL
N
NE
E
47 VI WILSON
TURBULENT
1,000-1,500 FT
NO TURBULENCE
TREES AND HOUSES
S
W
N
47 III WILSON
As
SMOOTH
HEAVY PRECIPITATION
FUNNEL
NE
E
47 VII WILSON

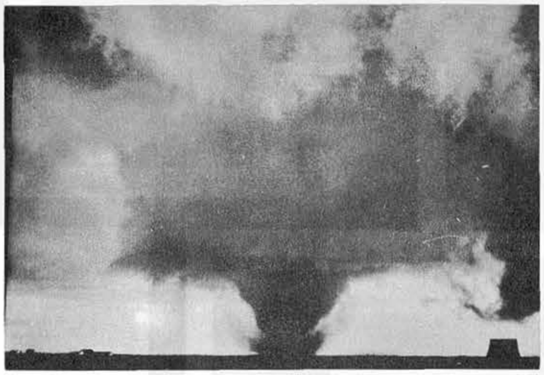
FIG. 34



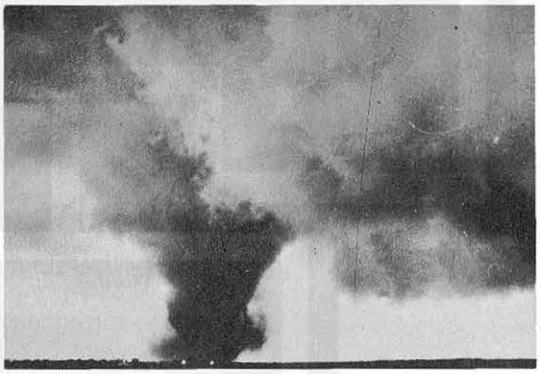
48A HAGEN



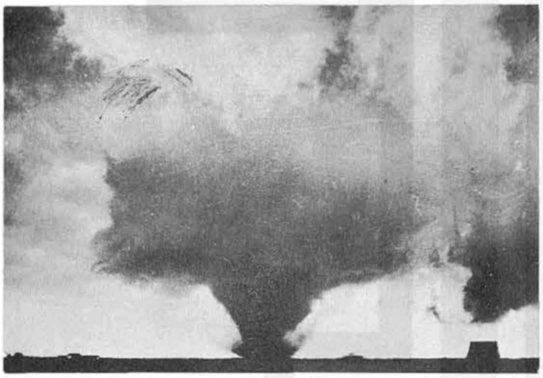
49E HAGEN



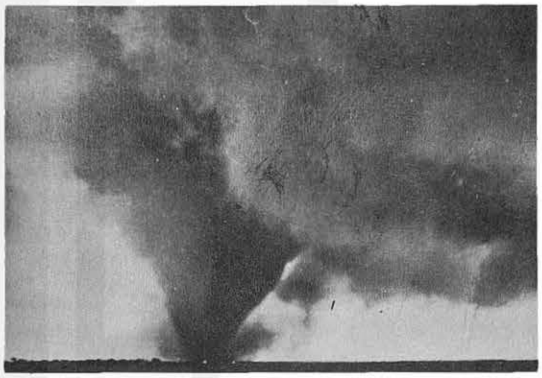
49B HAGEN



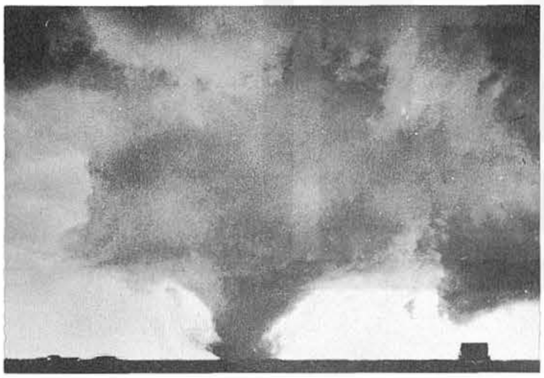
49F HAGEN



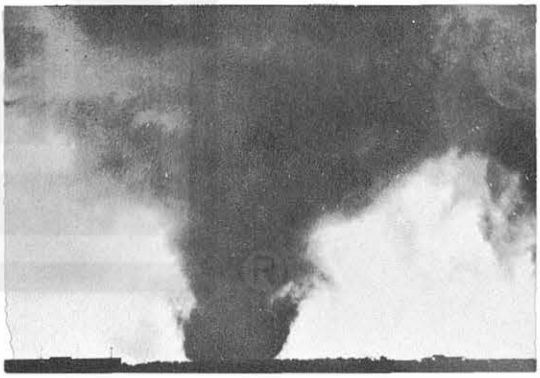
49C HAGEN



49G HAGEN

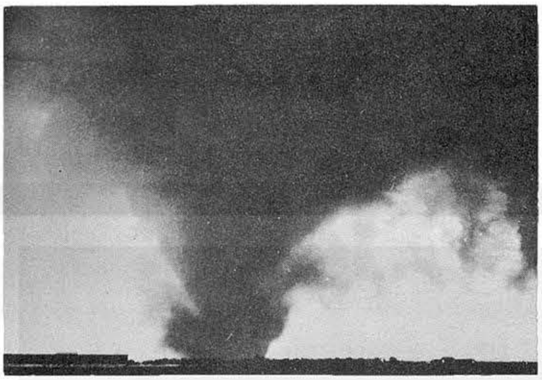


49D HAGEN

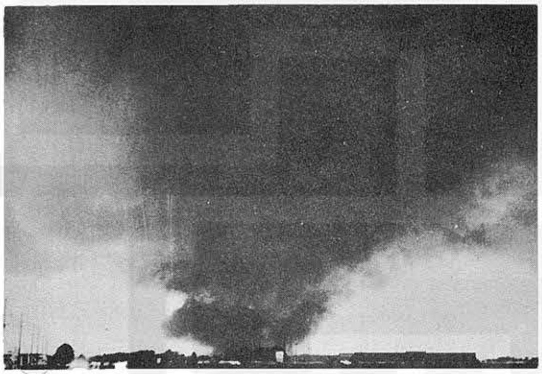


49H HAGEN

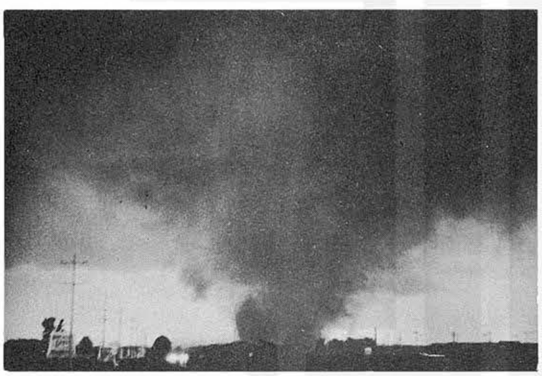
FIG. 35



49 I HAGEN



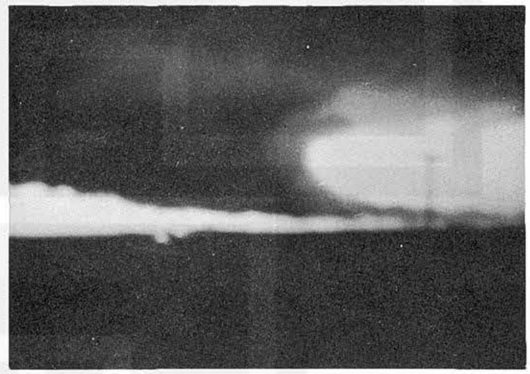
49 J HAGEN



49 K HAGEN

4 E FRADET

50 A FRAHM



50 B FRAHM

50 C FRAHM

50 D FRAHM

FIG. 36

50E FRAHM

51D PAYNE

50F FRAHM

51E PAYNE

FIG. 37

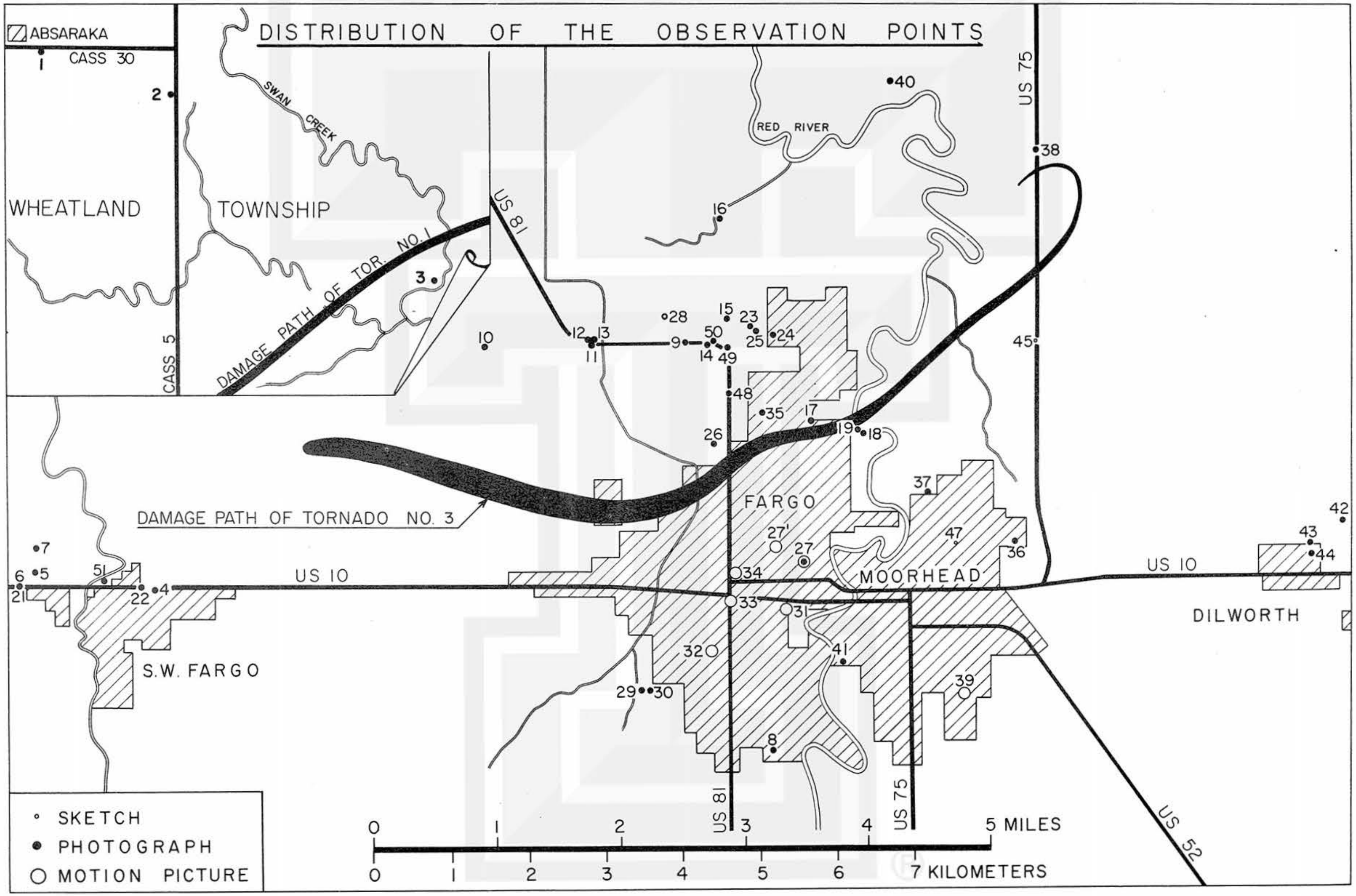

DISTRIBUTION OF THE OBSERVATION POINTS
ABSARAKA
CASS 30
WHEATLAND
TOWNSHIP
SWAN CREEK
RED RIVER
CASS 5
US 81
US 75
US 10
US 52
DAMAGE PATH OF TOR. NO. 1
DAMAGE PATH OF TORNADO NO. 3
FARGO
MOORHEAD
S.W. FARGO
DILWORTH
SKETCH
PHOTOGRAPH
MOTION PICTURE
0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 7 KILOMETERS

FIG. 38

CHAPTER III: TORNADO PICTURES COLLECTED

CHAPTER IV: MOTHER CLOUD OF FARGO TORNADO FAMILY

In view of the successive formations of five independent tornadoes in a narrow zone 6 x 64 miles centered around Fargo, North Dakota, 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; 09A, B; 10C, D; 23A, B, C; and 40A, 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—a disc-like cloud with spiral streaks on it. The diameter of the disc was about 10 miles.

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 39 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 Fig. 40. It can be seen that the tail cloud grew in length and width as it moved northwest of southwest 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 1827½ CST about 1/2 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 tunnel gradually moved east southeast 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 41, 42, and 43 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.

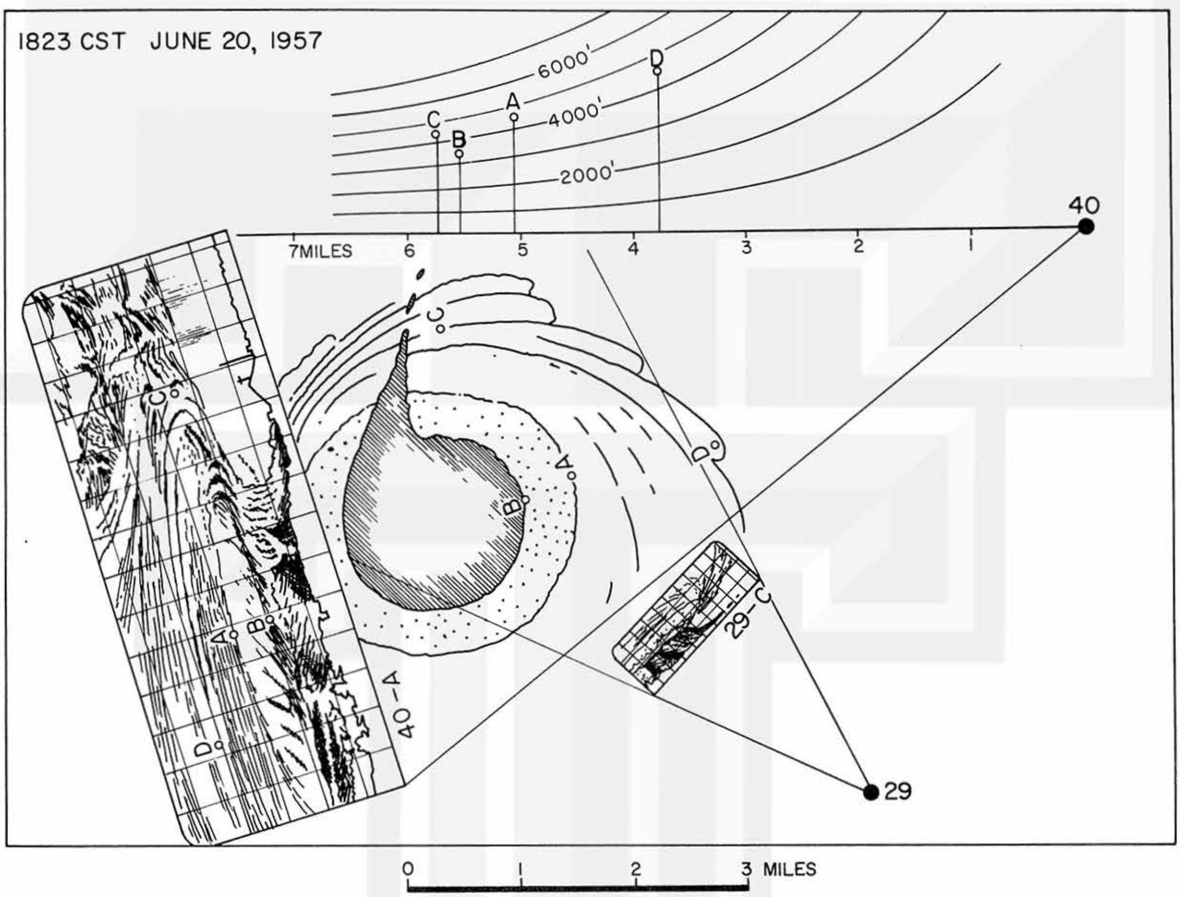
The degrees and miles are the direction and the distance of the center of the rotating cloud from the photographer. As seen in most of the photographs, a tail-like cloud extended to the right, with the exception of 20A and 21B, photographed facing toward the axis of the tail, and 05A, with the tail extending 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 Fig. 44. 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 feet per second 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 and $\Delta z = 3000$ ft/sec. The value thus obtained is about 3000×10^{-5}. 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 feet per second. Although this value seems too high, an incloud updraft of 100-200 feet per second can be considered a relatively realistic value.

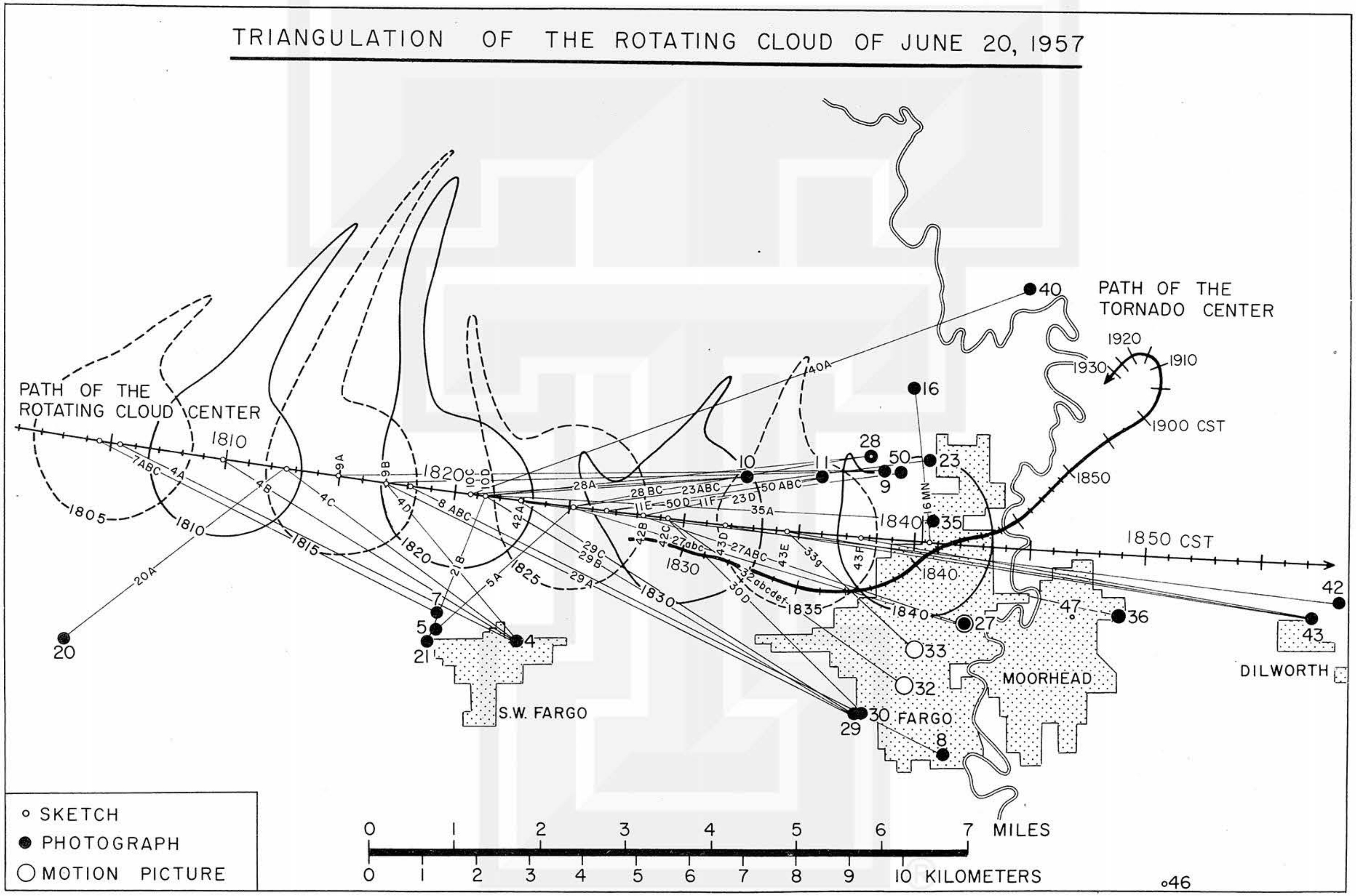
In order to compute the rotational motion of the cloud under discussion, every 30th frame of Jennings' movie (27a, b) was transcribed in Fig. 45. This film includes 810 frames taken at 24 per second. The results of computation revealed that the ring cloud circling around the uprising cloud mass was rotating at only 25 mph, 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 (49B, C, D, E) taken by Mr. Hagen. Although the time intervals of these photographs is unknown, the displacement 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 49B-E and 43D, Fig. 46 was made. The individual movement 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.



1823 CST JUNE 20, 1957
6000'
4000'
2000'
D
A
C
B
40
7MILES
6
5
4
3
2
1
C
D
A
B
40-A
29-C
29
0
1
2
3 MILES

FIG. 39



TRIANGULATION OF THE ROTATING CLOUD OF JUNE 20, 1957
PATH OF THE ROTATING CLOUD CENTER
PATH OF THE TORNADO CENTER
1805
1810
1815
1820
1825
1830
1835
1840
1850 CST
1850
1900 CST
1910
1920
1930
S.W. FARGO
FARGO
MOORHEAD
DILWORTH
SKETCH
PHOTOGRAPH
MOTION PICTURE
0 1 2 3 4 5 6 7 MILES
0 1 2 3 4 5 6 7 8 9 10 KILOMETERS

FIG. 40

ROTATING CLOUD SHOWN IN THE SAME SCALE

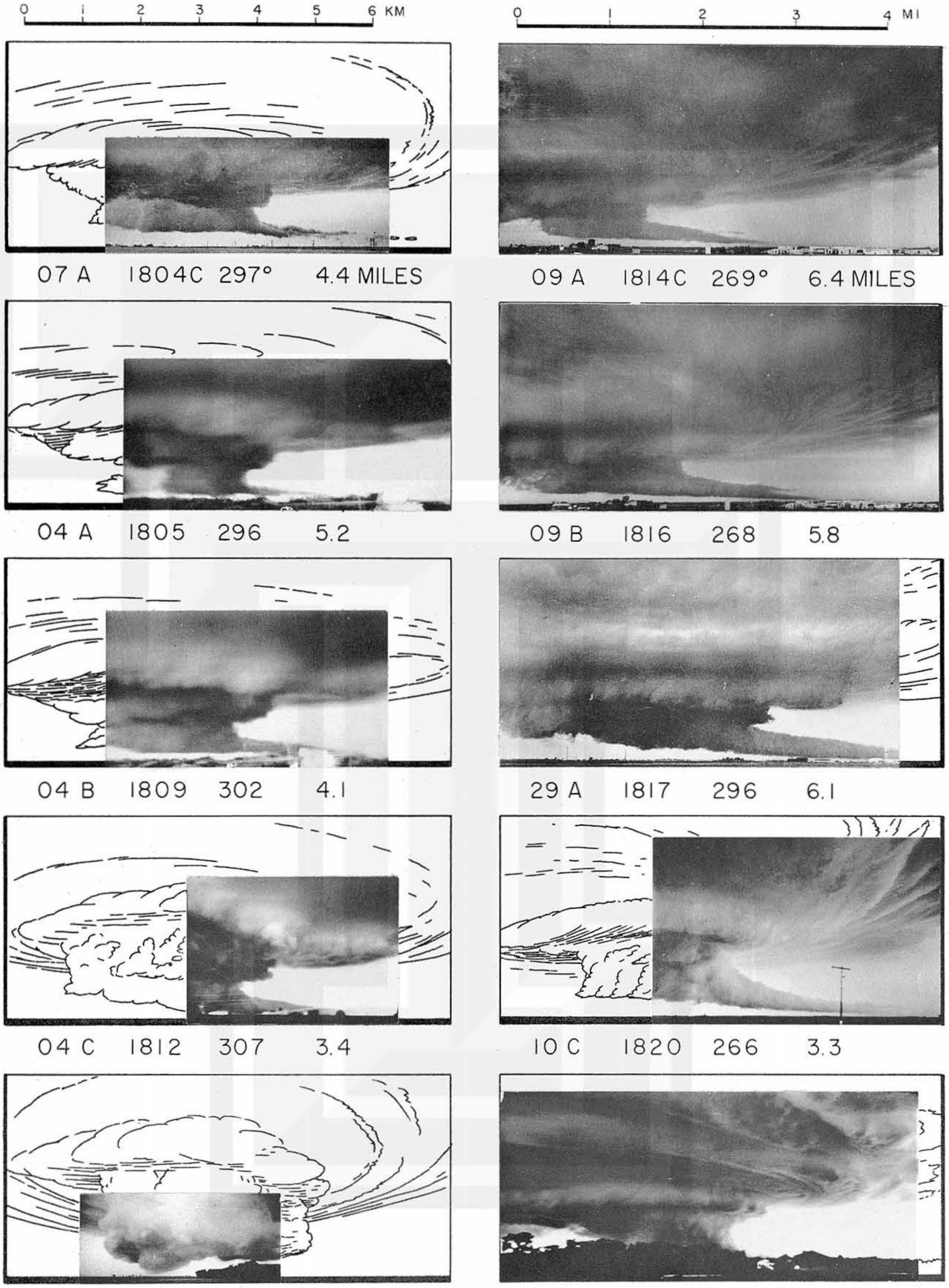


FIG. 41

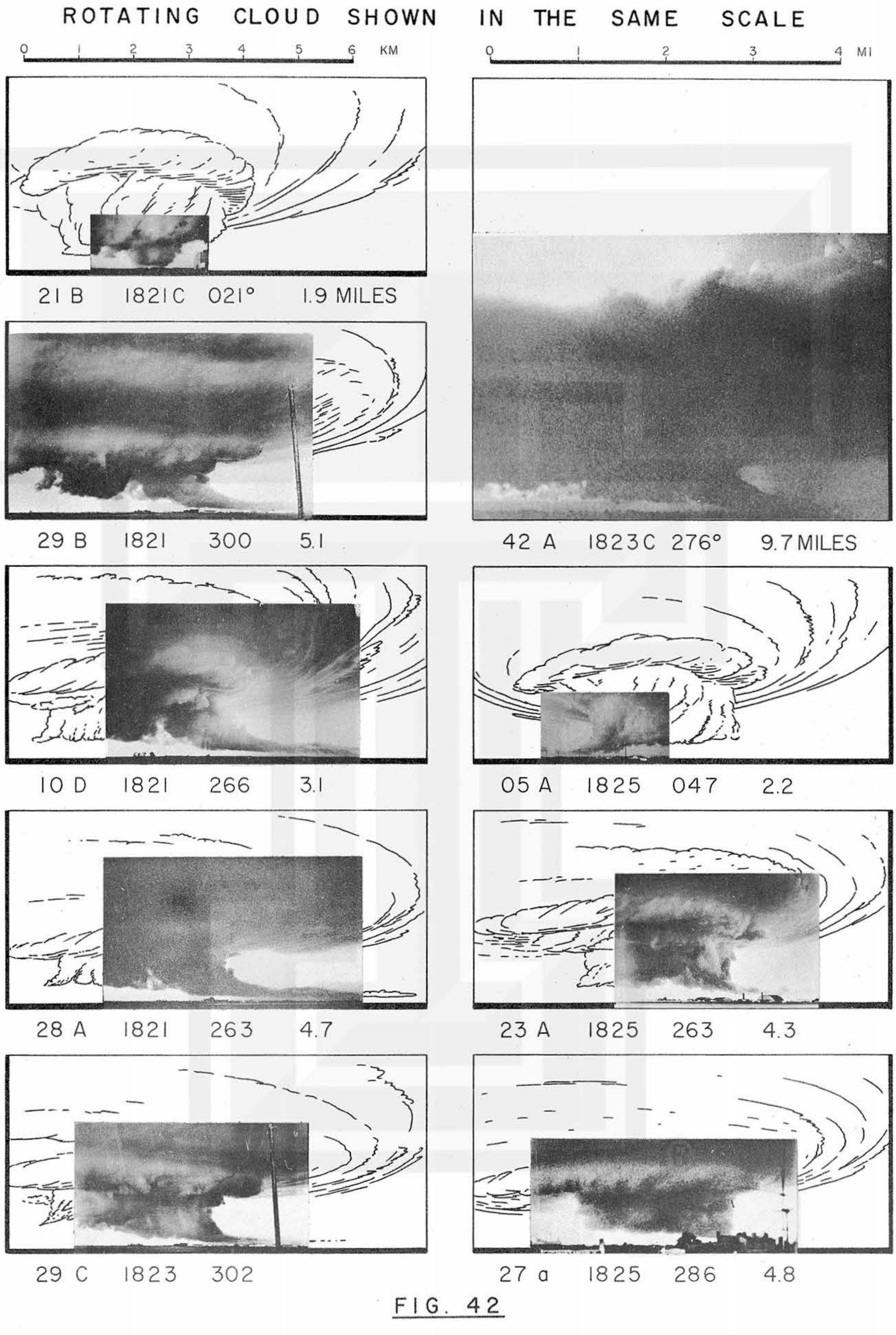

ROTATING CLOUD SHOWN IN THE SAME SCALE
0 1 2 3 4 5 6 KM
0 1 2 3 4 MI
21 B 1821C 021° 1.9 MILES
42 A 1823C 276° 9.7 MILES
29 B 1821 300 5.1
10 D 1821 266 3.1
05 A 1825 047 2.2
28 A 1821 263 4.7
23 A 1825 263 4.3
29 C 1823 302
27 a 1825 286 4.8

FIG. 42

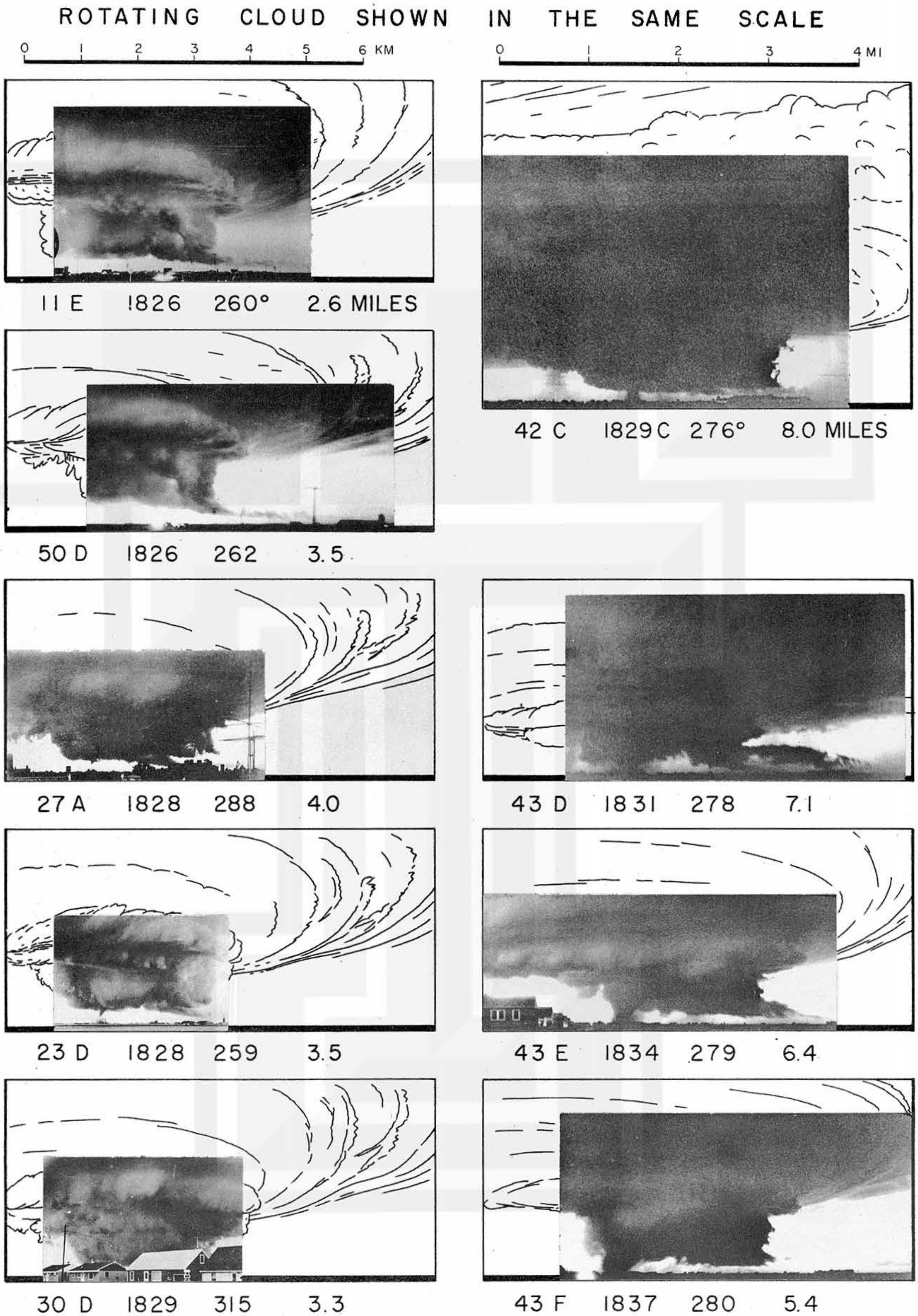

ROTATING CLOUD SHOWN IN THE SAME SCALE
0 1 2 3 4 5 6 KM
0 1 2 3 4 MI
11 E 1826 260° 2.6 MILES
42 C 1829C 276° 8.0 MILES
50 D 1826 262 3.5
27 A 1828 288 4.0
43 D 1831 278 7.1
23 D 1828 259 3.5
43 E 1834 279 6.4
30 D 1829 315 3.3
43 F 1837 280 5.4

FIG. 43

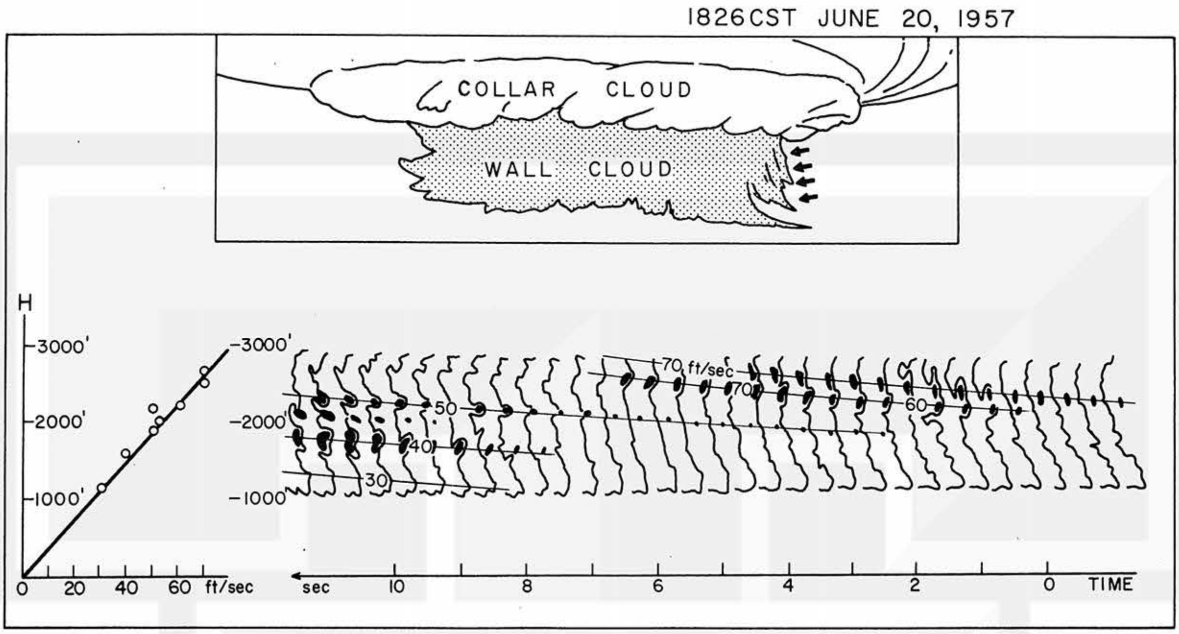

1826CST JUNE 20, 1957
COLLAR CLOUD
WALL CLOUD
H
3000'
2000'
1000'
0
20
40
60
ft/sec
70 ft/sec
70
60
50
40
30
sec
10
8
6
4
2
0
TIME

FIG. 44

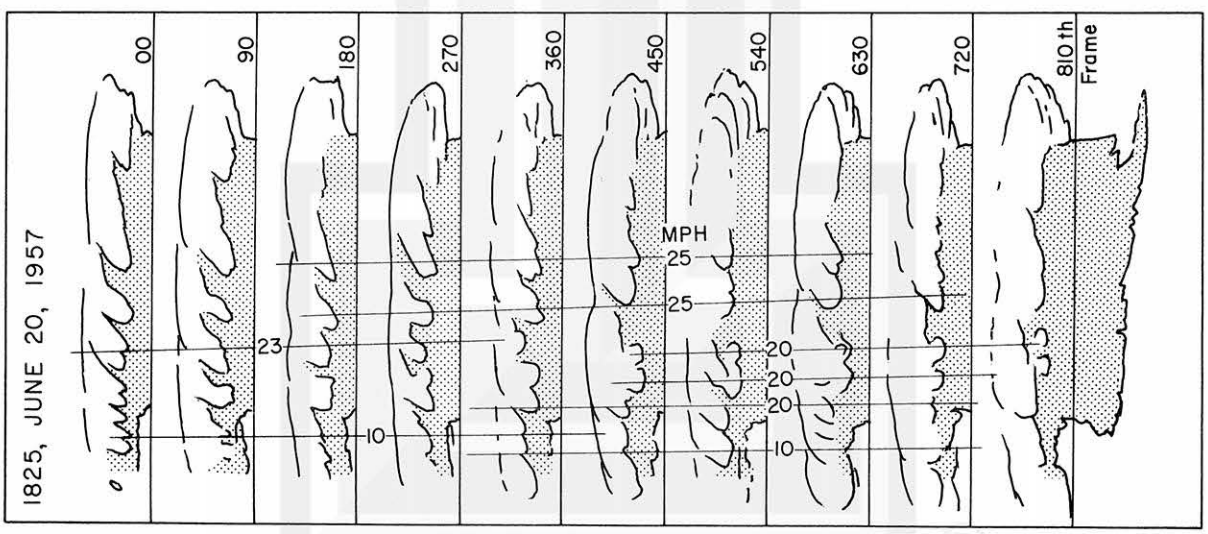
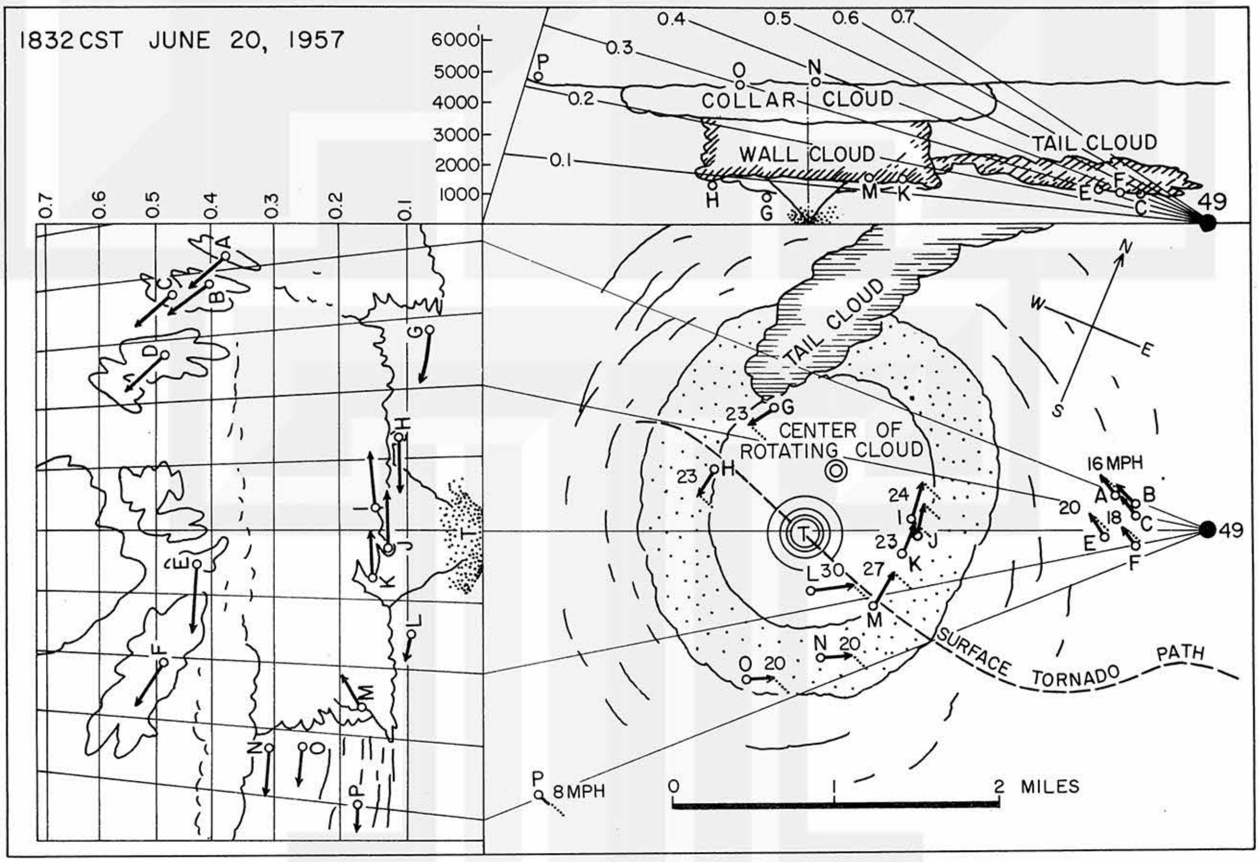

1825, JUNE 20, 1957
00
90
180
270
360
450
540
630
720
810th Frame
MPH
25
25
23
20
20
20
10
10

FIG. 45



1832 CST JUNE 20, 1957
COLLAR CLOUD
WALL CLOUD
TAIL CLOUD
CENTER OF ROTATING CLOUD
SURFACE TORNADO PATH
16 MPH
8 MPH
0
1
2 MILES

FIG. 46

CHAPTER IV: MOTHER CLOUD OF FARGO TORNADO FAMILY

CHAPTER V: 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 Fig. 47. 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. The following table shows the number of pictures taken during each two- or ten-minute period after the appearance of the funnel:

Minutes after the tornado	Number of photographs	Remarks
0-2	24	Cone-shaped funnel dropped to the ground.
2-4	8	Funnel appeared like a cylinder.
4-6	13	Huge cone funnel.
6-8	4	" " "
8-10	10	Funnel was over Golden Ridge residential area.
10-12	11	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	" " " "
30-40	8	Rope funnel appeared.
40-50	4	Rope funnel in its dissipating stage.
50-60	1	Rope funnel dissipated.

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 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 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 47 indicates the time of each tornado picture as determined from this scale.

A. Cone-Shaped Funnel.

Using the technique described in the previous chapter, 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 48-52 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 Fig. 53. 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 54 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 Fig. 55. It can be seen that the funnel dropped at the rate of about 333 meters per minute or 5 meters per second. 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.

B. 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 8 short movie strips and 7 still photographs.

The first indication of the transformation from cone to rope-type funnel was witnessed by Mr. Arhart (451), who observed a grayish white funnel traveling east. His observation point and sketch are shown in Figs. 44 and 19, respectively. Heavy rain in the area prevented people from observing or photographing the cone funnel as it was redeveloping into a rope funnel.

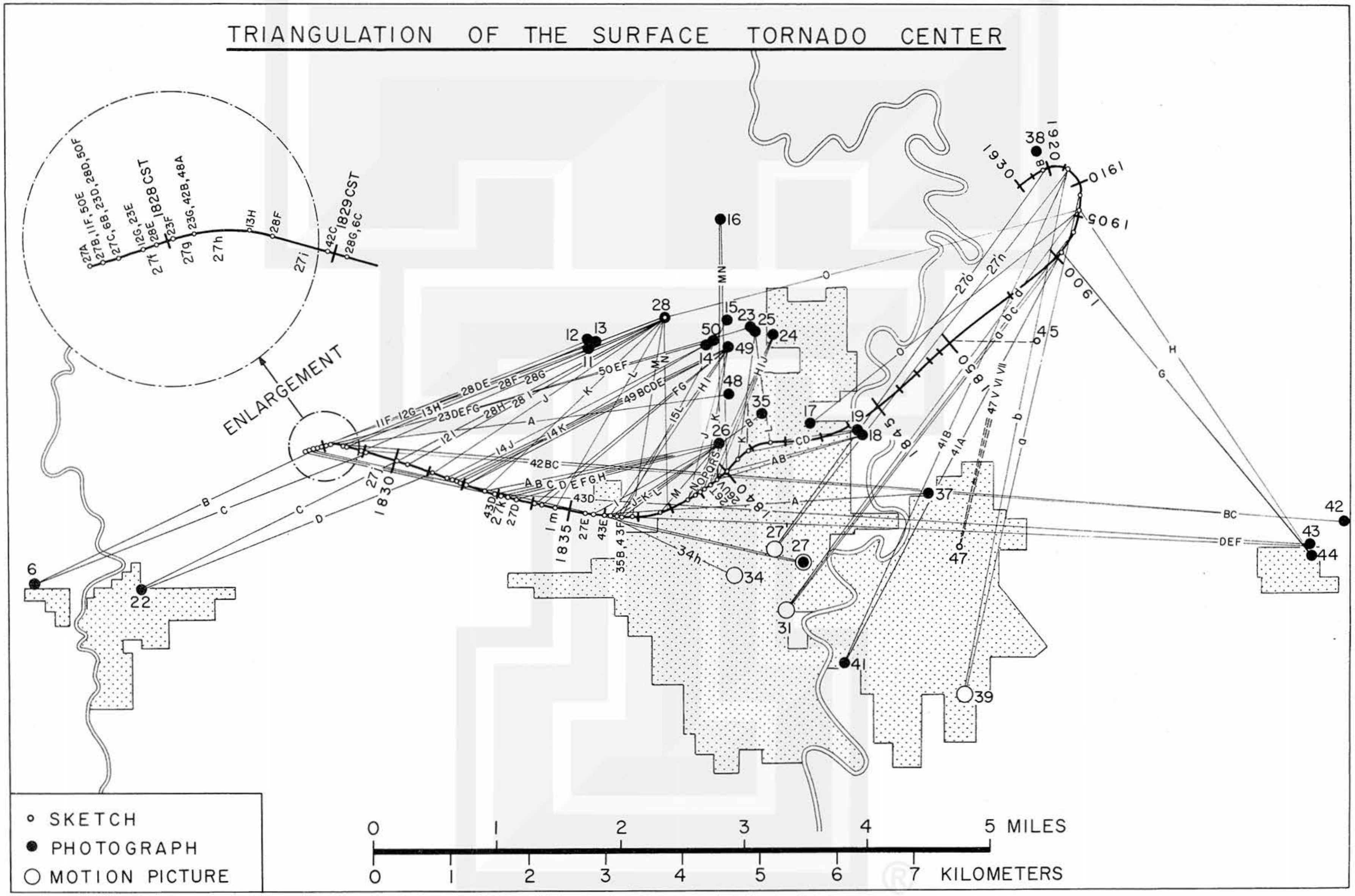
Soon after, a still (44G) and a motion picture (31a) were made. The three-dimensional triangulation of the funnel shown in Fig. 56 revealed that the funnel, slender and slightly curved, was tilted at about 45 degrees toward the direction of the rotating cloud center, which had moved east past Dilworth. The top of the funnel was visible up to the 5000-foot level.

Mr. Mickelson took two movie strips (39a and b). The shape of the funnel at two-second intervals appears in Fig. 57. 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 58, with the rope funnel looking north, reveals that the upper portion was moving east while the lower portion of the funnel moved west 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 Fig. 59. It should be noted that the funnel was vertically inclined near the ground and tilted almost horizontally near the cloud base.

FIG. 47



TRIANGULATION OF THE SURFACE TORNADO CENTER
ENLARGEMENT
1828 CST
1829 CST
1830
1835
1840
1900
1905
1910
1920
1930
SKETCH
PHOTOGRAPH
MOTION PICTURE
0 1 2 3 4 5 MILES
0 1 2 3 4 5 6 7 KILOMETERS

TORNADO FUNNEL SHOWN IN THE SAME SCALE

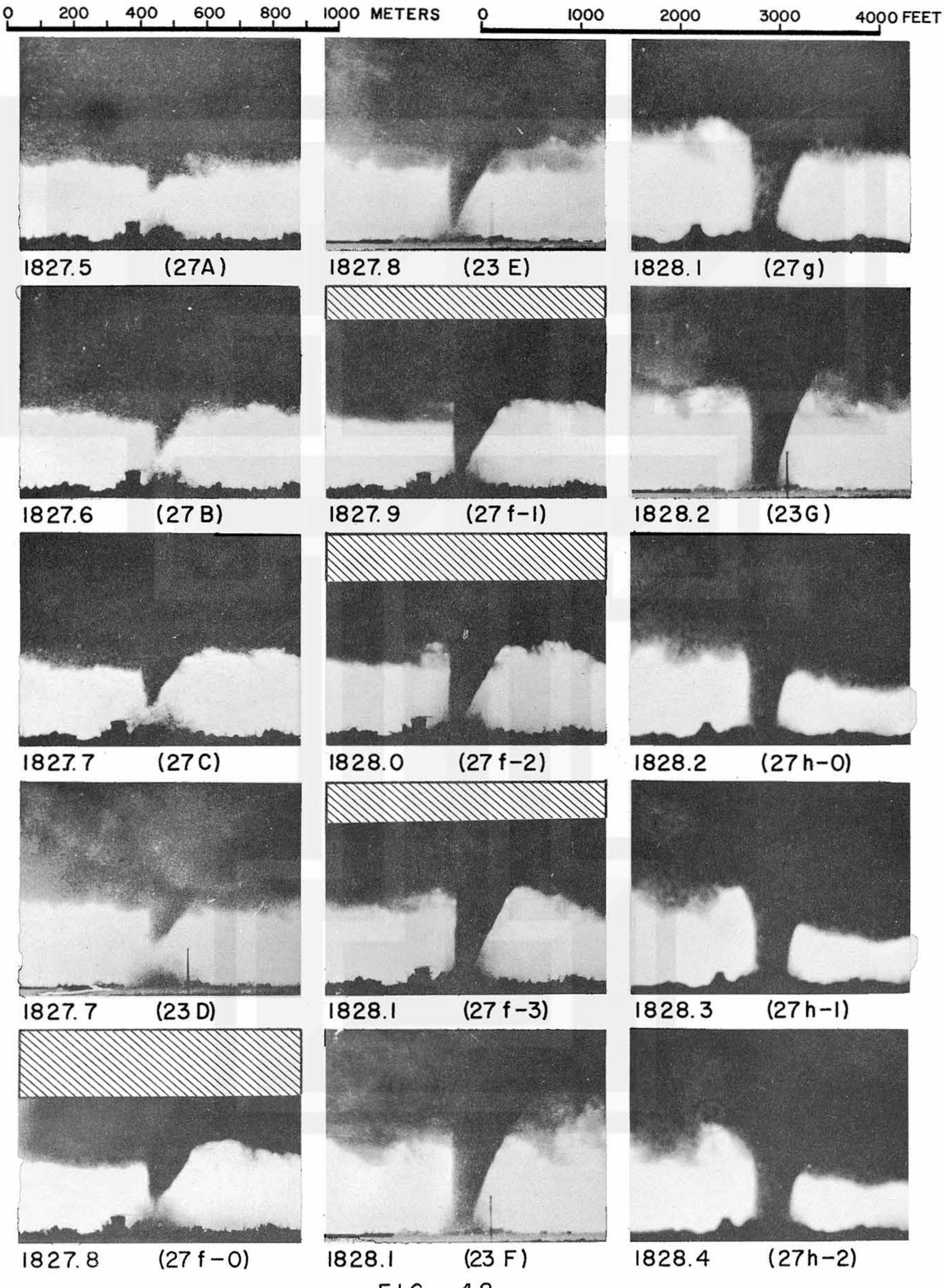


FIG. 48

TORNADO FUNNEL SHOWN IN THE SAME SCALE

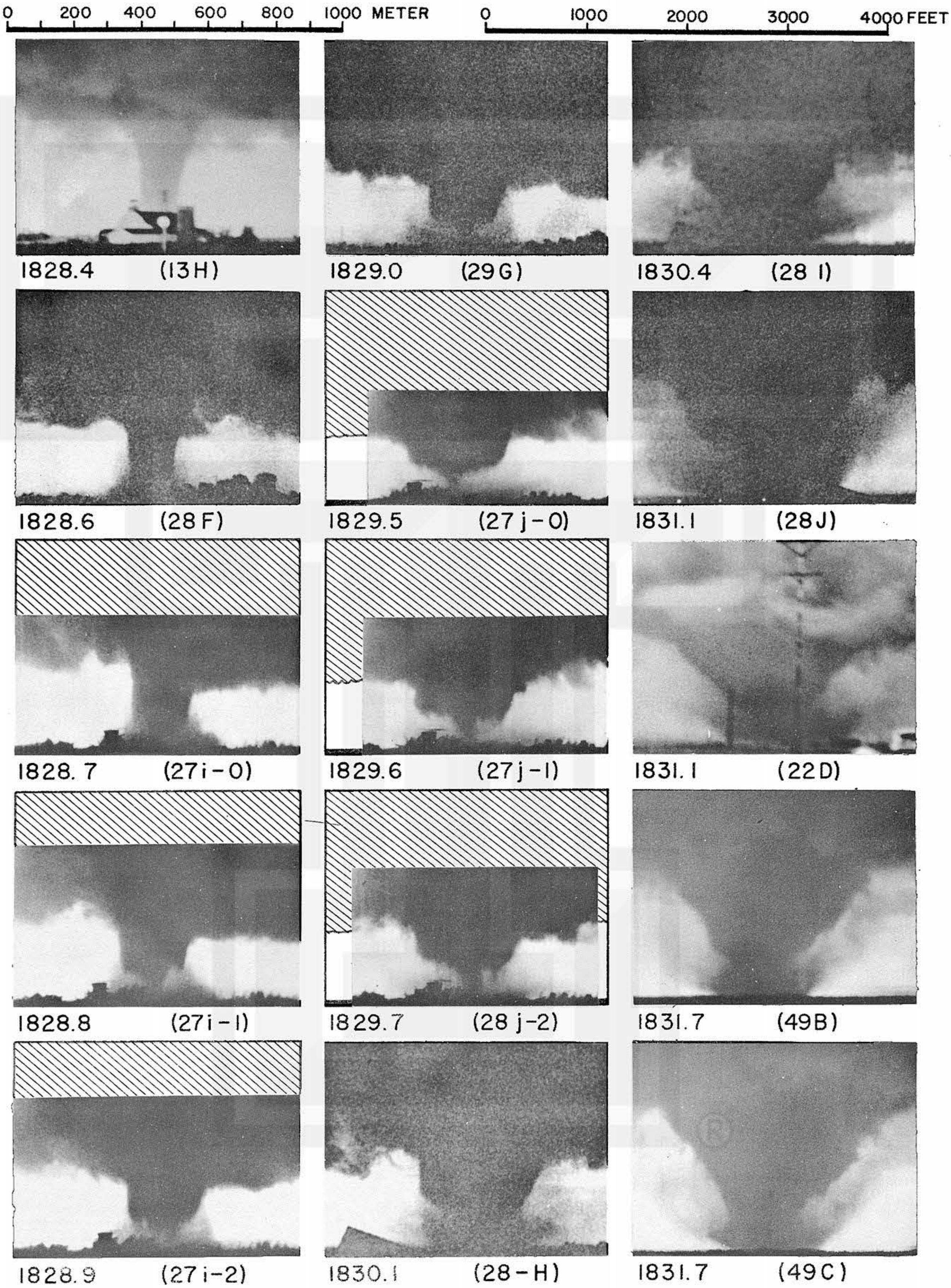


FIG. 49

TORNADO FUNNEL SHOWN IN THE SAME SCALE

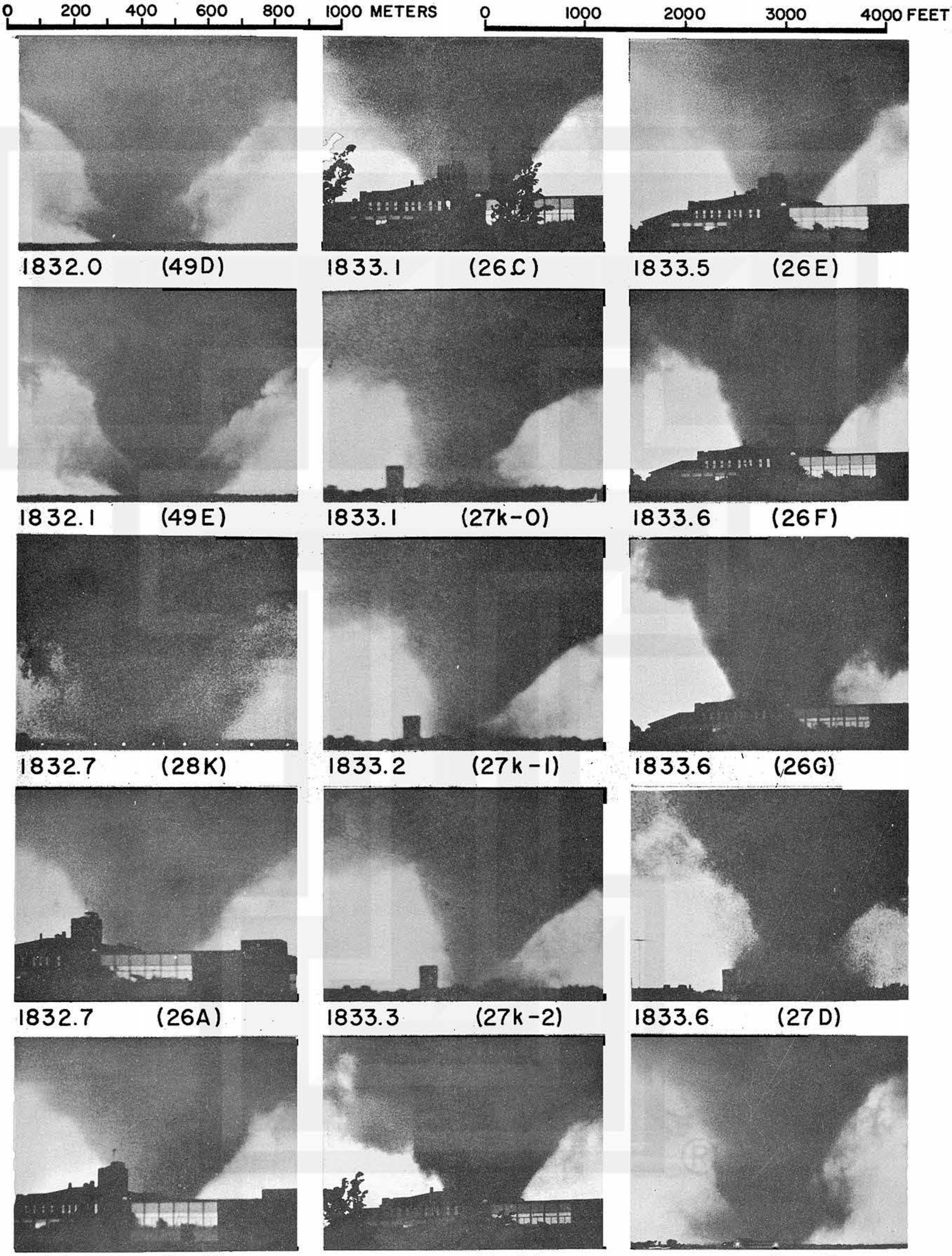


FIG. 50

TORNADO FUNNEL SHOWN IN THE SAME SCALE

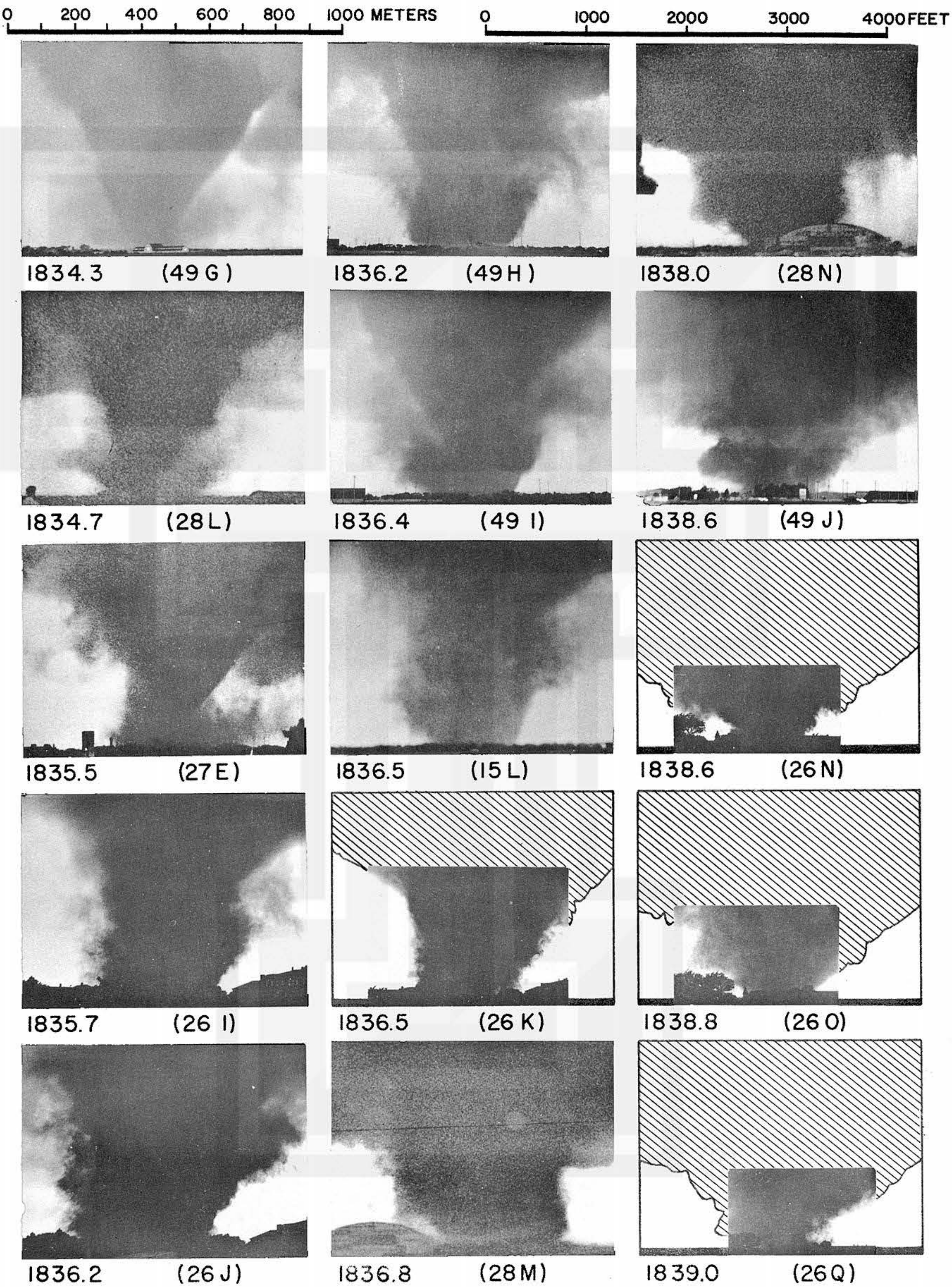


FIG. 51

TORNADO FUNNEL SHOWN IN THE SAME SCALE

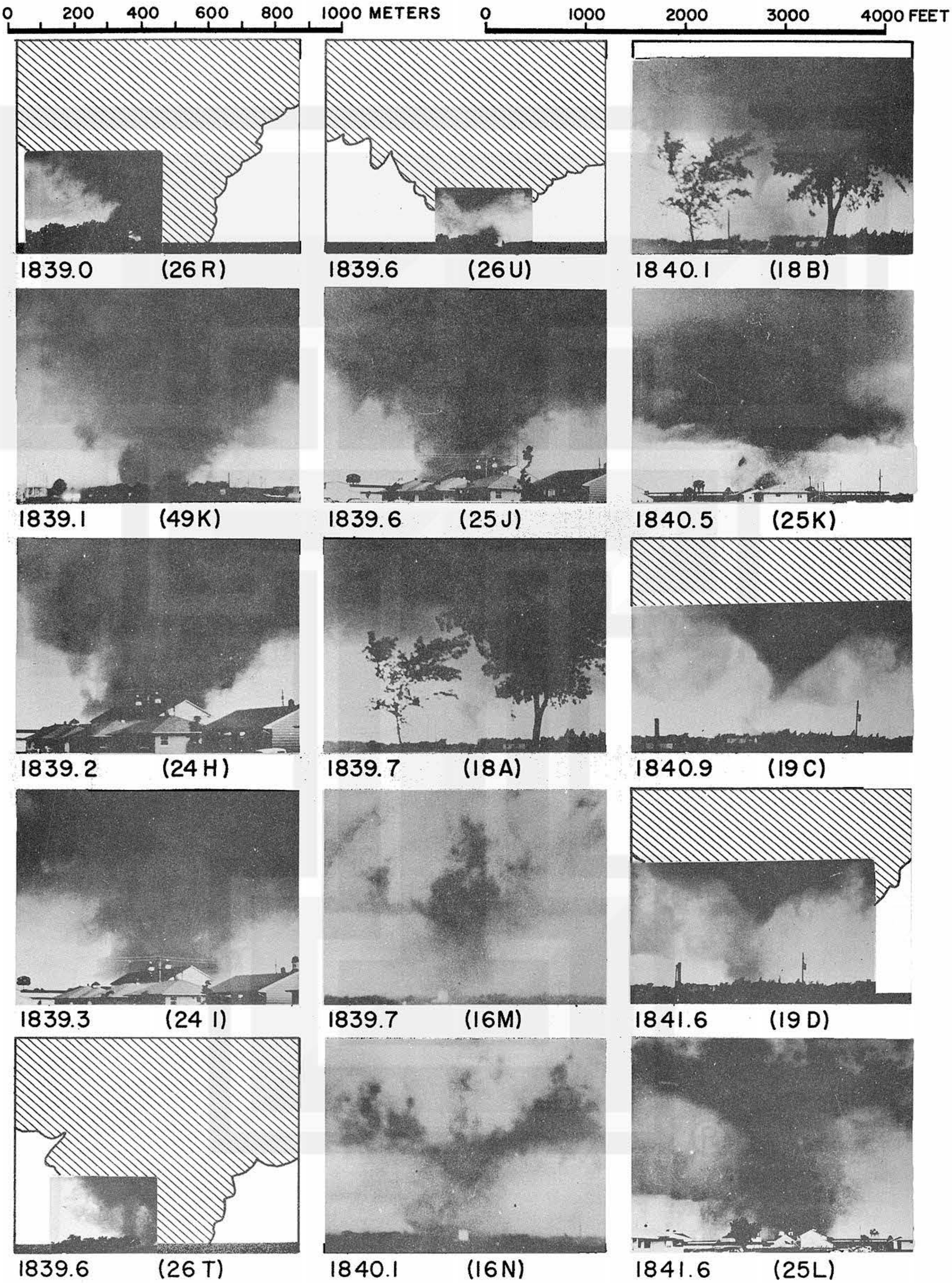


FIG. 52

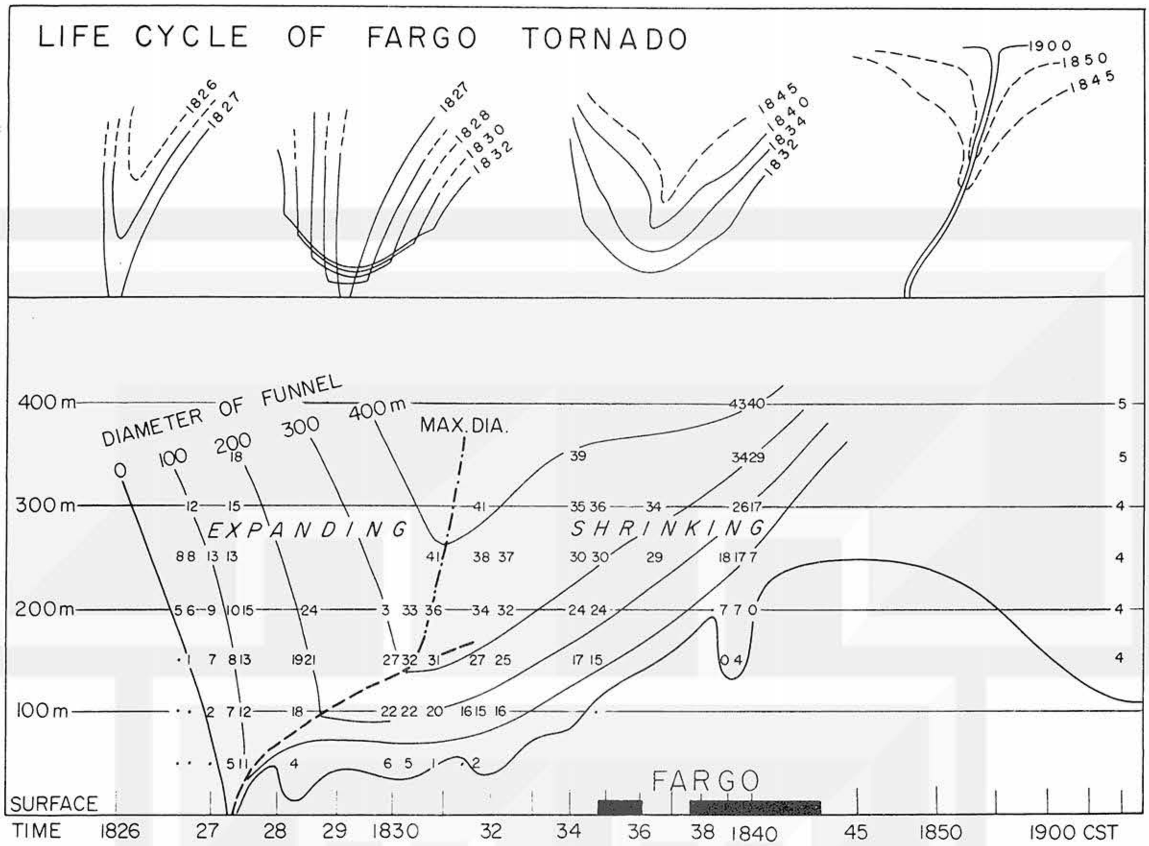

LIFE CYCLE OF FARGO TORNADO
DIAMETER OF FUNNEL
MAX. DIA.
EXPANDING
SHRINKING
FARGO
400 m
300 m
200 m
100 m
SURFACE
TIME 1826 27 28 29 1830 32 34 36 38 1840 45 1850 1900 CST

FIG. 53

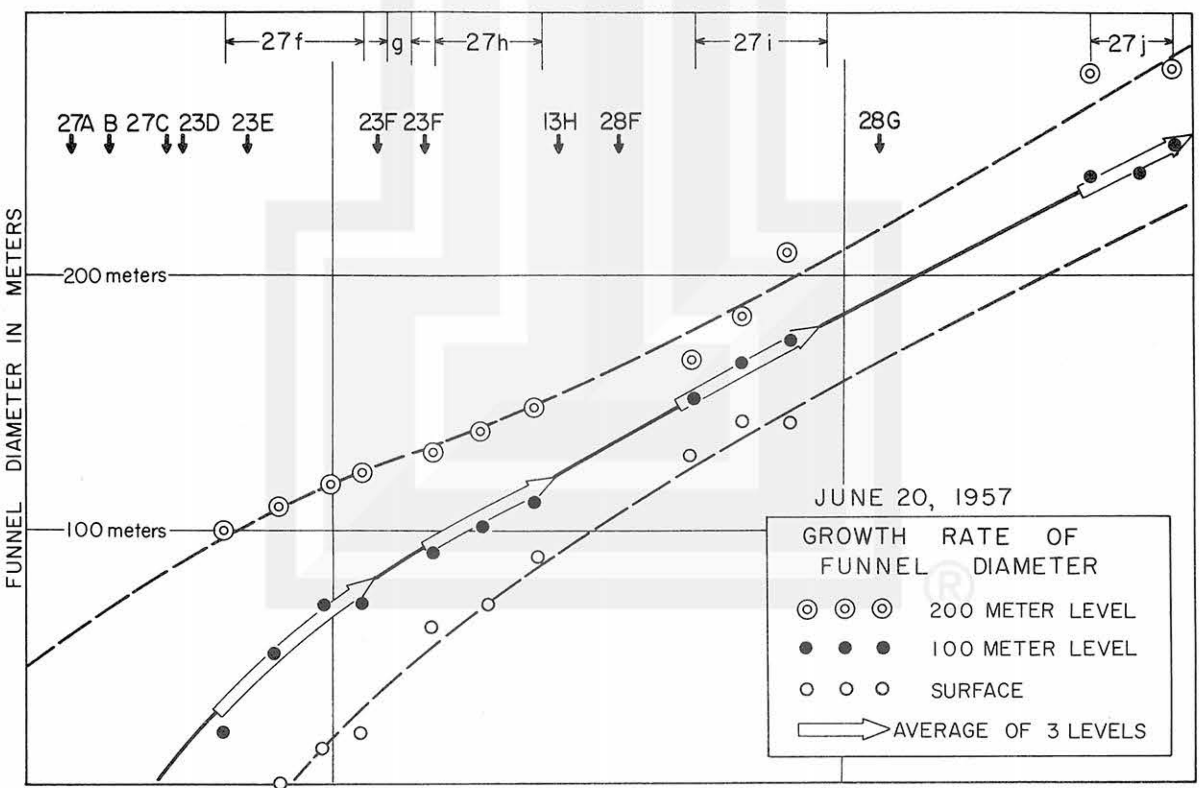

27f
g
27h
27i
27j
27A B 27C 23D 23E
23F 23F
13H 28F
28G
FUNNEL DIAMETER IN METERS
200 meters
100 meters
1828C
1829C
JUNE 20, 1957
GROWTH RATE OF FUNNEL DIAMETER
200 METER LEVEL
100 METER LEVEL
SURFACE
AVERAGE OF 3 LEVELS

FIG. 54

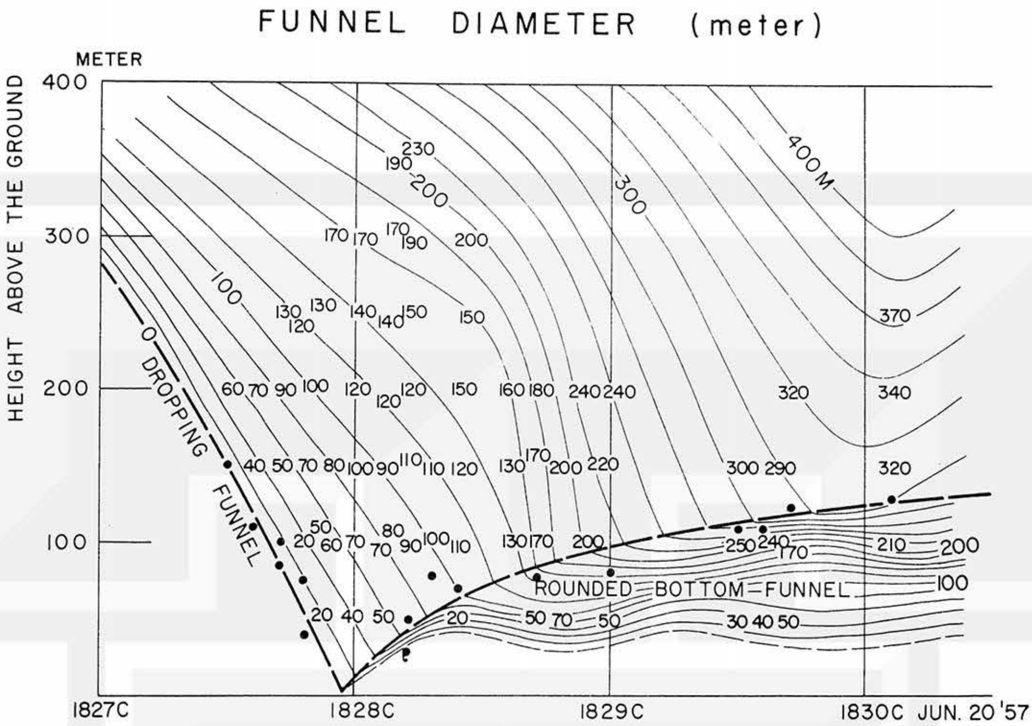

FUNNEL DIAMETER (meter)
METER
HEIGHT ABOVE THE GROUND
O DROPPING FUNNEL
ROUNDED BOTTOM FUNNEL
400M
1827C
1828C
1829C
1830C JUN. 20 '57

FIG. 55

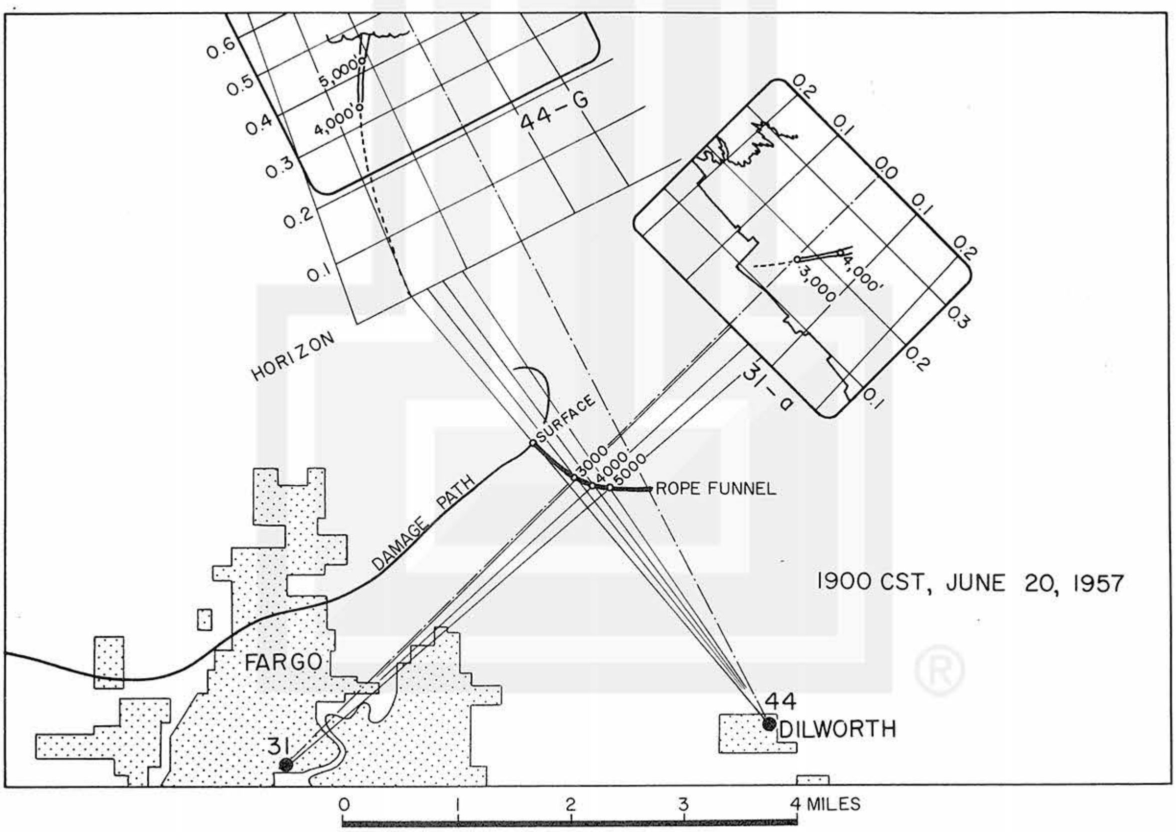

44-G
31-D
HORIZON
SURFACE
ROPE FUNNEL
DAMAGE PATH
1900 CST, JUNE 20, 1957
FARGO
31
44
DILWORTH
0 1 2 3 4 MILES

FIG. 56

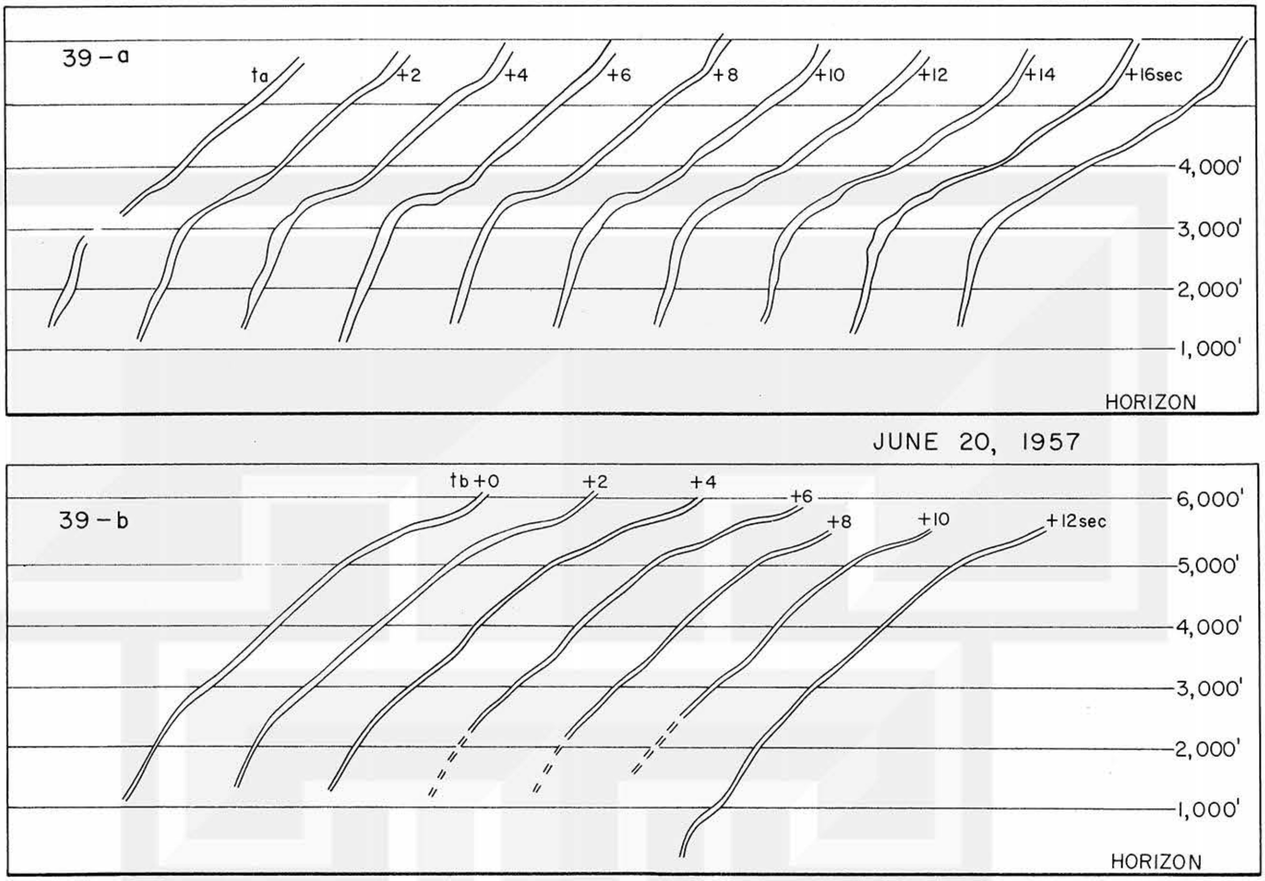

39 – a
ta
+2
+4
+6
+8
+10
+12
+14
+16sec
4,000'
3,000'
2,000'
1,000'
HORIZON
JUNE 20, 1957
tb +0
+2
+4
+6
+8
+10
+12sec
39 – b
6,000'
5,000'
4,000'
3,000'
2,000'
1,000'
HORIZON

FIG. 57

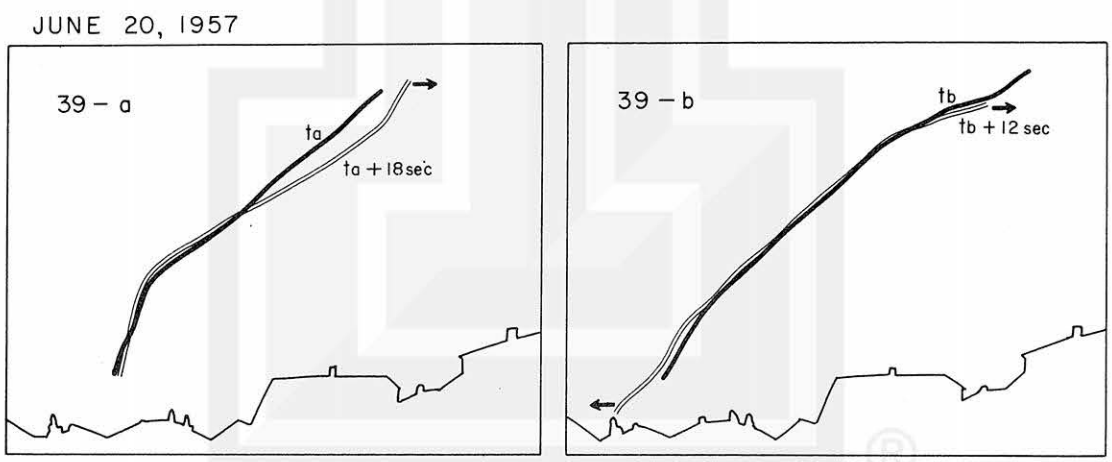

JUNE 20, 1957
39 – a
ta
ta + 18 sec
39 – b
tb
tb + 12 sec

FIG. 58

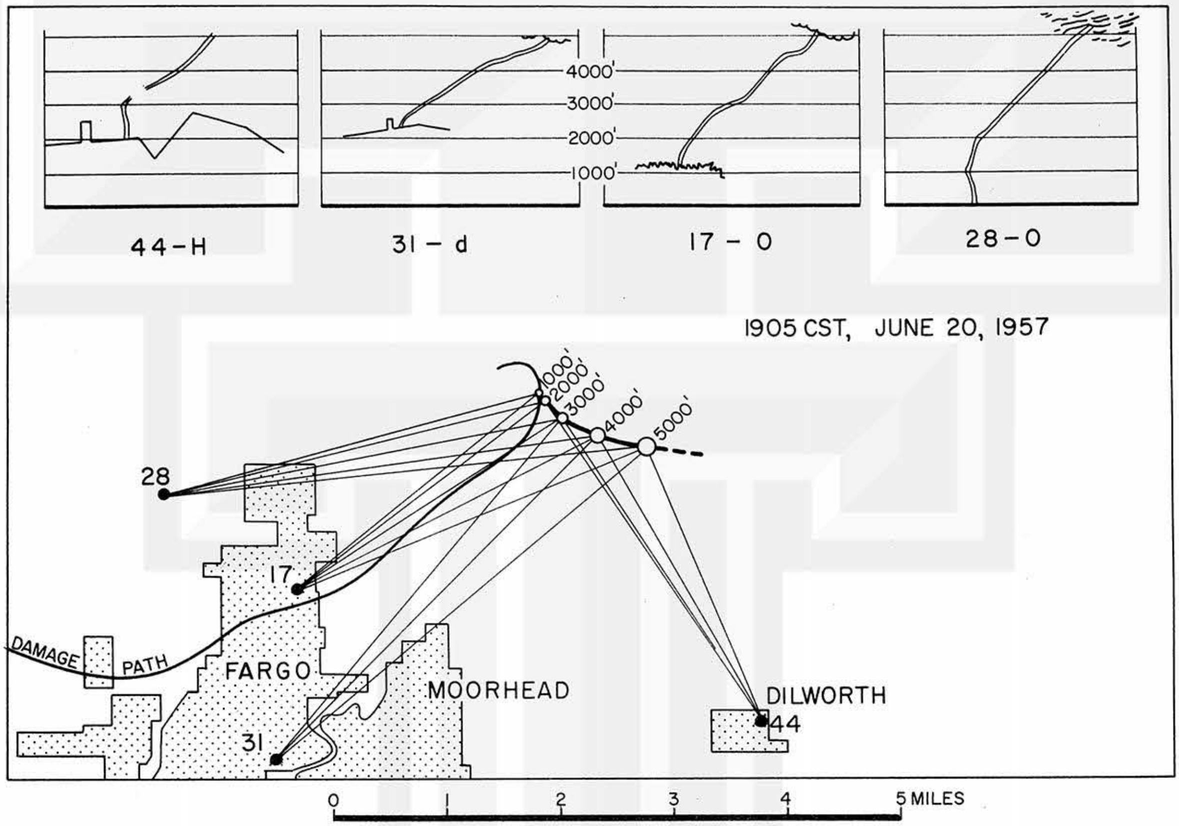

4000'
3000'
2000'
1000'
44-H
31 - d
17 - 0
28-0
1905 CST, JUNE 20, 1957
1000'
2000'
3000'
4000'
5000'
28
17
DAMAGE PATH
FARGO
MOORHEAD
DILWORTH
44
31
0
1
2
3
4
5 MILES

FIG. 59

CHAPTER V: CHANGE IN SHAPE OF THE TORNADO FUNNEL

CHAPTER VI: 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 rising air parcels condensed at the funnel edge, along which the pressure was constant, the hydrostatic and cyclostrophic assumptions enable us to write:

$$-\frac{1}{\rho}\frac{\Delta P}{\Delta R} = \frac{V^2}{R}$$

$$\Delta P = -\rho g \Delta z$$

Therefore, we have

$$\frac{\Delta z}{\Delta R} = \frac{1}{g}\frac{V^2}{R}$$

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 Fig. 60. As shown in the equation, this slope denotes the centrifugal acceleration in terms of g, the gravity of the earth. The maximum acceleration appeared at the 130-meter level shortly before 1829 CST, when the funnel looked like a huge cylinder with a flat bottom.

Using the centrifugal acceleration given in Fig. 60, cyclostrophic wind speeds at the funnel edge were computed (see Fig. 61). 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 mph.

The second computation method employed the motion picture showing a rotating funnel. For this purpose Jennings' films 27i and 27j were used. Figures 62-65 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 Fig. 66. The following table summarizes the computation;

Pendant	Meters from Center	Duration of Existence	Meters Traveled	Average Speed
A	90	18h28m49.7s-55.5s	280	48 m/sec
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

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 Fig. 67. The open and painted 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 will 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 meters per second.

CENTRIFUGAL FORCE AT THE FUNNEL EDGE

$$\frac{\Delta Z}{\Delta R} = \frac{V^2}{R} \Big/ g = \frac{\text{CENTRIFUGAL FORCE}}{\text{GRAVITY}}$$

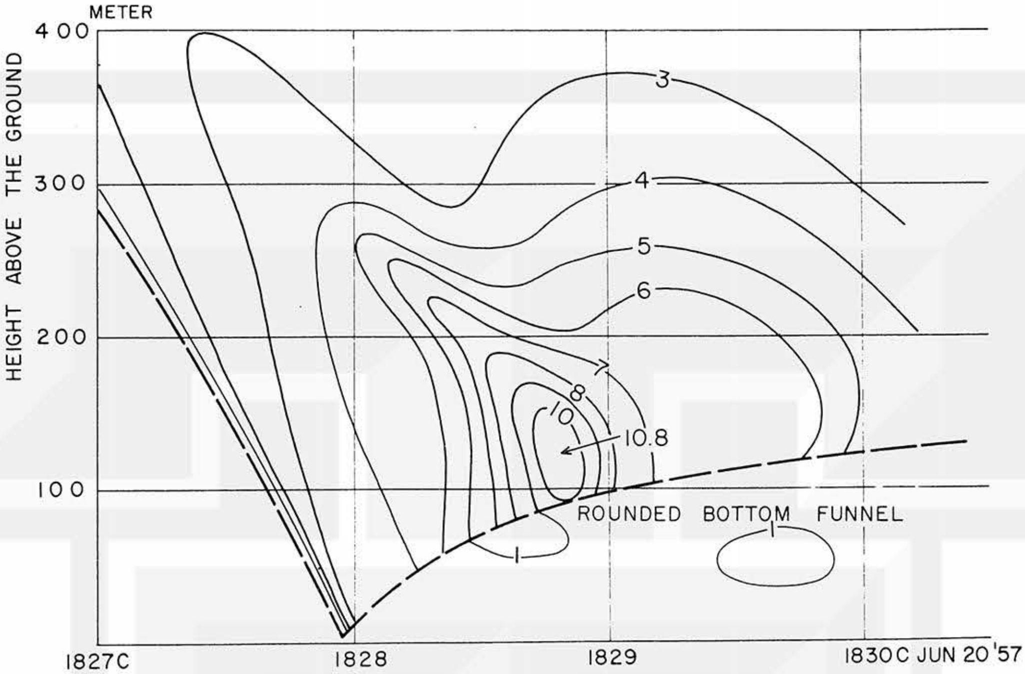


FIG. 60

$$V = \sqrt{R \frac{\Delta Z}{\Delta R}}$$

m / sec	40	50	60	70	80	90	100
MPH	90	110	130	160	180	200	220

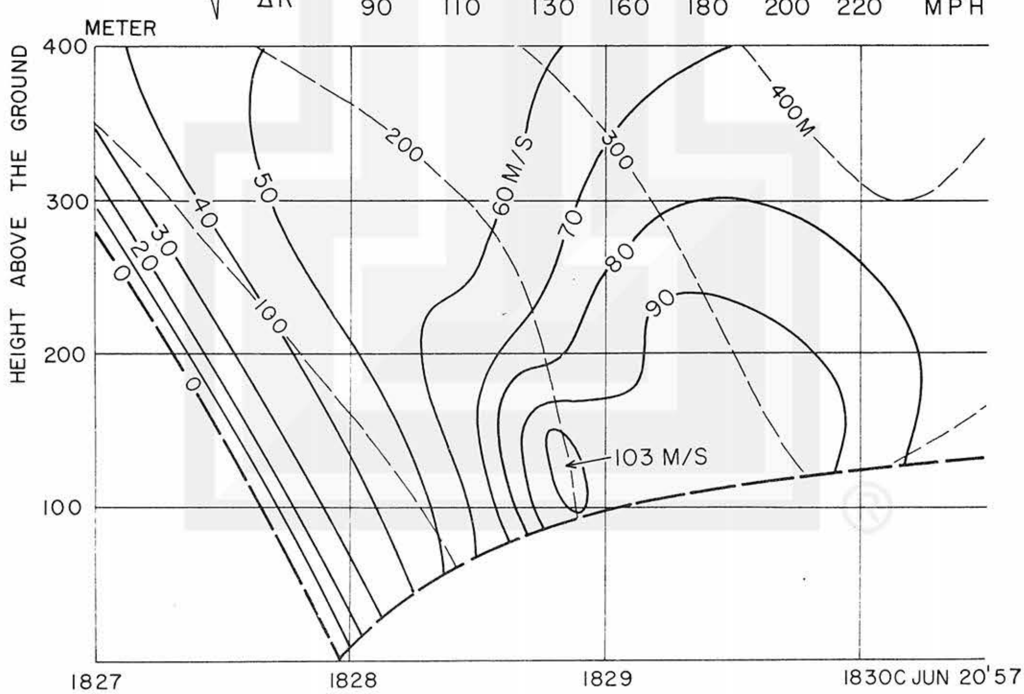


FIG. 61

1828CST (42 – 49 sec) MOVIE 27i JUNE 20, 1957

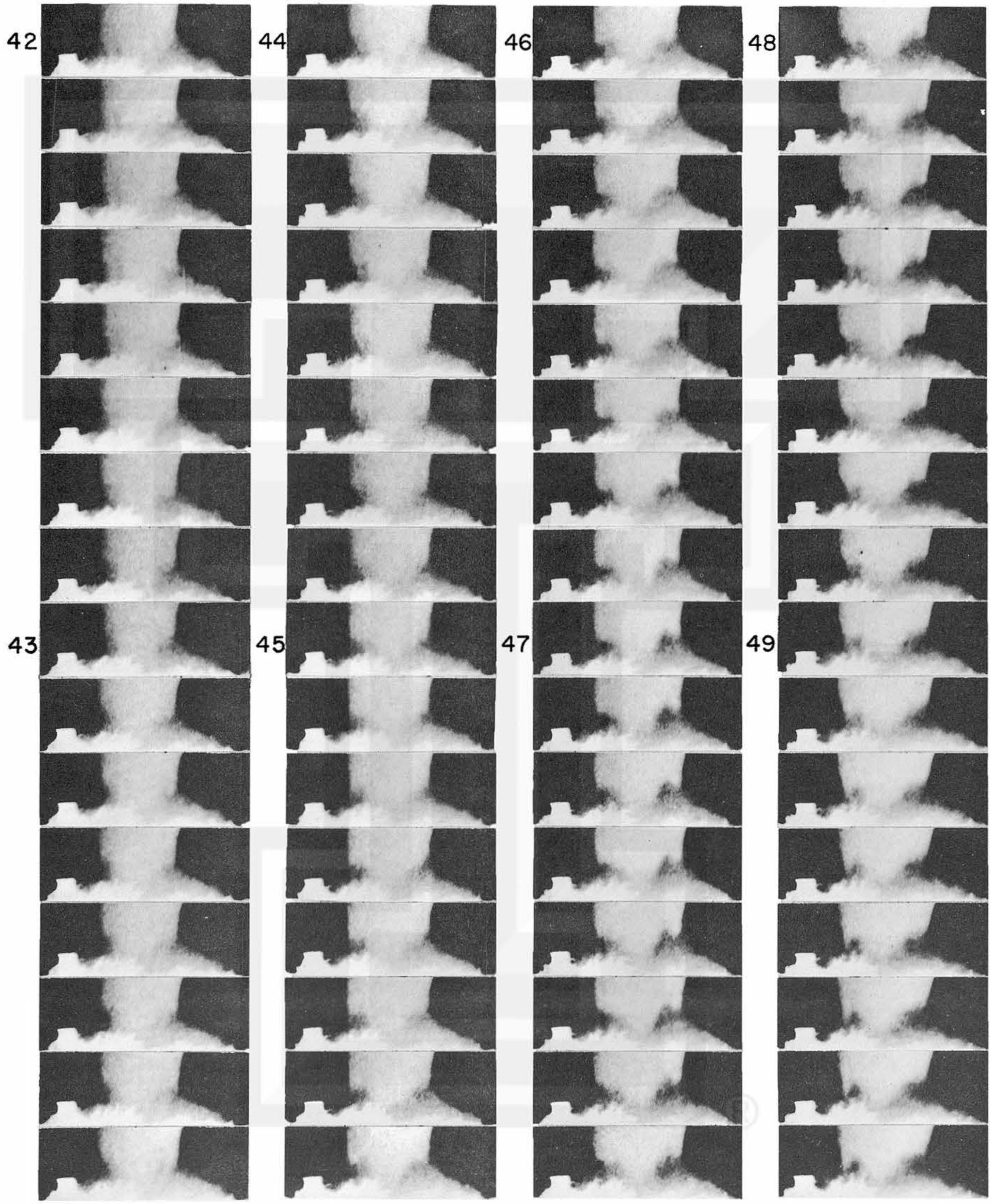


FIG. 62

1828CST (50 – 57sec) MOVIE 27i JUNE 20, 1957

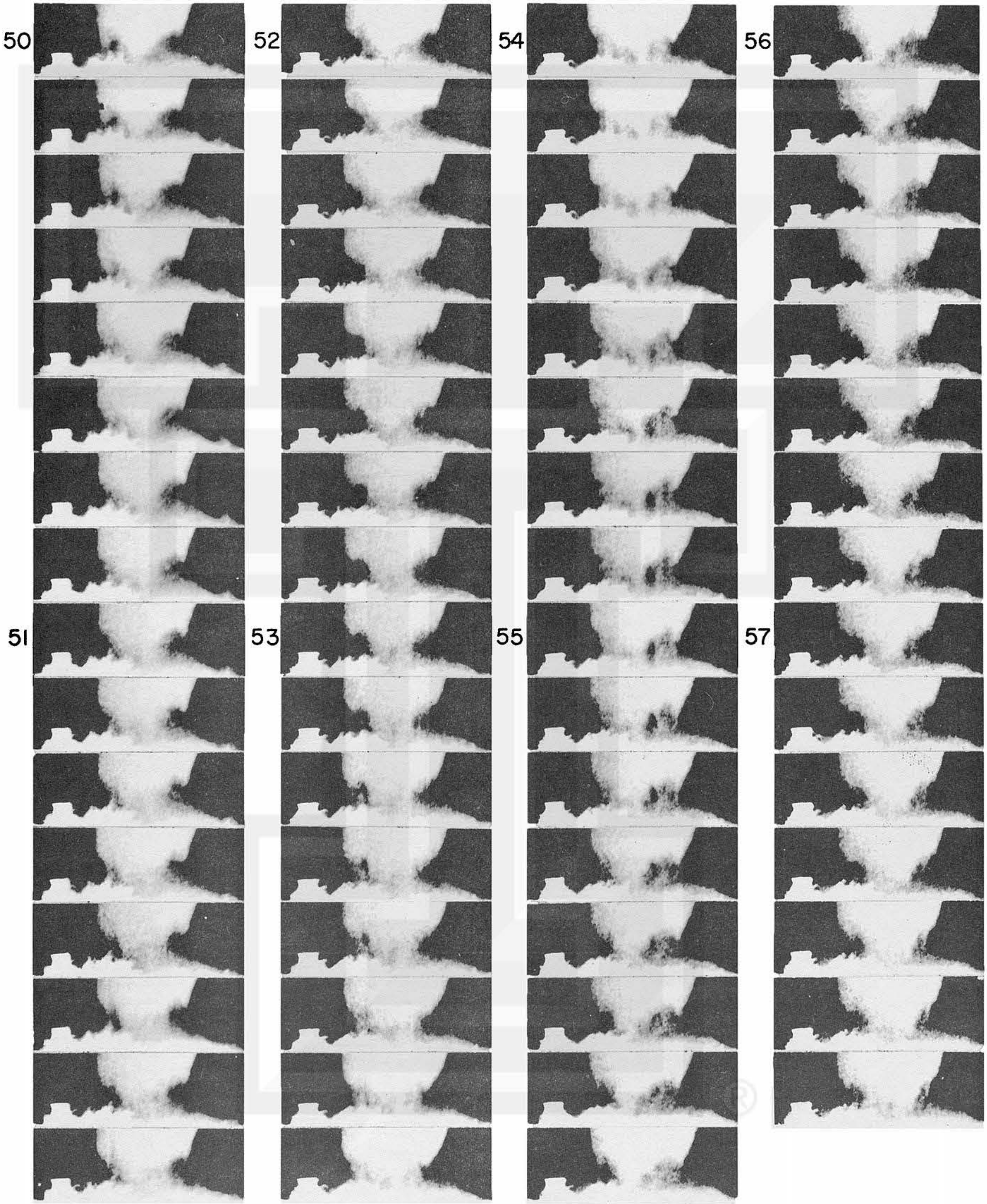


FIG. 63

1829 CST (28 - 35 sec) MOVIE 27j JUNE 20, 1957

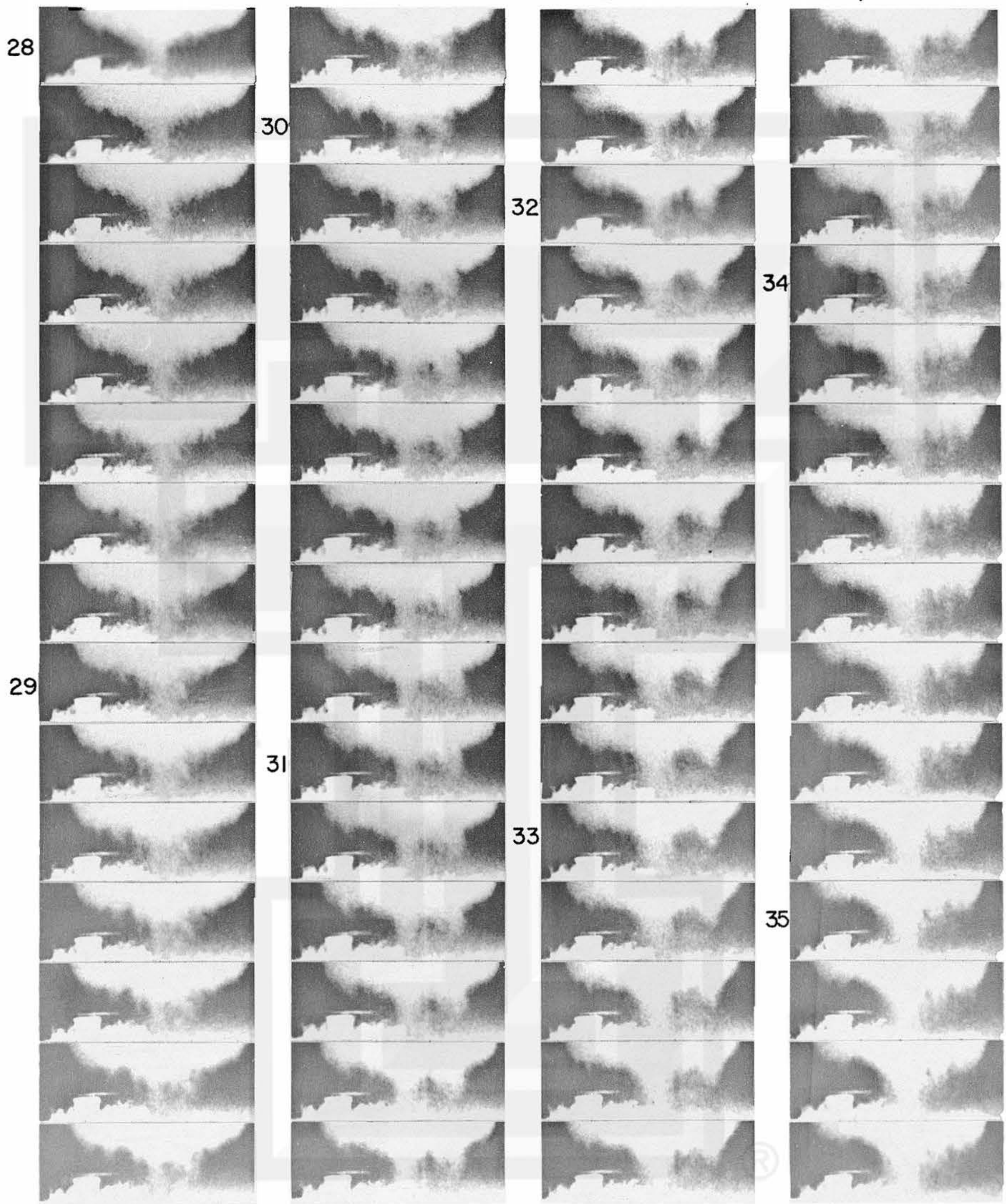


FIG. 64

1829CST (36-39sec) JUNE 20, 1957

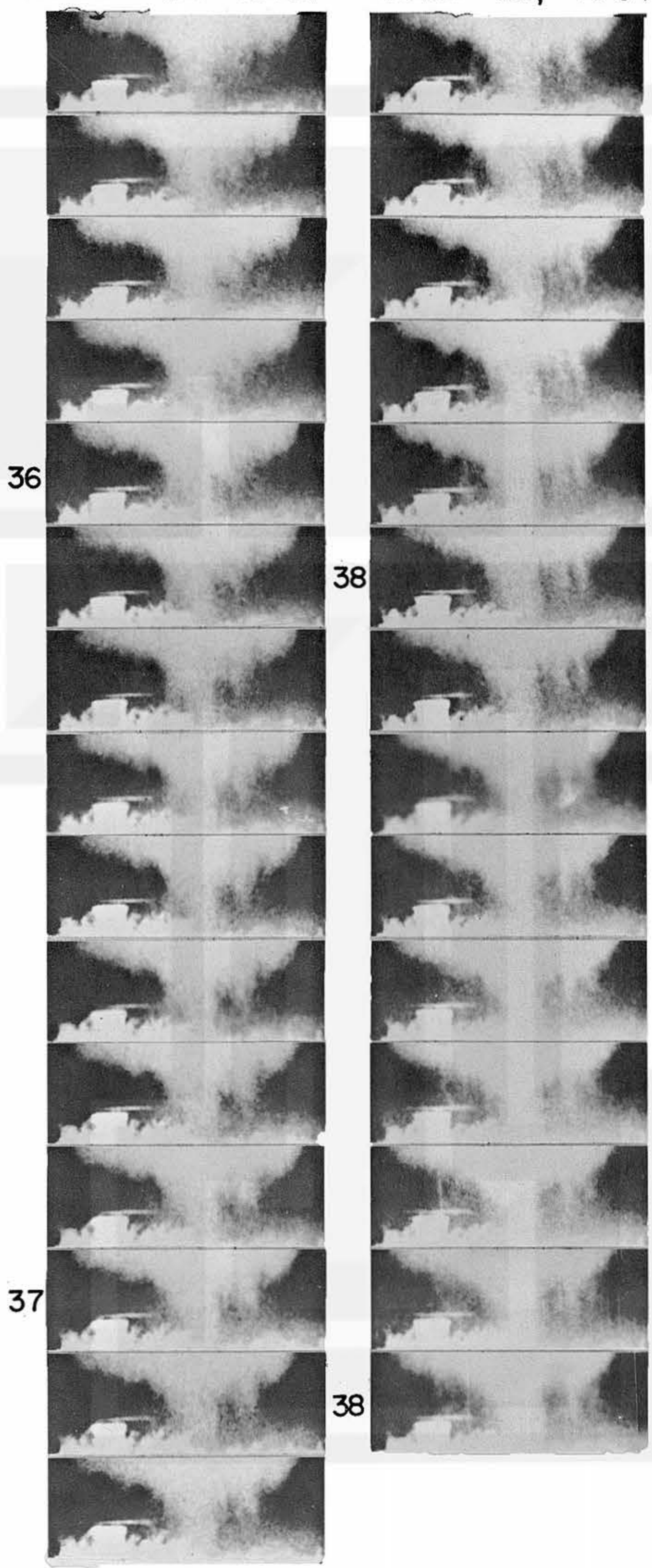


FIG. 65

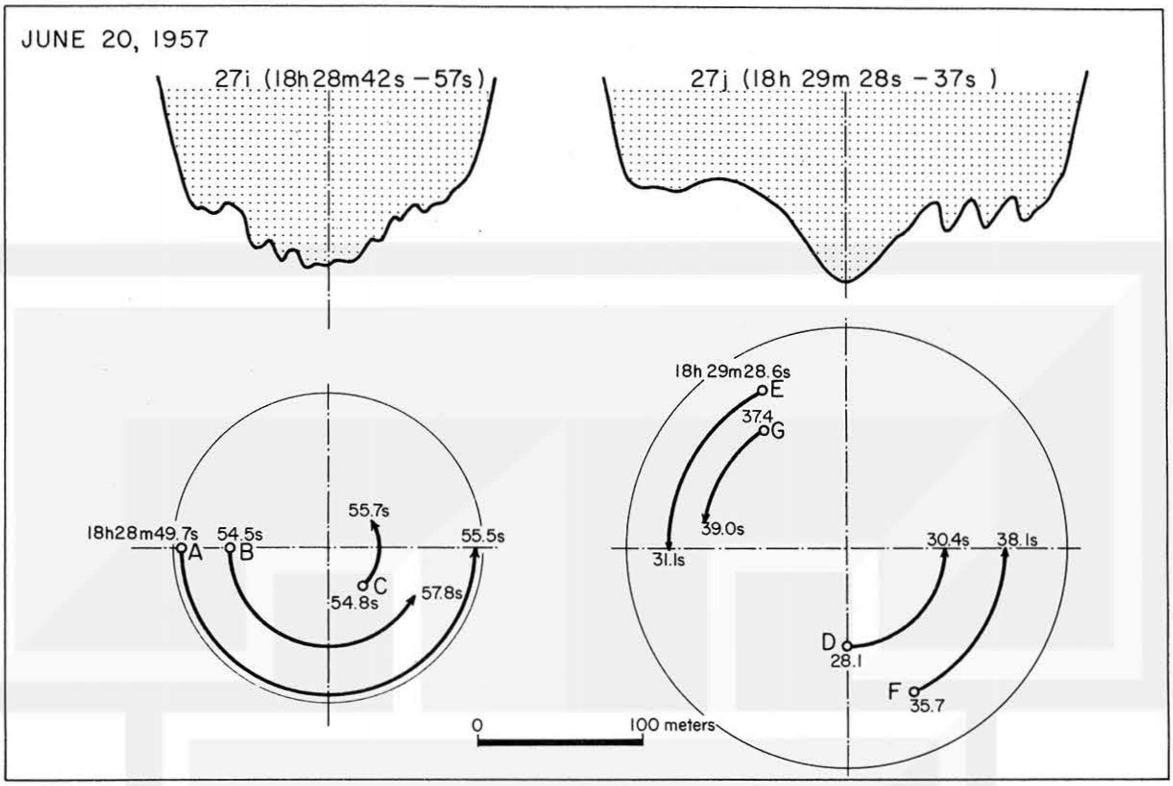

JUNE 20, 1957
27i (18h 28m42s – 57s)
27j (18h 29m 28s – 37s)
18h28m49.7s
54.5s
55.7s
55.5s
A
B
C
54.8s
57.8s
18h 29m28.6s
E
37.4
G
39.0s
31.1s
30.4s
38.1s
D
28.1
F
35.7
0
100 meters

FIG. 66

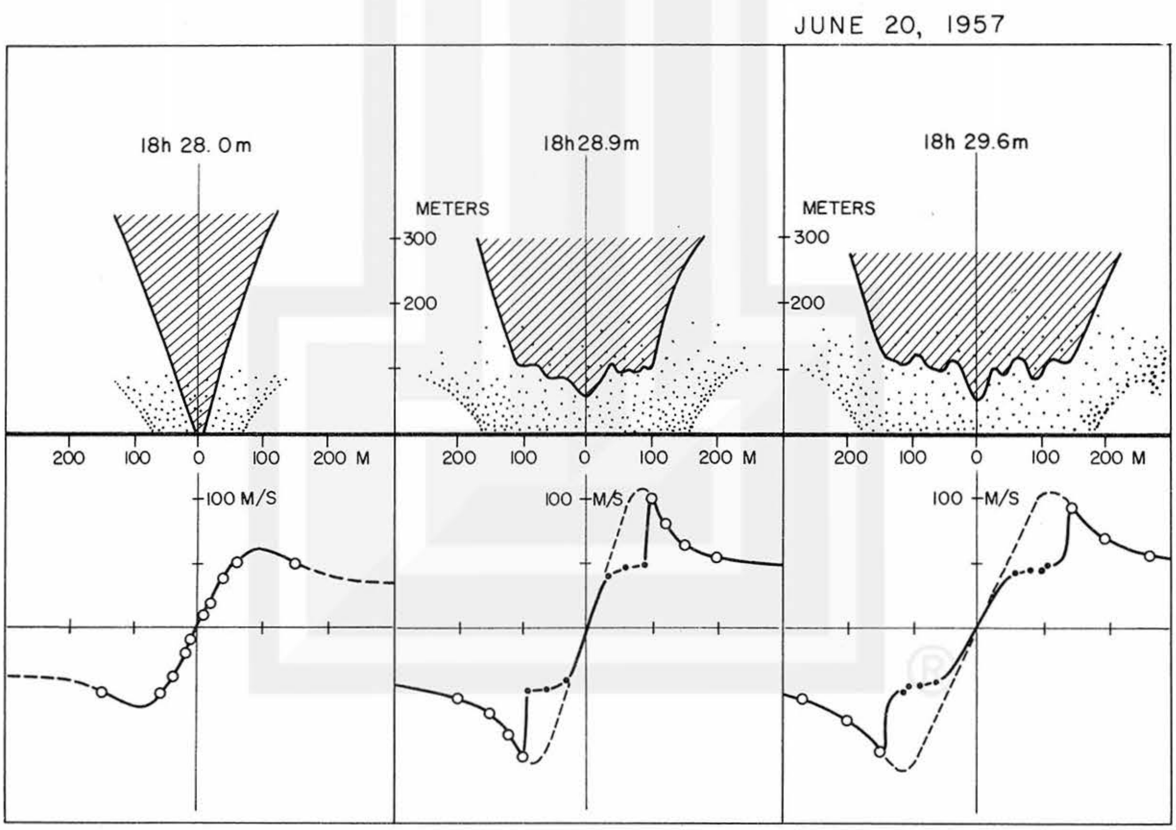

JUNE 20, 1957
18h 28.0m
18h28.9m
18h 29.6m
METERS
300
200
200
100
0
100
200 M
100 M/S

FIG. 67

CHAPTER VI: ROTATION OF THE FUNNEL

CHAPTER VII: 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 station been operating within fifty miles from the storm, it would 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 radarscope as a "hook" or in ordinary photographs as a "rotating cloud."

A. 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-minute intervals, a x-t diagram was constructed in the lower portion of Fig. 68. 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 Fig. 69 reveals several extremely important facts:

1) Each of the five tornadoes was initiated within five 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 two miles from the cloud center. Rope funnels were observed in the region beyond two miles from the center.

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

B. Axis of Tornado Funnel.

Examination of the tornado photographs appearing 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 70 gives the result. It is not possible to obtain directly the upper portion of the cone-shaped funnel because it was hidden at the 1000-3000 foot level by the base of the cloud. The axis of the rope funnel was triangulated up to the 6000-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 displaces 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.

C. Pressure Field Beneath the Rotating Cloud and the Liquid Water Storage.

Two barograph traces, one from the U. S. Weather Bureau 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.

As shown in Fig. 71, the relative positions of these barograph stations A-A' and B-B' were obtained by converting the time change into space change. The 16 mph 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 three 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 stippled 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 air column would be about 3 g/cm^2. The depths of the storage corresponding to the possible liquid water content are given in the following table:

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

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 Fig. 72 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 mph as it reached H_1, the point of highest pressure along the ring.

The precipitation which accompanied the rotating cloud fell between 1842-45 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 at a one-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

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

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

$$(4 \times 10^7 \text{ m}^3/\text{sec}) \times (15 \text{ g/m}^3) \doteqdot 6 \times 10^5 \text{ kg/sec}$$

In order to change 10^9 kg, the total amount of the liquid water in the cloud, at the rate of 6×10^5 kg/sec, it would take 2×10^3 sec $\doteqdot$ 30 minutes. 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 change period of the liquid water. Taking these points into consideration, it will be 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.

D. Winds Inside the Rotating Cloud and the Fargo Tornado.

The tangential wind speed shown in Fig. 73 summarizes the computation presented in Figs. 45 and 46. If a velocity profile were made through the center of the tornado funnel, the peak speed would be over 200 mph as described in Fig. 67.

The estimation of the vertical wind speed given in Fig. 44 reveals that the vertical motion at the edge of the cylindrical wall cloud was about 50 mph and was still increasing upward. Based upon this result, a mechanically driven ring vortex (M in Fig. 73) 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 74 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 diameter on each photograph. Figures 75 and 76 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 Fig. 67 consistently reveal that the edge of the dust cloud corresponded to the circle of 60 m/sec tangential wind speed. The destruction outside these lines was very minor, indicating that most of the damage took place inside the clouds of dust.

E. Irreversible Process Taking Place Inside 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. 66). 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 will suggest that the constant pressure surface should cut through the bottom of the funnel.

Based upon this assumption Fig. 75 was made. The figure will serve for a reconsideration of the thermodynamical process taking place inside the air flowing into the tornado funnel.

Through an irreversible adiabatic process, heat is continuously produced internally while the parcel expands. The parcel A_4, for instance, will show a small rate of cooling when it flows into a tornado, because the parcel moves near the ground under the influence of frictional force which produces heat; meanwhile the parcel loses its mechanical energy. Thermodynamically, the line along which the parcel expands lies between isentropes and isenthalps on adiabatic charts.

Now, the illustration shows that the parcels expanding along stream lines $A_o - A_1 - C_1$ and $A_o - A_2 - C_2$ are friction free; therefore, the moisture inside the parcel would condense at C_1 and C_2, located at the surface of the same condensation pressure. On the other hand, the parcels following the paths $A_o - A_3 - C_3$ and $A_o - A_4 - C_4$ would increase their entropy through their irreversible expansion, reaching their condensation pressures at C_3 and C_4, respectively. Assuming that the expansion along the surface is given by a straight line $A_o - A_3$, $- A_4$, on the adiabatic diagram, and that the expansion along $A_3 - C_3$ and $A_4 - C_4$ is dry and adiabatic and reversible, the temperature and pressure changes of parcels flowing into the bottom of the rounded bottom funnel were qualitatively described.

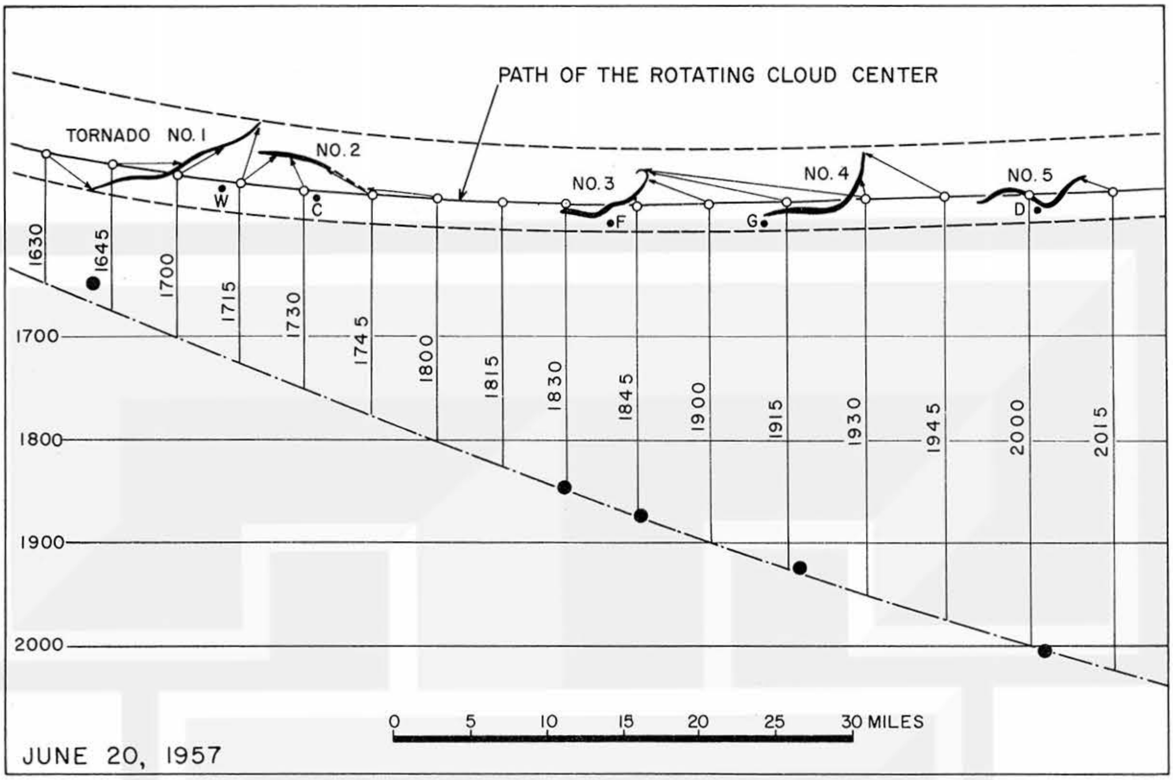

PATH OF THE ROTATING CLOUD CENTER
TORNADO NO. 1
NO. 2
NO. 3
NO. 4
NO. 5
W
C
F
G
D
1630
1645
1700
1715
1730
1745
1800
1815
1830
1845
1900
1915
1930
1945
2000
2015
1700
1800
1900
2000
0 5 10 15 20 25 30 MILES
JUNE 20, 1957

FIG. 68

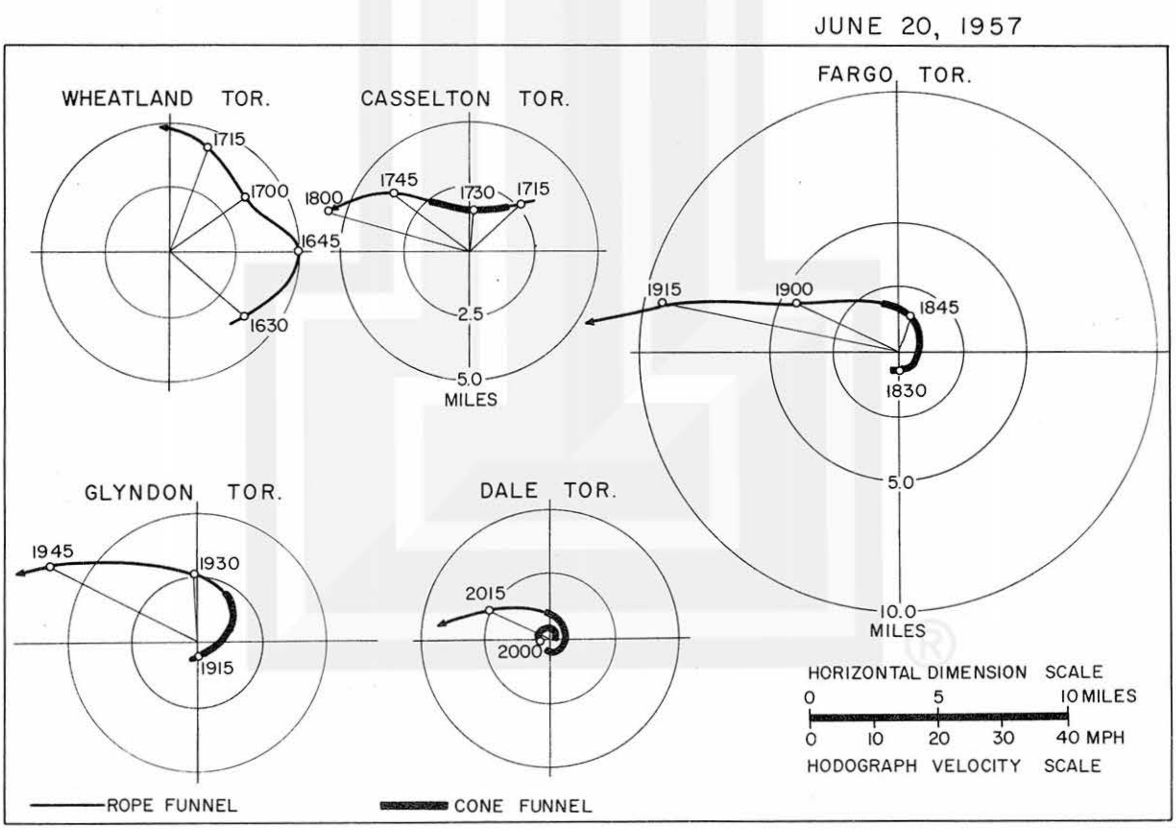
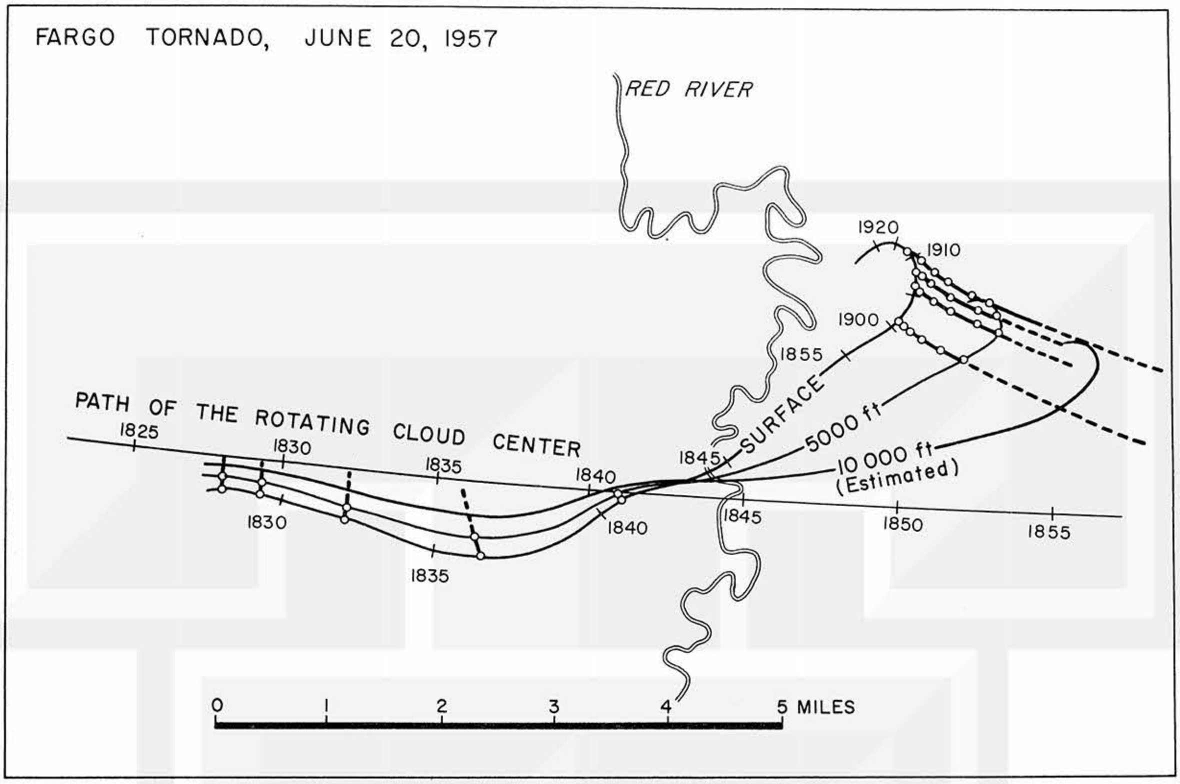
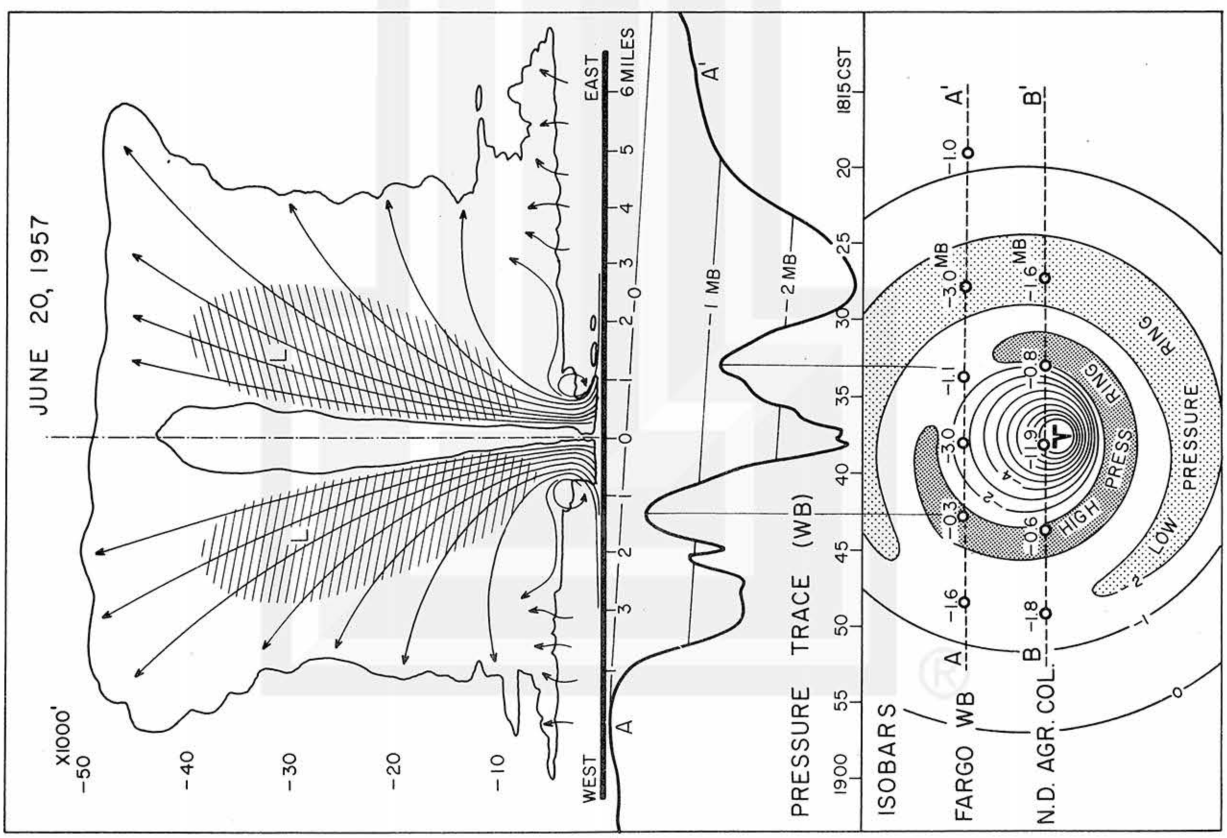

JUNE 20, 1957
WHEATLAND TOR.
CASSELTON TOR.
FARGO TOR.
1715
1700
1645
1630
1800
1745
1730
1715
2.5
5.0
MILES
1915
1900
1845
1830
5.0
10.0
MILES
GLYNDON TOR.
DALE TOR.
1945
1930
1915
2015
2000
HORIZONTAL DIMENSION SCALE
0 5 10 MILES
0 10 20 30 40 MPH
HODOGRAPH VELOCITY SCALE
ROPE FUNNEL
CONE FUNNEL

FIG. 69



FARGO TORNADO, JUNE 20, 1957
RED RIVER
PATH OF THE ROTATING CLOUD CENTER
1825
1830
1835
1840
1845
1850
1855
1900
1910
1920
SURFACE
5000 ft
10 000 ft
(Estimated)
0
1
2
3
4
5 MILES

FIG. 70



JUNE 20, 1957
X1000'
-50
-40
-30
-20
-10
L
WEST
EAST
6 MILES
A
A'
PRESSURE TRACE (WB)
1815CST
1900
-1 MB
-2 MB
ISOBARS
FARGO WB
N.D. AGR. COL.
B
B'
-3.0 MB
-1.6 MB
HIGH PRESS RING
LOW PRESSURE RING

FIG. 71

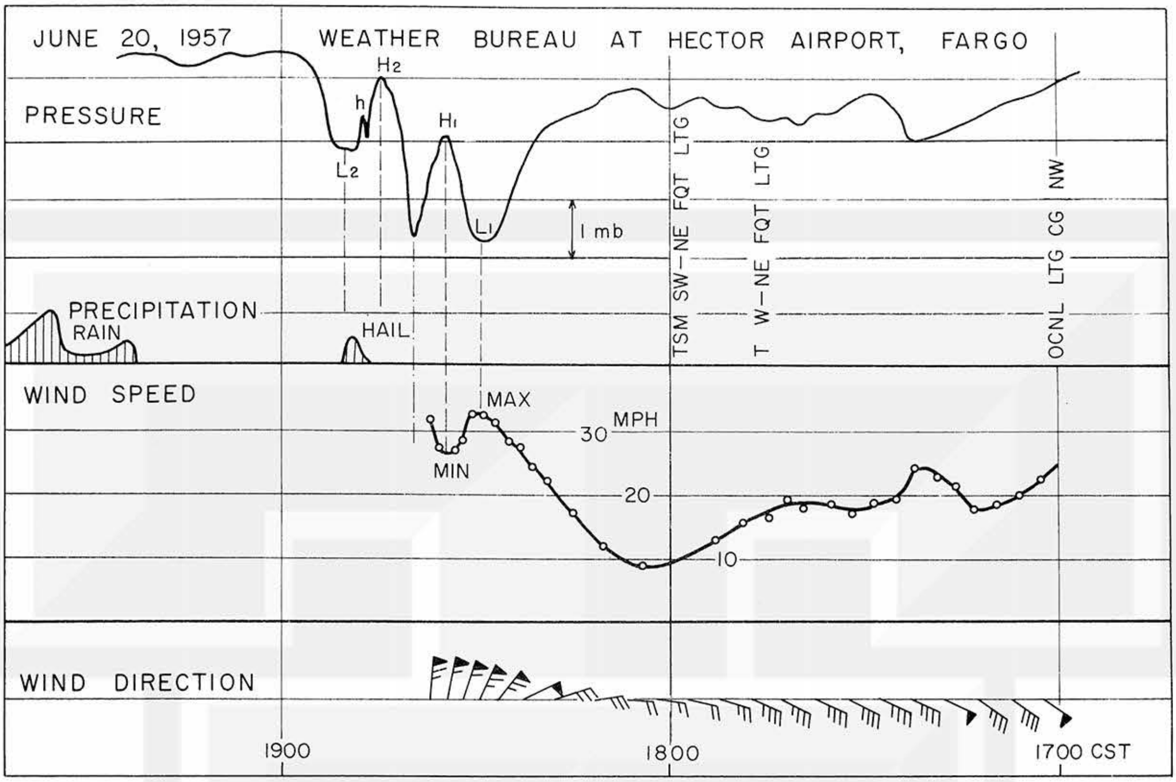

JUNE 20, 1957
WEATHER BUREAU AT HECTOR AIRPORT, FARGO
PRESSURE
H2
h
H1
L2
L1
1 mb
TSM SW-NE FQT LTG
T W-NE FQT LTG
OCNL LTG CG NW
PRECIPITATION
RAIN
HAIL
WIND SPEED
MAX
MIN
30 MPH
20
10
WIND DIRECTION
1900
1800
1700 CST

FIG. 72

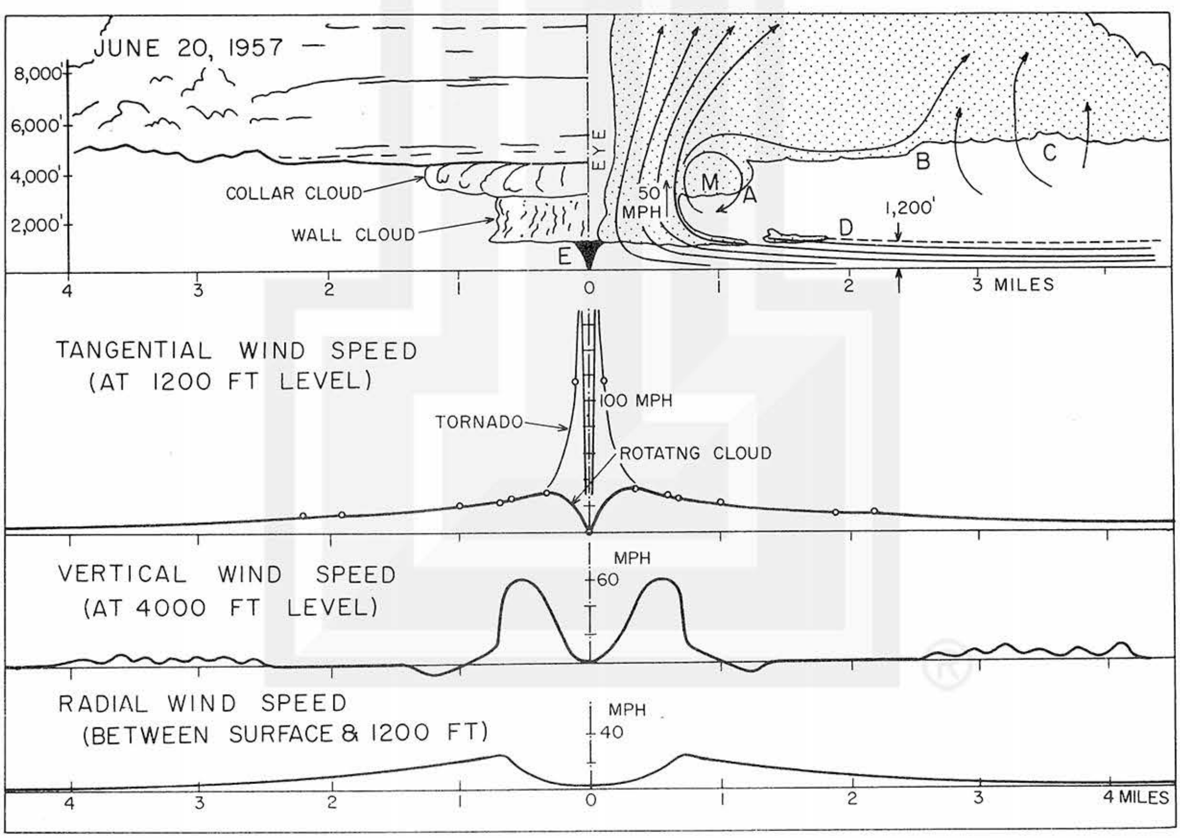
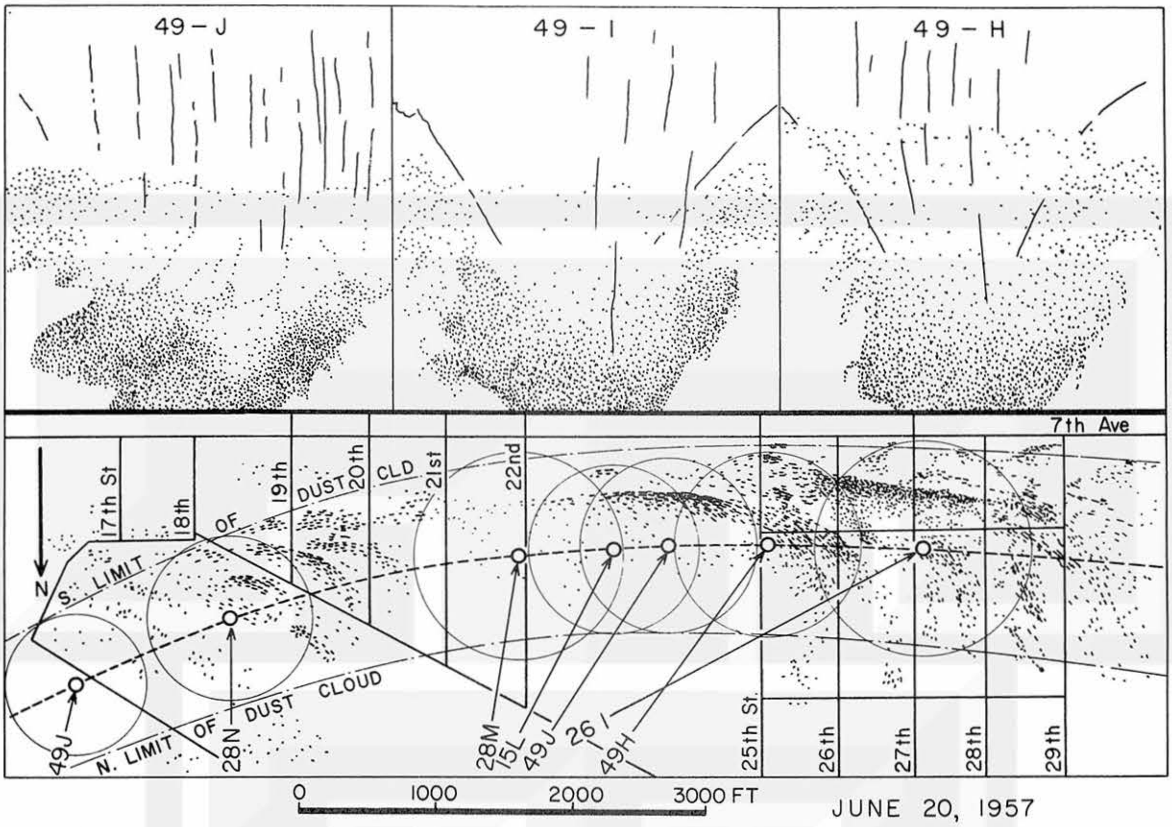
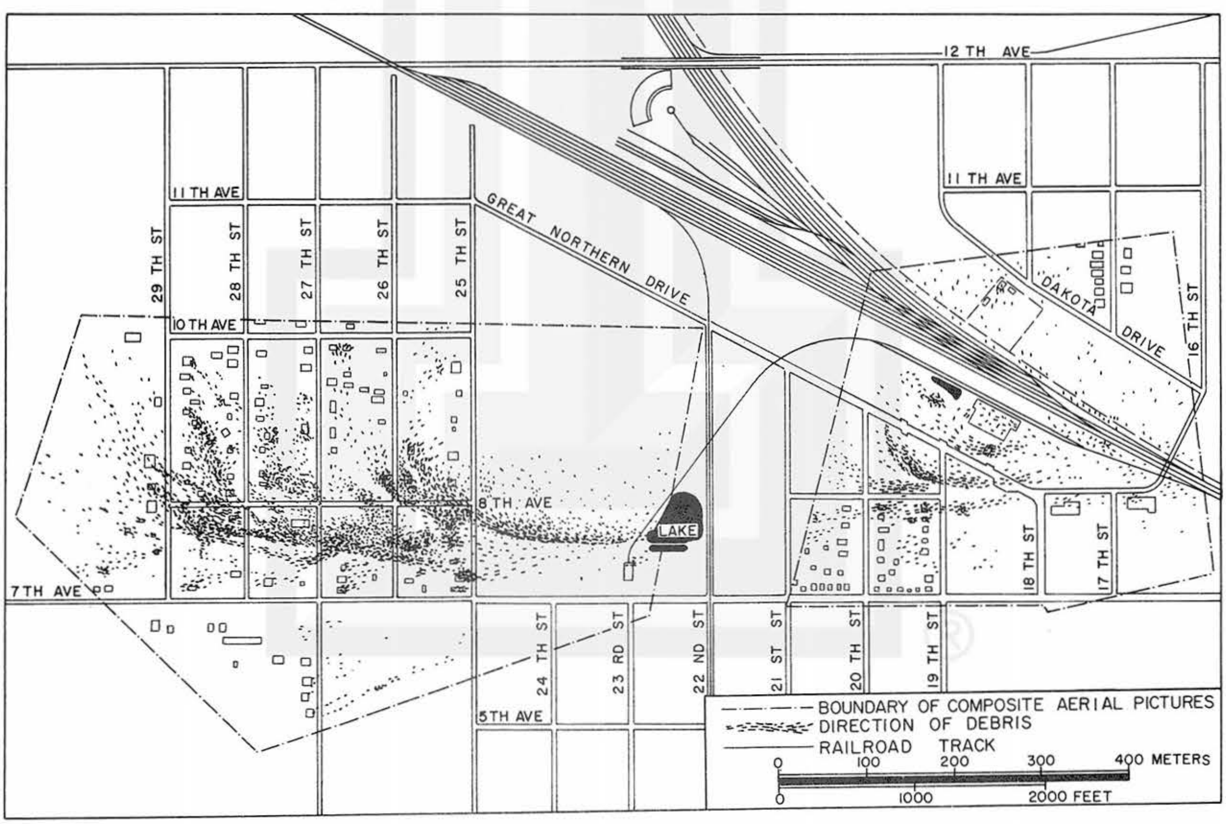

JUNE 20, 1957
8,000'
6,000'
4,000'
2,000'
COLLAR CLOUD
WALL CLOUD
EYE
E
50 MPH
M
A
B
C
D
1,200'
4
3
2
1
0
1
2
3 MILES
TANGENTIAL WIND SPEED
(AT 1200 FT LEVEL)
100 MPH
TORNADO
ROTATNG CLOUD
VERTICAL WIND SPEED
(AT 4000 FT LEVEL)
MPH
60
RADIAL WIND SPEED
(BETWEEN SURFACE & 1200 FT)
MPH
40
4 MILES

FIG. 73



49-J
49-I
49-H
7th Ave
17th St
18th
19th
20th
21st
22nd
S. LIMIT OF DUST CLD
N. LIMIT OF DUST CLOUD
N
49J
28N
28M
15L
49J
26 I
49H
25th St.
26th
27th
28th
29th
0
1000
2000
3000 FT
JUNE 20, 1957

FIG. 74



12 TH AVE
11 TH AVE
11 TH AVE
10 TH AVE
8 TH AVE
7 TH AVE
5TH AVE
29 TH ST
28 TH ST
27 TH ST
26 TH ST
25 TH ST
24 TH ST
23 RD ST
22 ND ST
21 ST ST
20 TH ST
19 TH ST
18 TH ST
17 TH ST
16 TH ST
GREAT NORTHERN DRIVE
DAKOTA DRIVE
LAKE
BOUNDARY OF COMPOSITE AERIAL PICTURES
DIRECTION OF DEBRIS
RAILROAD TRACK
0
100
200
300
400 METERS
0
1000
2000 FEET

FIG. 75

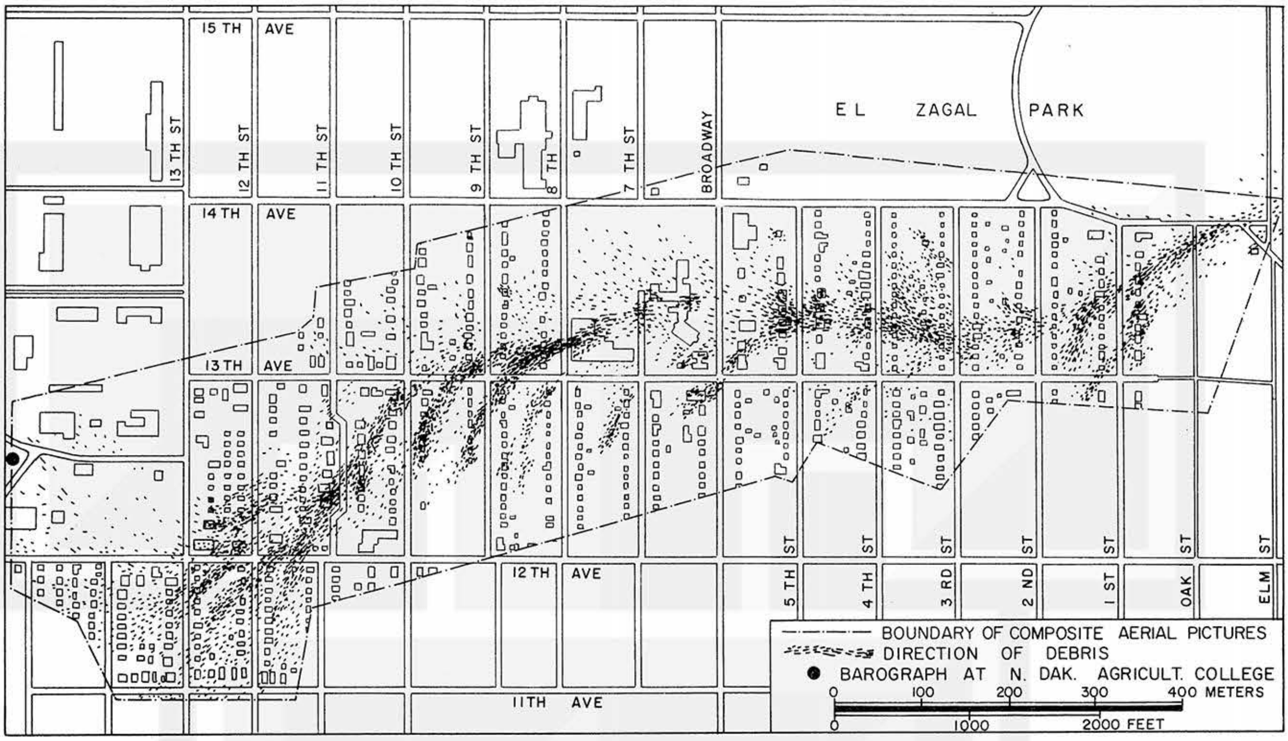

15 TH AVE
14 TH AVE
13 TH AVE
12 TH AVE
11TH AVE
13 TH ST
12 TH ST
11 TH ST
10 TH ST
9 TH ST
8 TH
7 TH ST
BROADWAY
EL ZAGAL PARK
5 TH ST
4 TH ST
3 RD ST
2 ND ST
1 ST ST
OAK ST
ELM ST
BOUNDARY OF COMPOSITE AERIAL PICTURES
DIRECTION OF DEBRIS
BAROGRAPH AT N. DAK. AGRICULT. COLLEGE
0 100 200 300 400 METERS
0 1000 2000 FEET

FIG. 76

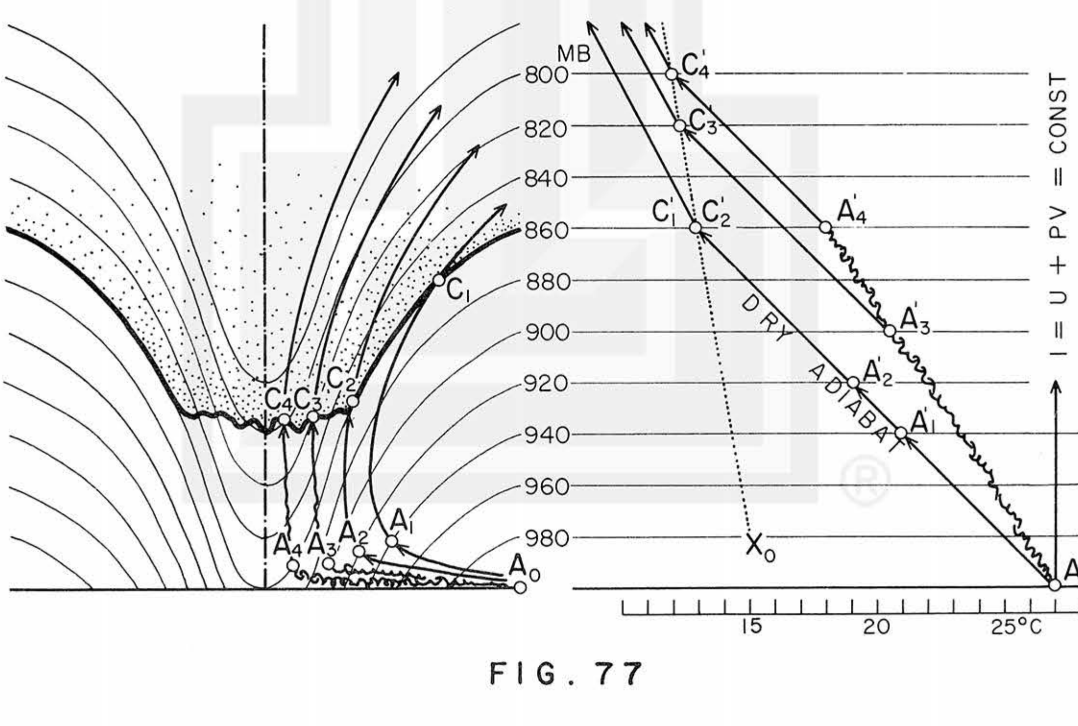

MB
800
820
840
860
880
900
920
940
960
980
C4 C3 C2 C1
A4 A3 A2 A1 A0
C'4 C'3 C'1 C'2
A'4 A'3 A'2 A'1 A0
X0
DRY ADIABAT
I = U + PV = CONST
15 20 25°C

FIG. 77

CHAPTER VII: STATEMENT OF THE RESULTS OBTAINED