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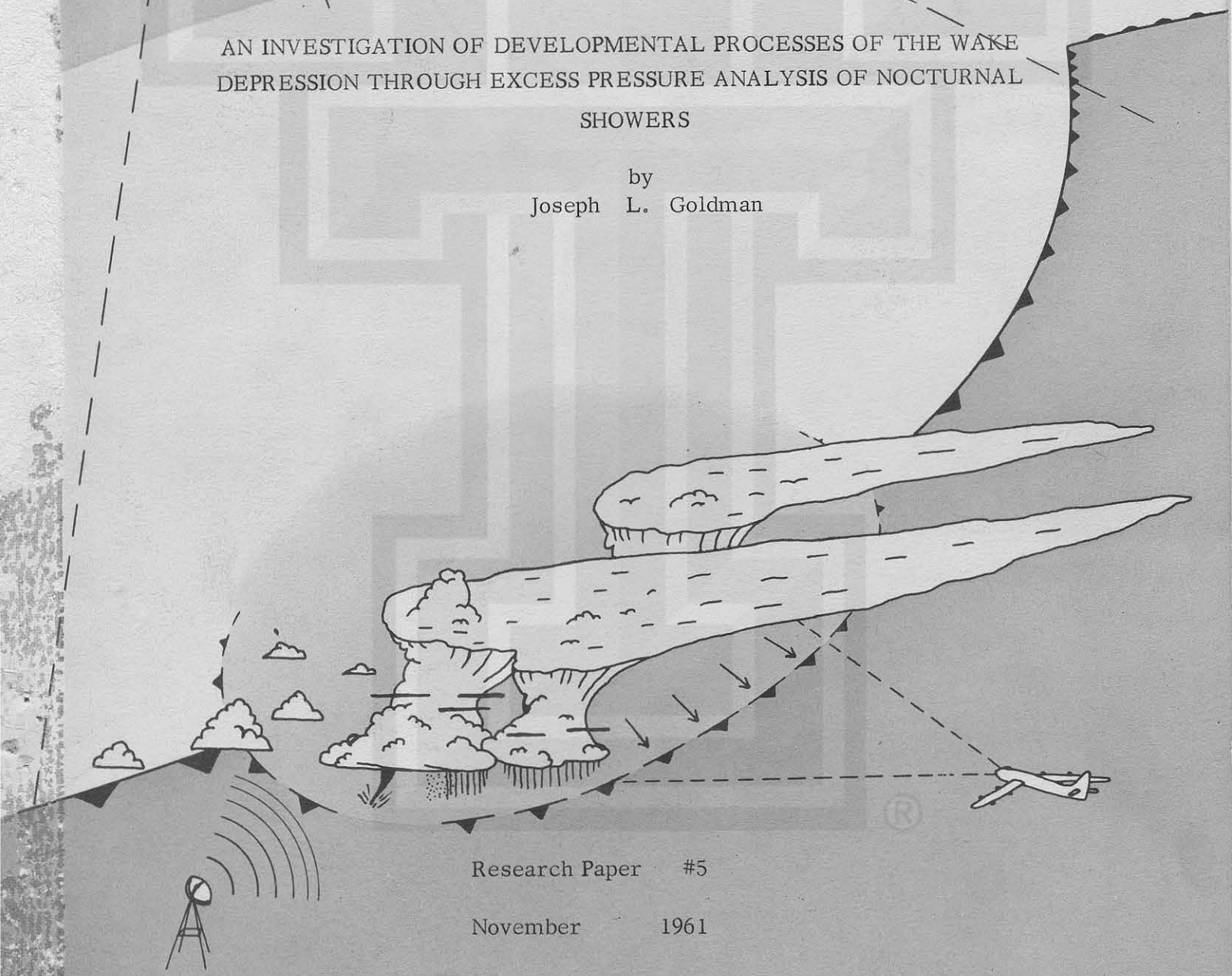
MESOMETEOROLOGY PROJECT

Department of the Geophysical Sciences
The University of Chicago

AN INVESTIGATION OF DEVELOPMENTAL PROCESSES OF THE WAKE DEPRESSION THROUGH EXCESS PRESSURE ANALYSIS OF NOCTURNAL SHOWERS

by
Joseph L. Goldman



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An Investigation of Developmental Processes of the Wake Depression Through Excess Pressure Analysis of Nocturnal Showers

Joseph L. Goldman

Abstract

A normalization technique by which the material change of excess pressure in a mesosystem can be computed graphically is devised and used in a case study of a system which originated and developed totally within another mesoscale system. Resulting patterns, which include excess pressure production rate and wake production rate, comply with implications from Fujita's computations which show that the wake depression may form due to the vorticity generated by the interaction of friction and the translating downdraft of a storm. It is suggested that the normalization technique for graphical computation is also applicable to other scales of meteorological research and to geophysical research in general.

1. Introduction

Results of mesoscale analyses by Fujita[1;2;3;4] and Brown[5] have shown that a wake depression, or region of low pressure to the rear of the pressure dome, was present, in many cases, at some time during the life cycle of the systems studied. From analyses of many different cases of the development of mesoscale disturbances, Fujita[1] has shown that the model pressure trace changes in time from a small dome of high pressure (initially) to a large depression. This occurs through a process in which the wake depression expands in area while the dome of high pressure flattens.

Results of computations of vorticity and divergence within the boundary of stationary systems undergoing expansion[3] and moving systems undergoing expansion[6] indicate that the wake depression is a function of the interaction of surface friction with the kinematics of the mesoscale disturbance. In his most recent study of the dynamics associated with nocturnal showers within the mesosystem, Fujita[6] has shown that the wake depression may form due to the vorticity generated by the downward course of the translating downdraft.

This study is also a case study of nocturnal showers; however, the particular system investigated in detail remained within another system throughout the period of analysis.

2. Case Study of the Period 18 C June 3 to 18 C June 4, 1959, in the Region of the Texas-Oklahoma Severe Storms Network

Macrosynoptic sea-level pressure analyses for this period show a trough to the lee side of the Rockies and the Bermuda High influencing the region east of the trough, with the perennial quasi-stationary front extending southward in the trough and eastward across northern Texas. A squall line extending from southern Oklahoma to central Texas has developed, moved eastward, and dissipated within this period.

Investigation of this period in the mesoscale revealed that from 18 C June 3 to 00 C June 4 thunderstorms existed in the region occupied by the lee side trough. Figure 1 is the mesoscale base map for pressure, showing the locations of full-time reporting stations (call letters) and severe storms stations (numbered) in the region of analysis. Figure 2 is the base map for the precipitation network in this region (x indicates no precipitation reported throughout the period). Within this period the station data showed evidence of severe thunderstorms in the region of the trough. In Fig. 3 are the station data for Clovis, New Mexico, and Dalhart and Wink, Texas, for the period 18 C to 00 C. The continuous traces of pressure for these stations are presented to show the varied influence of hail on the pressure trace at individual stations, a subject that needs further investigation.

The mesoanalysis necessitated corrections of the reported sea-level pressures, especially from mountain stations. This was done by the method developed by Fujita and Brown[7] as was previously reported[8]. The reported winds from the stations in the mountains in most instances had to be neglected because of the predominance of the effects of local topography over the effects of the mesoscale disturbances. The hourly precipitation was analyzed independently of the other parameters. From the time and space continuity of rainfall maxima, the distribution of isochrones of these maxima was determined. An independent analysis of the successive positions of wake depressions showed that the difference in spacing of isochrones of wake depressions and of rainfall maxima was within the limits of the station spacing. The isochrones of both maximum rainfall and wake depression were used to convert the continuous pressure trace from the time to the space dimension. Ordinarily the surface wind shift would be used as another guide to the motion of the surge line; in this case, however, the lack of a well defined prevailing pressure surge and the paucity of surface wind reports both precluded the use of that technique.

Analyses of the hourly amounts of accumulated rainfall and the isochrones of their maxima showed little organization of these showers into continuous patterns in time before 00 C June 4. By 00 C the showers formed into three mesosystems oriented north-south and located in the region of the lee-side trough. Figures 4 through 11 are the hourly mesoscale analyses from 00 C through 07 C. On these figures the continuous solid lines are isobars; dashed lines are boundaries of the systems; light and heavy stippling cover the areas of hourly accumulated rainfall of 0.1 in or greater and 0.5 in or greater, respectively; the wind arrows are the same as in Fig. 3; and the discontinuous thin lines are the pressure traces. From the areal extent of the systems, the pressure distribution within the boundaries of the systems, and the patterns of hourly rainfall, it was evident that system I was in its decaying stage while systems II and III were in their developing stages at 00 C. Perusal of the series of maps shows that by 04 C system I became indistinguishable from the macroscale pattern and systems II and III merged to become

system IV. Without a denser network it is impossible to place the origin of system V; however, from continuity considerations the origin of the system was considered to be sometime between 02 and 03 C. By 04 C system V became well defined as an individual system. The large pressure gradients at the leading edge of system III are associated with accumulated rainfalls of greater than 3 in/hr at 22 C, 2.5 in/hr at 23 C, and 1 in/hr at 00, 01, and 02 C. As can be seen from the analyses, the pressure produced by the outflow of these and later showers influenced the southern region of systems III and (later) IV throughout the period of analysis. By 08 C the showers in the northeastern portion of the systems either ended or became disorganized. In the southern portions of the systems the pressure surge or relatively large gradient remained; however, it should be noted that the location of the southward extension of the mesosystem boundary beyond the region of the severe storms network is at this time less objective, since the pressure gradients to the northeast were either small or nonexistent. The detailed analysis was therefore restricted to the period 00 C through 07 C, the period of relatively well defined boundaries of the systems. Examination of network data through June 5 showed that mesosystems existed in the southern and southeastern portions of the network throughout the period.

3. Excess Pressure Analysis

The excess pressure is defined as that pressure caused by the accumulated net outflow of the storms within the boundary of the mesosystem. If the effect of the mesoscale perturbation on the macroscale pressure pattern is a depression, then the excess pressure produced by the mesosystem is the observed value of pressure minus the depressed value of pressure of the macroscale pattern (called the disturbed pressure). With careful consideration given to the meridional variation in the range of semidiurnal pressure variations and to space-time continuity of the disturbed pressure, the patterns of disturbed pressure were drawn for the period 00 C to 07 C. These patterns were then graphically subtracted from the analyzed pressure patterns to obtain the hourly excess pressure patterns shown

in Figs. 12 through 19 (heavy solid lines are of equal excess pressure, thin lines are of equal disturbed pressure, and dashed lines are the boundaries, which are also zero values).

Through excess pressure analysis, the various stages of development and decay of the mesosystems became evident. At 00 C (Fig. 12) system I consisted of a large depression with a small amount of positive excess pressure which disappeared within a few hours. A large amount of the excess pressure in the region of the intersecting boundaries of systems I and II was from system II. System I is therefore considered to be in its decaying stage. Systems II and III had already formed small wake depressions which spread and deepened as the systems merged. Because of the increase in excess pressure with time and the lack of a well defined wake depression, it is evident that system III is at an earlier stage than II. The large values of excess pressure that predominate in the southern region of system III are substantiated by the large accumulation of precipitation mentioned previously.

> --The contributions of individual mesosystems to the total excess pressure would have been difficult to compute without making questionable assumptions concerning the pressure at the overlapping boundaries of the systems. Until a denser network of both surface and upper-air stations is available, this phase of the analysis is left to the future.--

By 03 C (Fig. 15) systems II and III had almost completely merged into IV. The excess pressure analysis indicates a new development within the two systems. By 04 C the boundary of excess pressure for system V became evident. The southern boundary of system IV remained evident throughout the period, since the excess pressure was being produced by new storms which developed near the southeastern portion of the boundary. This excess pressure is important for the discussion of wake formation in the following section. From 04 C to 06 C the positive excess pressure increased due to contributions from system V, and the spatial extent of the depression increased due to contributions from both systems IV and V.

4. Excess Pressure Production Rate

In Fig. 20 are the boundaries of system V for the period 04 C through 07 C. Since this sytem seemed to expand at a nearly constant rate, it was chosen for the computation of production rate. It will be recalled that system V remained within system IV throughout this period, thereby contributing difficulties in the determination of the excess pressure pattern. However, the determination of the boundary of system V does not involve so gross an assumption as with the boundaries of systems II and III. Since the cold air produced by system V had had little time to modify or mix when compared with that produced by system IV (II + III), it can be assumed that the maximum effect on the total excess pressure (systems IV + V) is the result of the more recent downdrafts, namely those of system V. The air of system V would then underlie or displace the relatively modified air of system IV in a fashion analogous to the structure of the "cold-front-type occlusion." Since system V remained within the boundary of IV, it was possible to interpolate the pressure pattern of system IV within the area of V from the pattern outside the boundary of V. In the case of systems II and III, an extrapolation would be necessary to extend the excess pressure pattern of the individual system. Also, since the stages of development of II and III are close when compared with those of V and IV, the question of which system displaces the other involves a conclusion with little evidence behind it. Patterns of precipitation and continuity of the excess pressure pattern of IV were also useful in determining its pattern within the boundaries of system V. The excess-pressure patterns of system V were then computed by subtracting the patterns of system IV from the pattern of total excess pressure at each hour from 04 C through 07 C.

In Fig. 20 is also shown the net effect on the size of the boundary due to expansion and translation of the system. An approximate mean orthogonal pair of axes were determined so that computations of the change in excess pressure within system V could be possible. The displacement of the intersection of these axes (the central point) between each hour of analysis is the mean translation

of the system for that hour. These displacements are indicated between the central points of the appropriate hours. The effect of expansion on the displacement of the leading edge of the system is also shown in Fig. 20. The net effect of expansion and translation on the leading edge of the system is an acceleration throughout the period.

In order to compute the change in excess pressure with time (production rate), the effect of the hourly expansion of the system had to be taken into account. This was done by expanding the system areally, thereby conserving the mass within the boundary of the system. If it is assumed that excess pressure is hydrostatic pressure alone (no vertical component of dynamic pressure gradient) then $dp = \frac{g}{A}\, dM$; where p is the total excess pressure within the boundary; g is the acceleration of gravity, A is the area within the boundary, and M is the total mass contained within the boundary.

Fig. 21 is an example of this type of expansion. The boundary of the system at 04 C is expanded to its size at 05 C, while the Laplacian of the excess pressure is kept constant. Since this method of expansion produces no change in the pressure distribution with respect to area, the total flux of mass through the boundary of the system could be computed simply by graphical techniques. The hourly hourly difference in excess pressure is computed by superimposing on the pattern of the hour in question (e.g., 05 C) the expanded pattern of the preceding hour (e.g., 04 C) so that the major and minor axes coincide; then the patterns are subtracted graphically. In summary, the normalization technique used for the computation of excess-pressure production rate was an areal expansion of the system with respect to the central point.

In both Figs. 21 and 22 are the excess-pressure patterns for system V at the indicated times. The solid and dashed lines are for increments of 1 and 1/2 mb, respectively. In the pattern at 04 C, system V had already developed a wake depression. At 05 C the maximum positive excess pressure increased near the leading edge of the system, as would be expected in a developing system. This increase in maximum value continued through 06 C, and by 07 C the value decreased. During this period the minima of excess pressure expanded in areal extent.

In order to illustrate the change in excess pressure with time, the patterns were graphically subtracted from each other after the systems were expanded in the manner discussed previously. The difference was taken with respect to the mean major and minor axes; therefore, only the rotation of the system about the reference point and the movement of the "excess-pressure cells" within the system are not taken into account. As can be seen in Fig. 20, there was little or no rotation of the system about the reference point, and in Figs. 21 and 22 the locations of the "cells" of excess pressure with respect to the central point for each hour were nearly identical. The differences computed are then considered a good approximation to the material change in excess pressure within the system. These hourly changes in excess pressure are shown in Fig. 23 (solid and dashed lines are as in Figs. 21 and 22). The areas of positive excess-pressure change at the leading edge of the system are regions of excess-pressure production during the one-hour interval, as can be seen by considering the patterns of Fig. 23 together with Figs. 21 and 22. Similarly, the areas of negative excess-pressure change immediately behind the positive areas are regions of wake production.

During the period 04 C to 05 C (see Fig. 23) the region of maximum excess pressure production rate was in the northeast sector of the system. From 05 C to 06 C this region moved slightly northward and the rate decreased. It is also seen that during the period 04 C to 06 C the region of wake production immediately behind this excess pressure production region decreased. During the period 05 C to 06 C a new region of excess-pressure production (as indicated by the +1 mb/hr isoline) formed. A region of wake production formed during this period immediately behind this new positive region. In the period 06 C to 07 C (Fig. 23) it is obvious from the negative values at the leading edge that production of excess pressure had decreased considerably. From Fig. 22 it is seen that the excess pressure at the leading edge of the system at 07 C was considerably less than that at 06 C, implying cessation of production during the period 06 C to 07 C. The positive values in the region of wake production indicate that the depressions were filling during this period.

The computation of excess-pressure production rate for this particular case has shown a relation between the increase of excess-pressure production and the increase of wake production. It will be recalled that the system was accelerating throughout the period, and that an increase and decrease in production rate was coexistent with an increase and decrease of wake formation rate.

In Fig. 23 for the period 05-06 C, the large region of negative change is of particular interest. In the excess-pressure pattern of the system at 06 C (Figs. 22), the zero value near the southern boundary of the system is south of the expected location of the wake depression with respect to the region of maximum positive excess pressure. Both the southward extension of this negative region and the large negative value of excess pressure change in the region may be due to contributions of new showers in system IV and possibly to the vertical stretching of the air after it has passed over the crest of the pressure dome of system IV, analogous to the lee-side effect.

5. Conclusions and Suggestions for Further Research

The results of this investigation have shown that for this particular case the interaction between the translating downdraft and surface friction may be an important dynamic consideration in wake depression development. It is inferred from Fujita's work[6] that either an increase in the downdraft of a system with no acceleration, or a constant downdraft in an accelerating system, would produce cyclonic vorticity in the northern region to the rear of the storm producing the downdraft (see Fig. 24). In the case used in this investigation the system was accelerating, and an increase of excess-pressure production coexisted with an increase of wake development. If an analogy can be made between the excess-pressure production rate and the rate of increase of outflow (or downdraft) from storms, then the results of this study confirm the implications of Fujita's work. Computations by Fujita[3] and Braham[9] have shown that a large part of the observed excess pressure in the cases studied can be accounted for by the effect of evaporation in the downdraft. In this study the cloud bases preceding the rain

showers were generally low (2000 to 4000 ft) compared with those used in Fujita's computations[3]. However, the heights of cloud bases in the southern part of the region of analysis were higher (approximately 6000 ft) where, it will be recalled, the maximum excess pressure was produced. The type of computations made by Fujita and by Braham necessitate data from a dense network of surface and upper-air stations, which was lacking for this case.

The techniques of normalizing patterns by areal expansion is applicable to other scales of meteorological research and to geophysical research in general. Assuming that boundaries enclosing the particular perturbation can be determined, say by harmonic or spectral analysis, then the areal expansion of the system with time can be taken into account when the material change of the disturbance itself is desired. This technique also reduces the problem of boundary effects in graphical computations.

In this study the case of a system originating and developing totally within another system was examined by excess pressure analysis. Although the technique of extracting the excess pressure patterns of the inner system is crude, it is hoped that this technique can be refined by considering higher frequencies of barometric, thermometric, hygrometric, and anemometric oscillations by means of data from denser networks of surface and upper-air stations.

It is suggested that computations of excess pressure be continued for mesosystems which are studied with the aid of a β network[10]. In a dense radiosonde network such as the β network the mass flux through the three-dimensional boundary of the mesosystem as well as the dynamics within the boundary could be investigated.

Acknowledgements

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The author is also indebted to Mr. Toshimitsu Ushijima for his helpful assistance in the preparation of the figures for this report.

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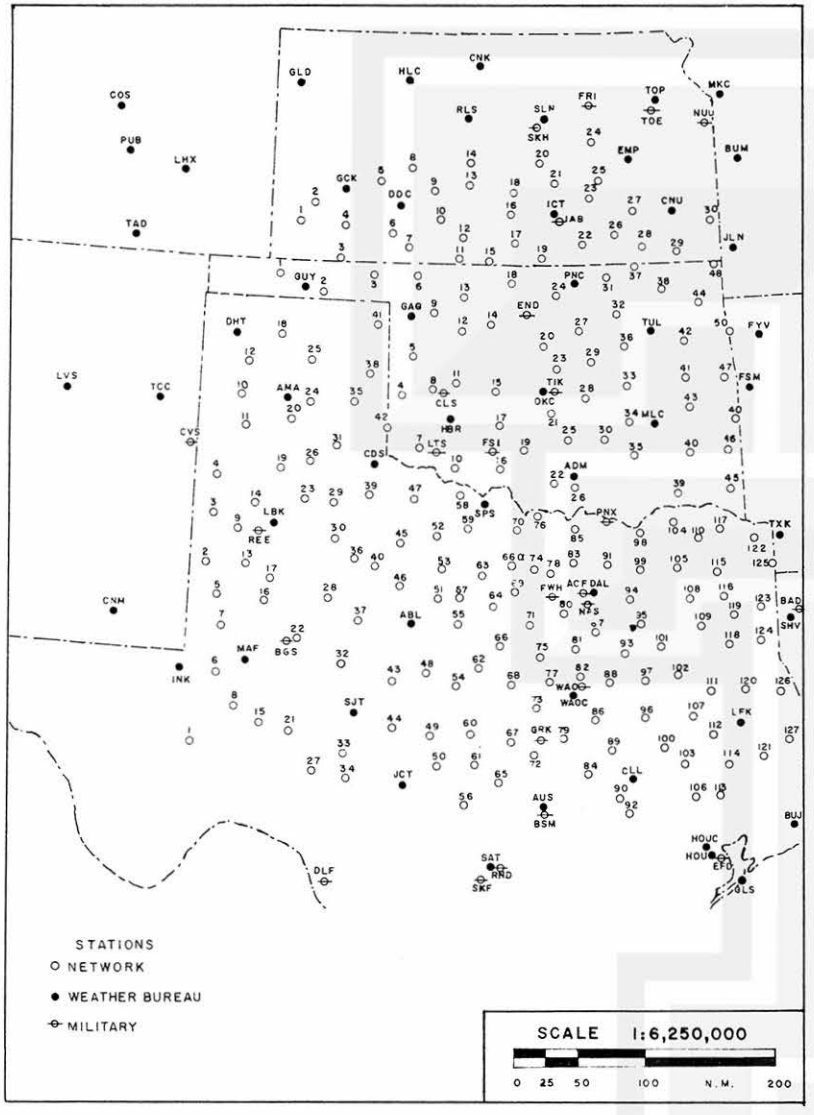

Fig. 1 Base map for pressure

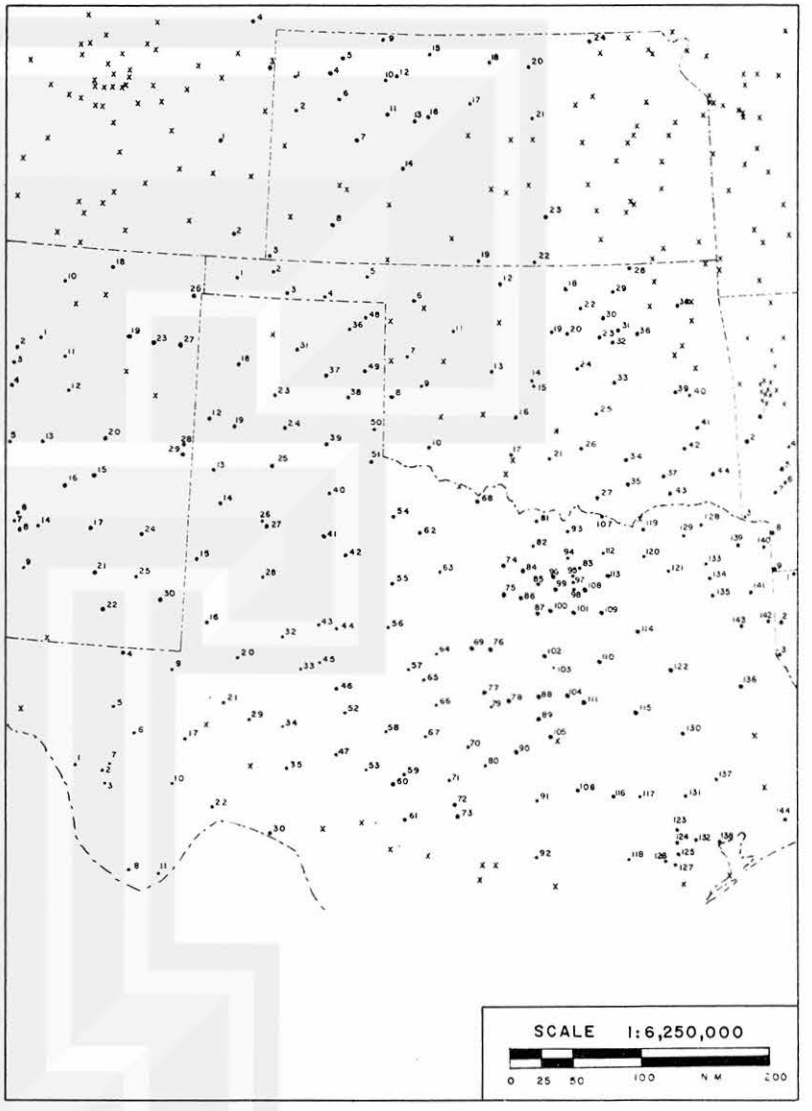

Fig. 2 Base map for precipitation

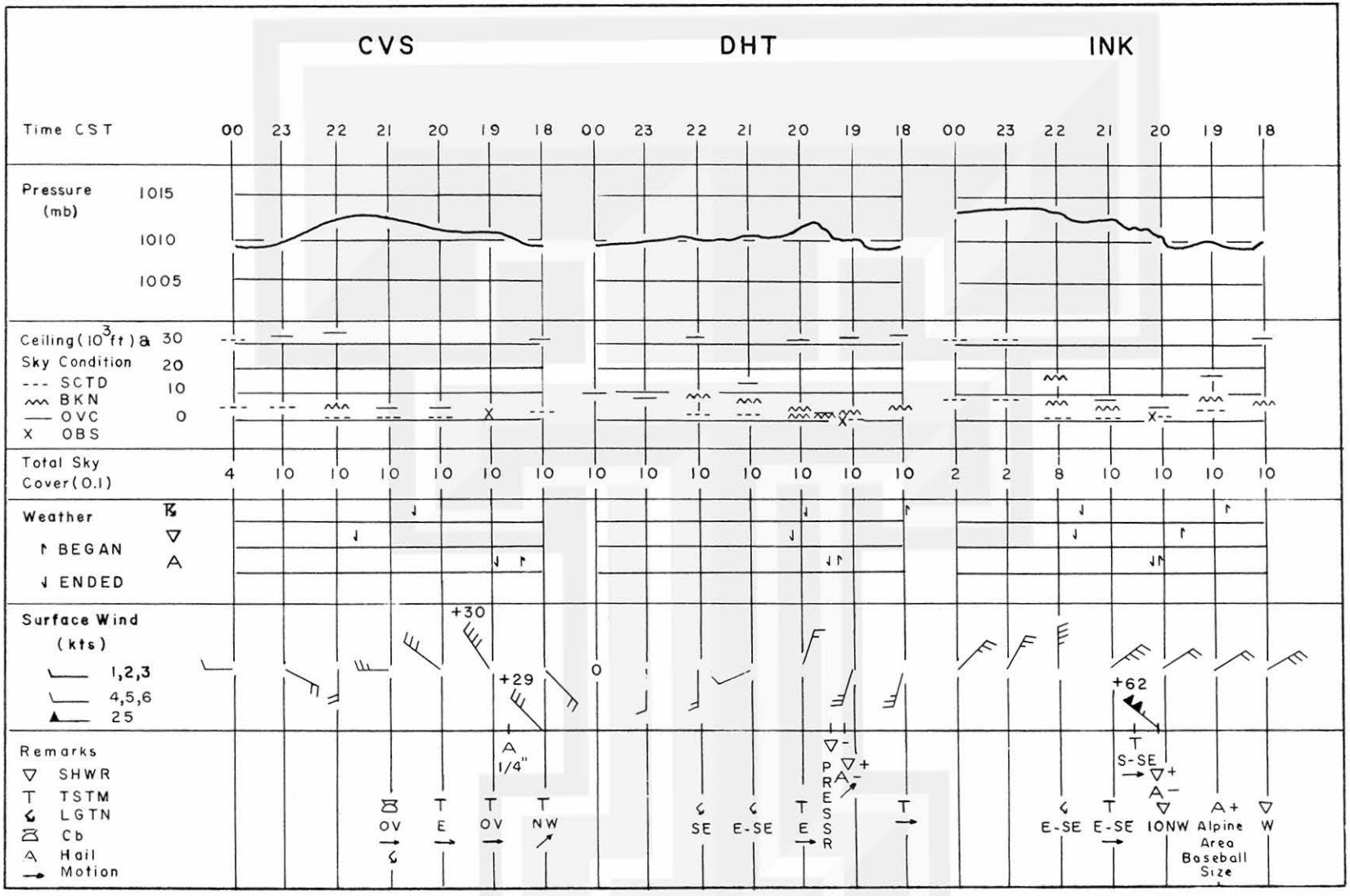

Fig. 3 Station data for Clovis, N. M.; Dalhart, Tex.; Wink, Tex.

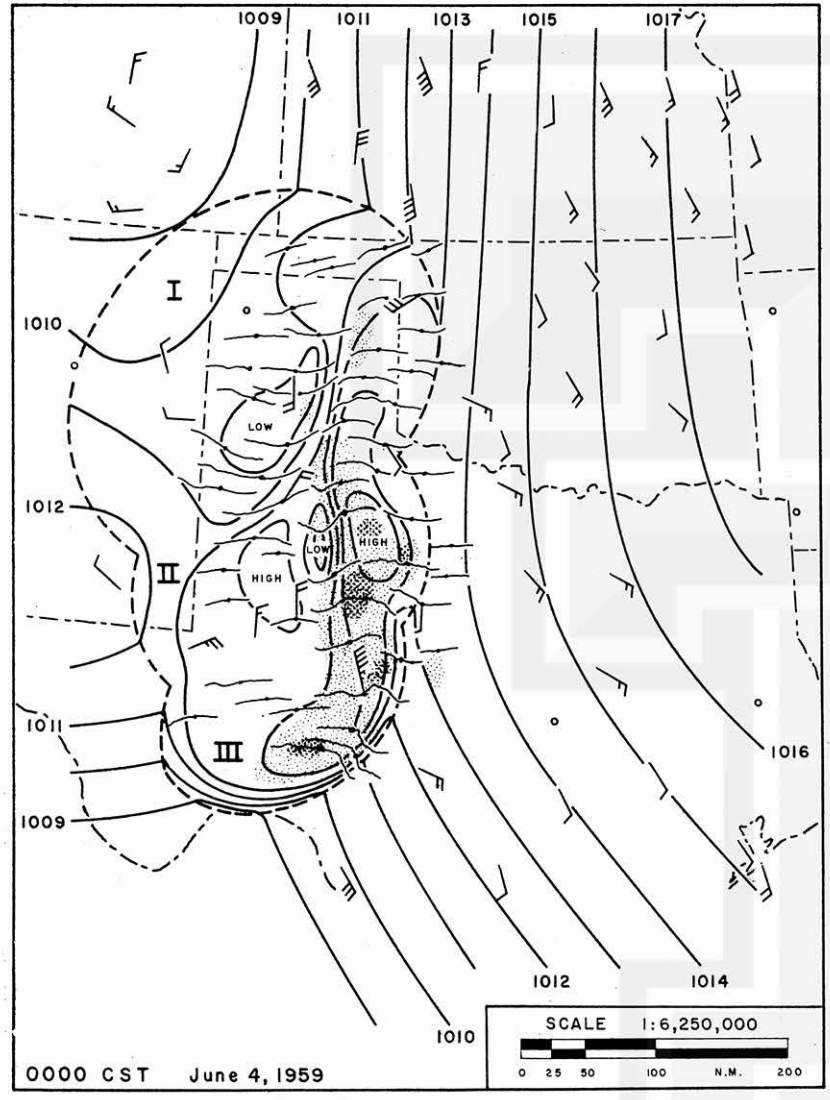

Fig. 4 Hourly mesoscale analysis

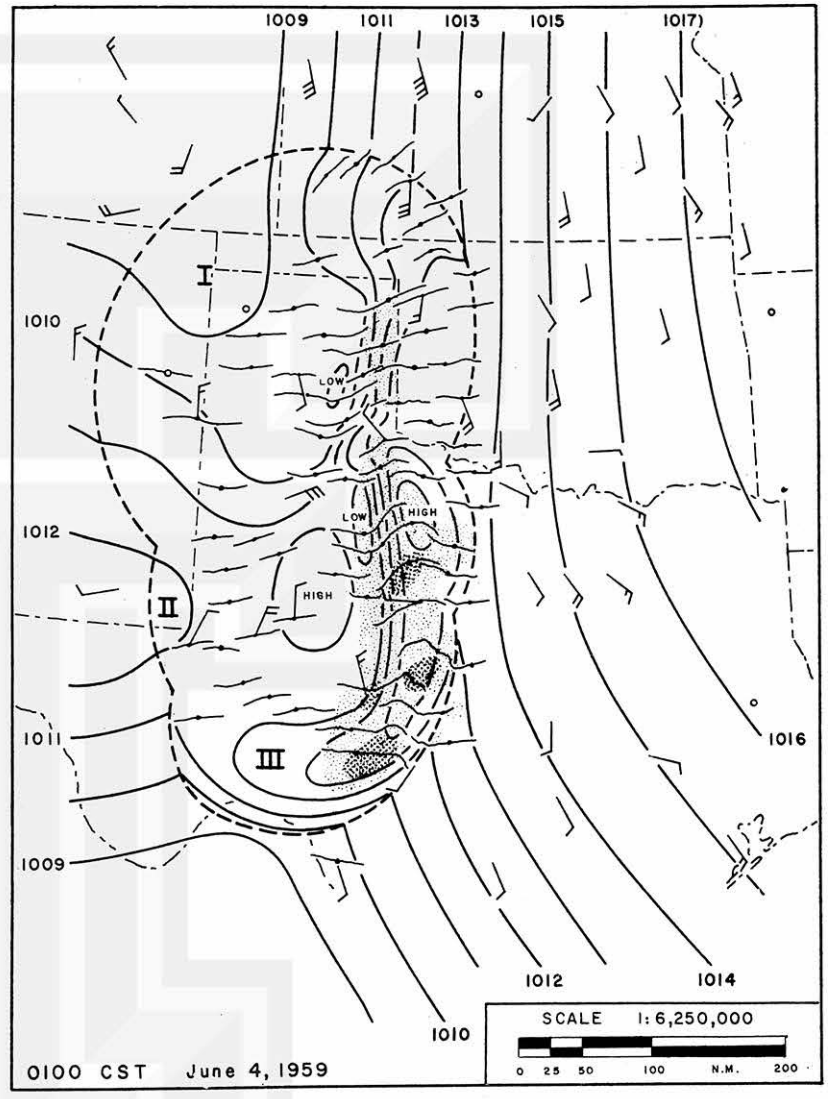

Fig. 5 Hourly mesoscale analysis

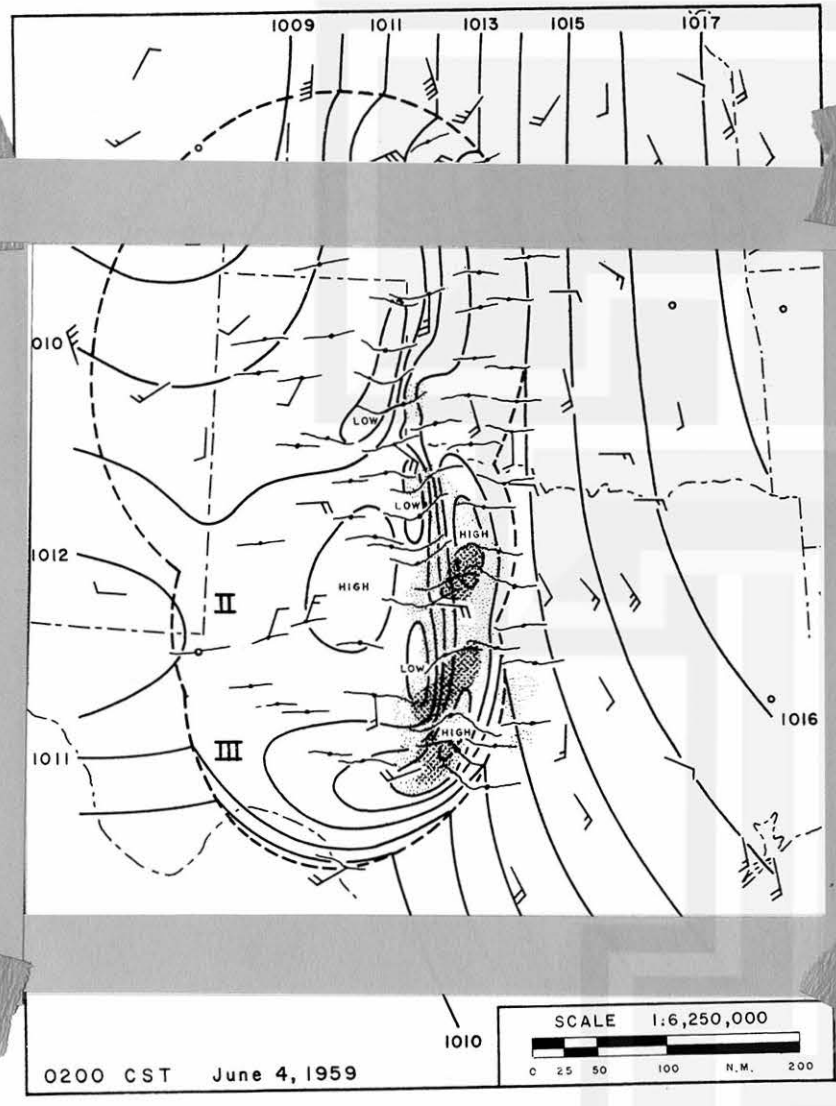

Fig. 6 Hourly mesoscale analysis

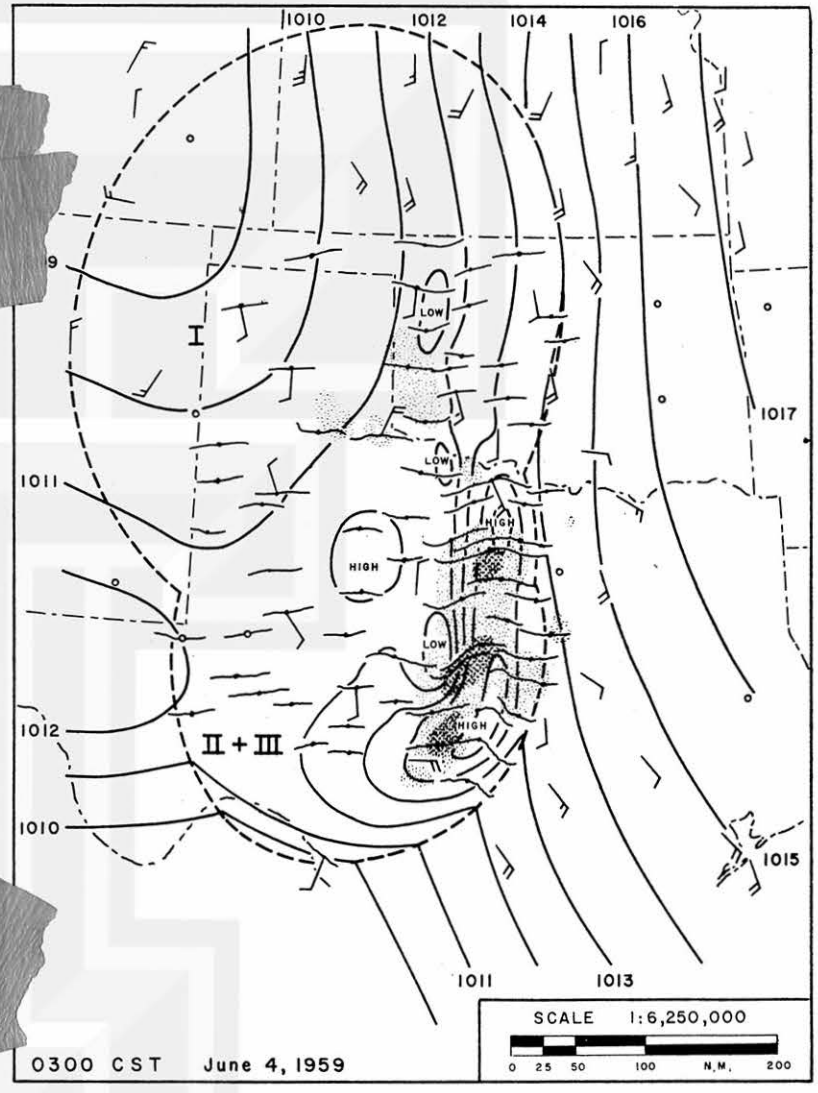

Fig. 7 Hourly mesoscale analysis

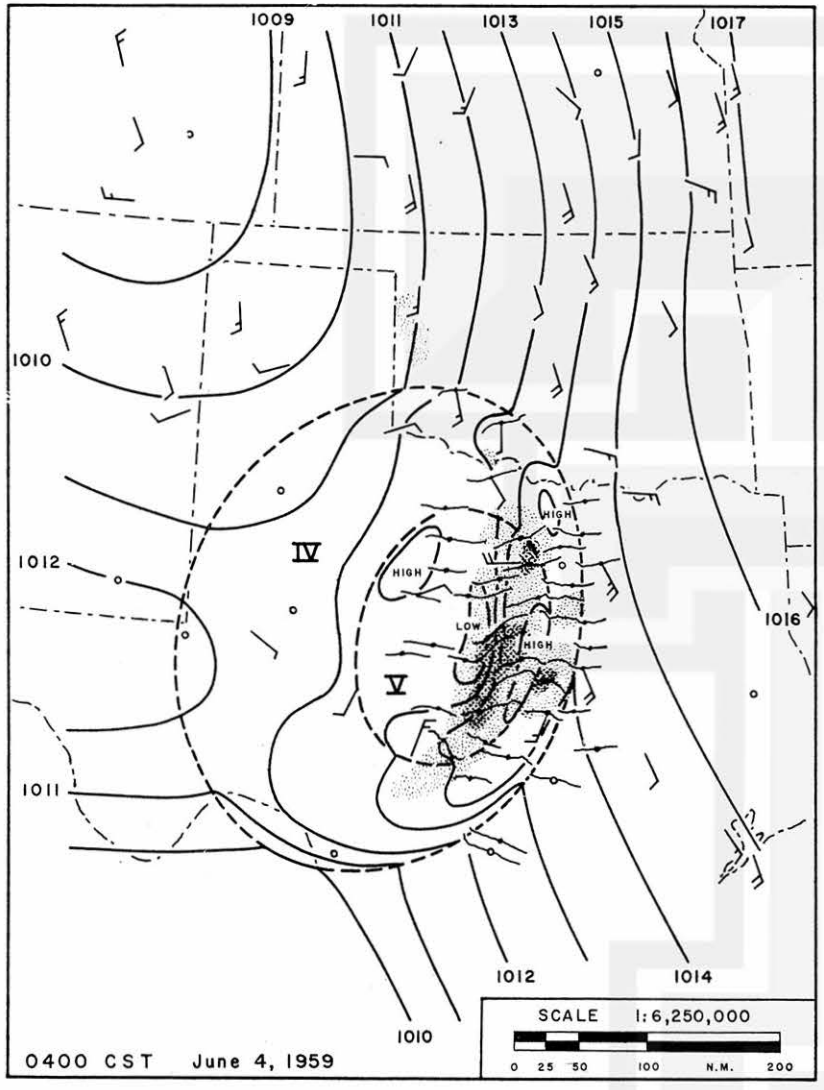

Fig. 8 Hourly mesoscale analysis

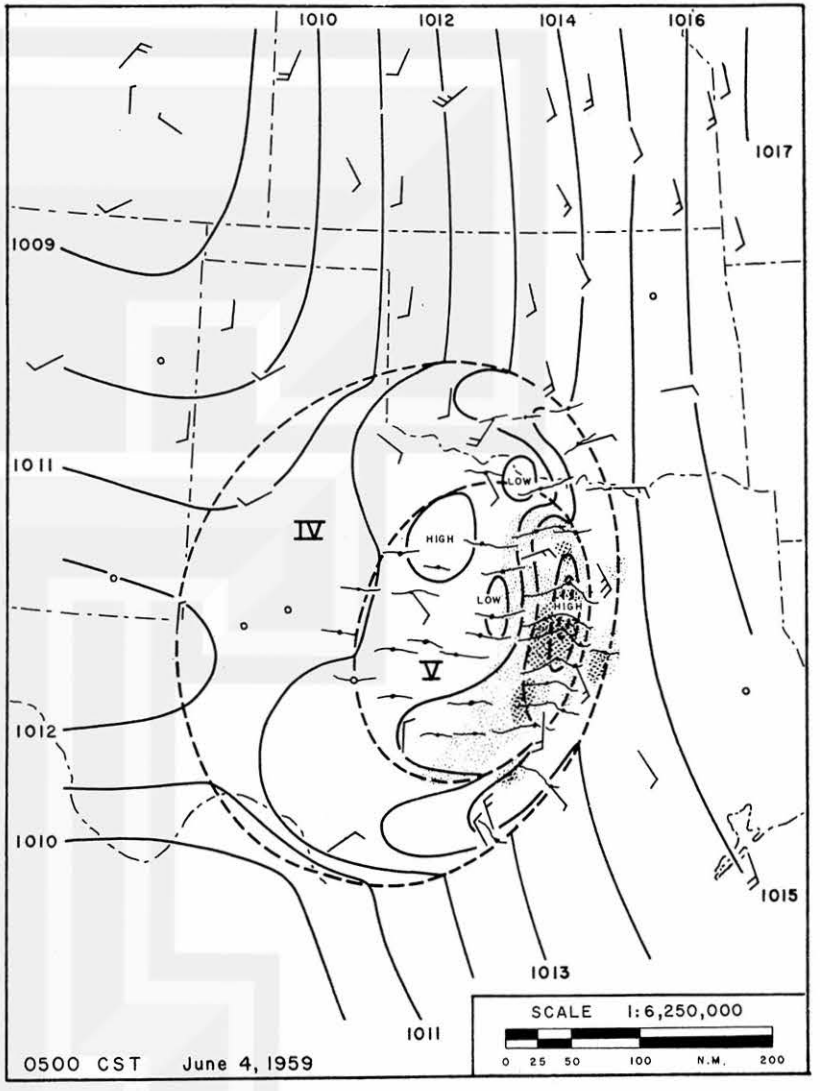

Fig. 9 Hourly mesoscale analysis

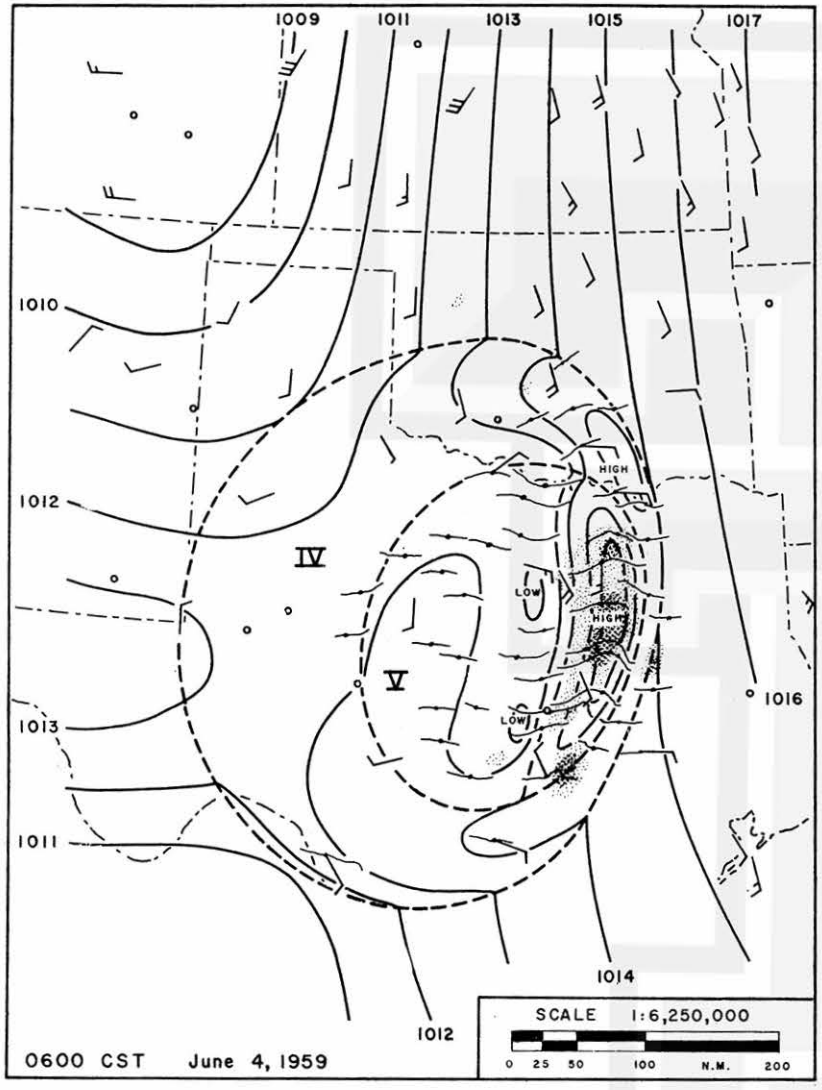

Fig. 10 Hourly mesoscale analysis

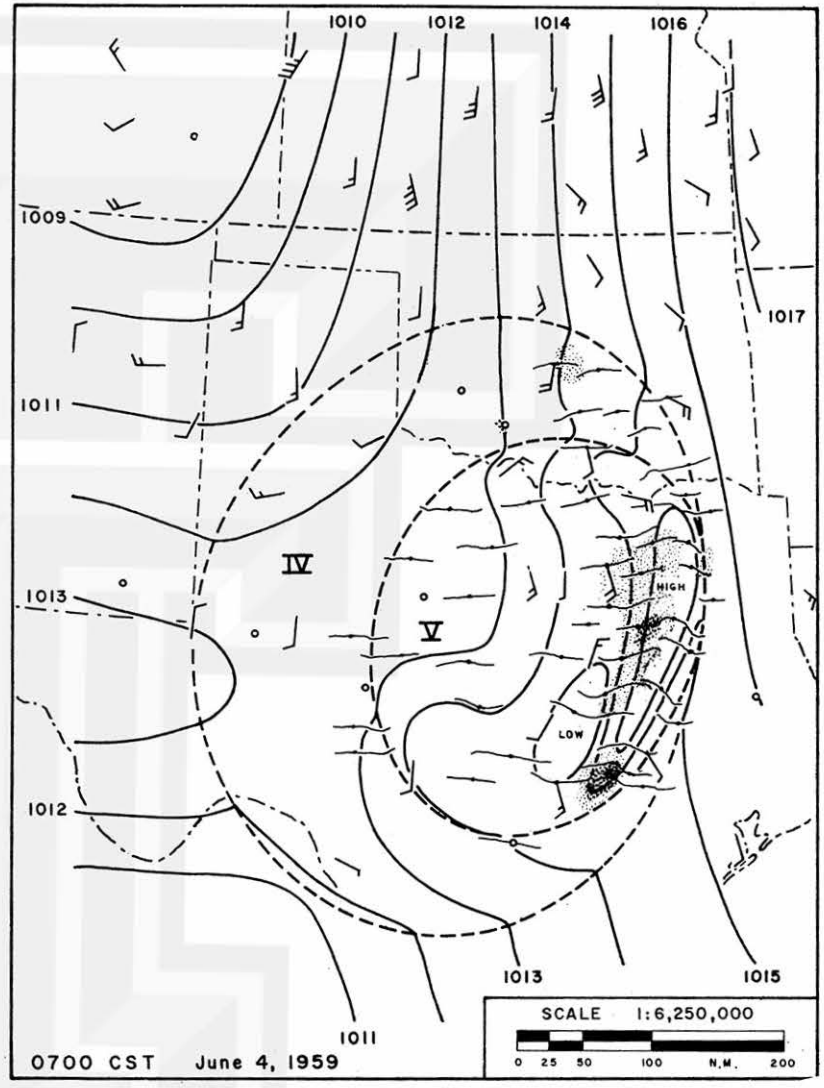

Fig. 11 Hourly mesoscale analysis

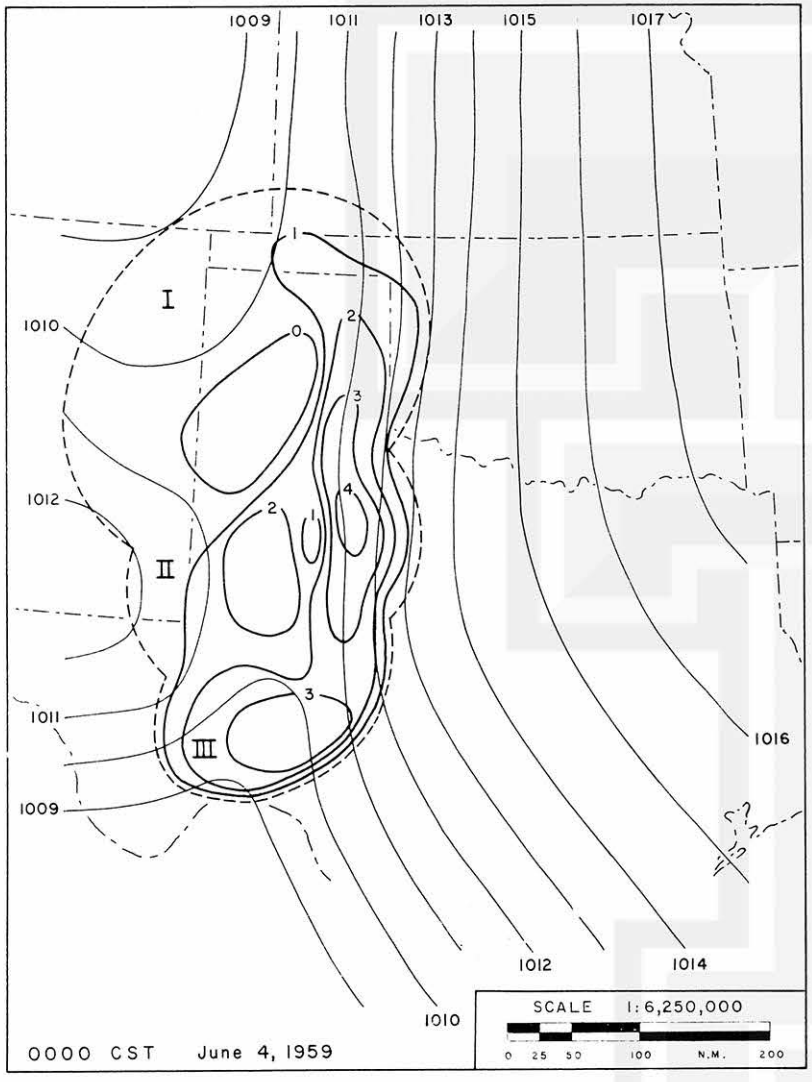

Fig. 12 Hourly excess pressure analysis

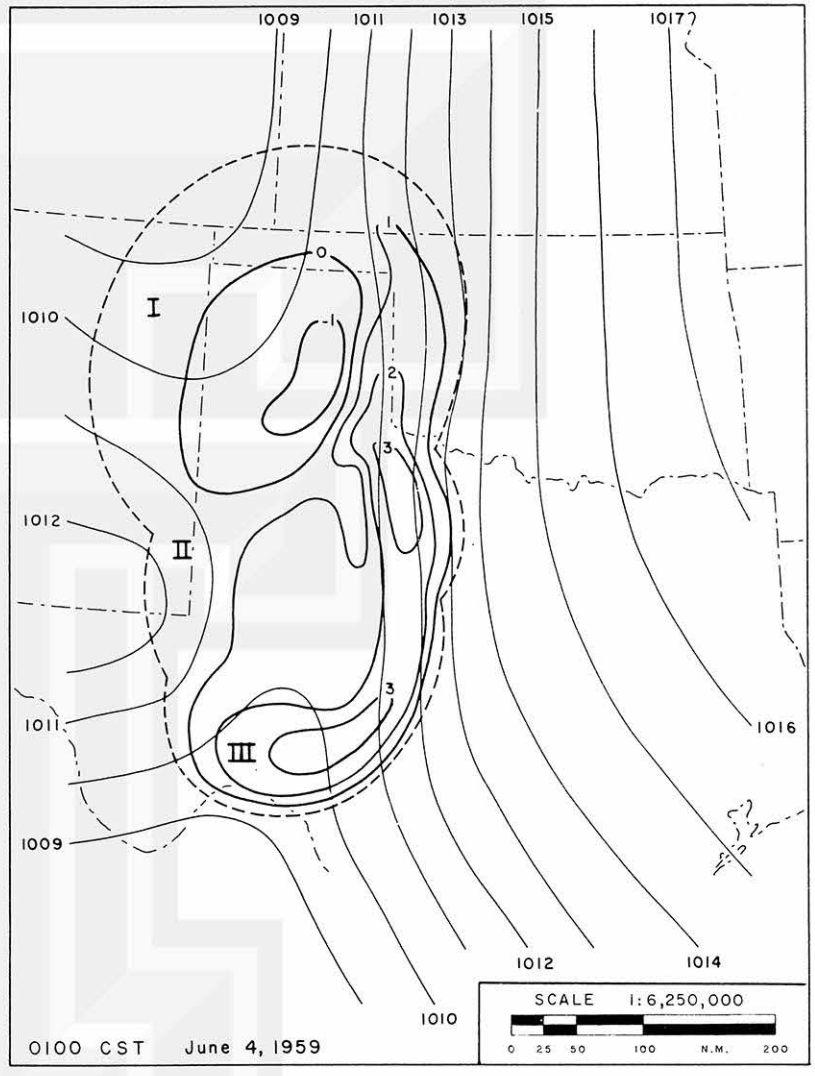

Fig. 13 Hourly excess pressure analysis

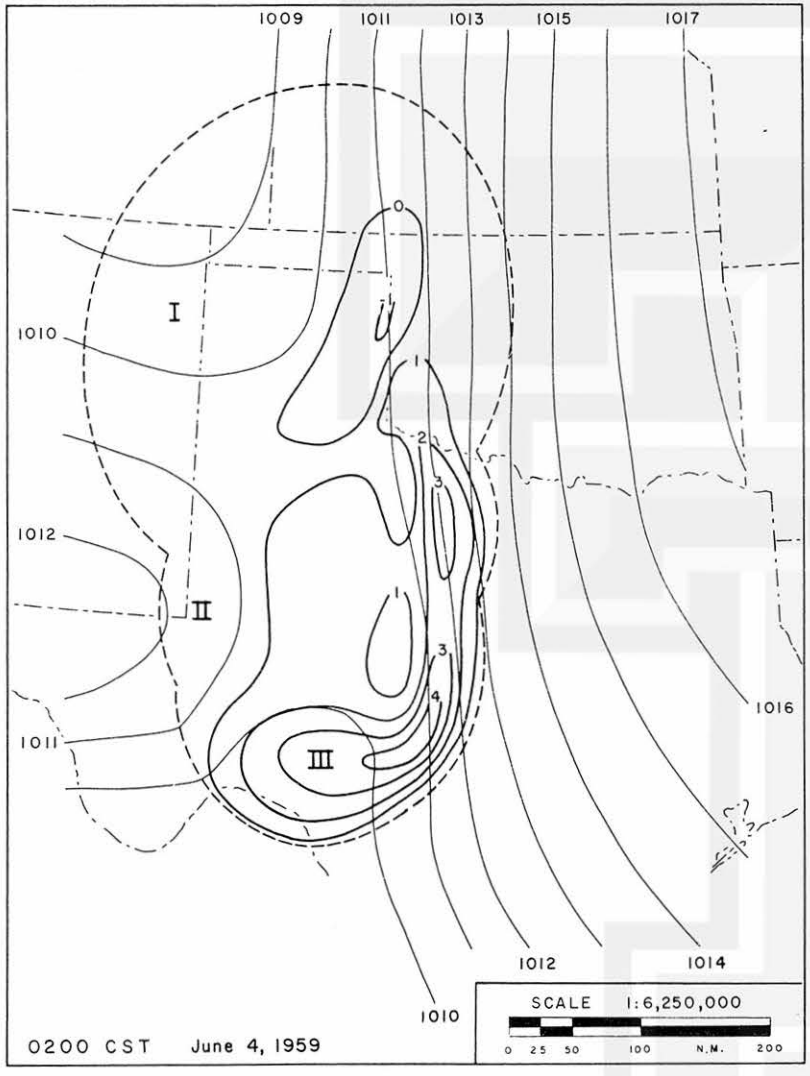

Fig. 14 Hourly excess pressure analysis

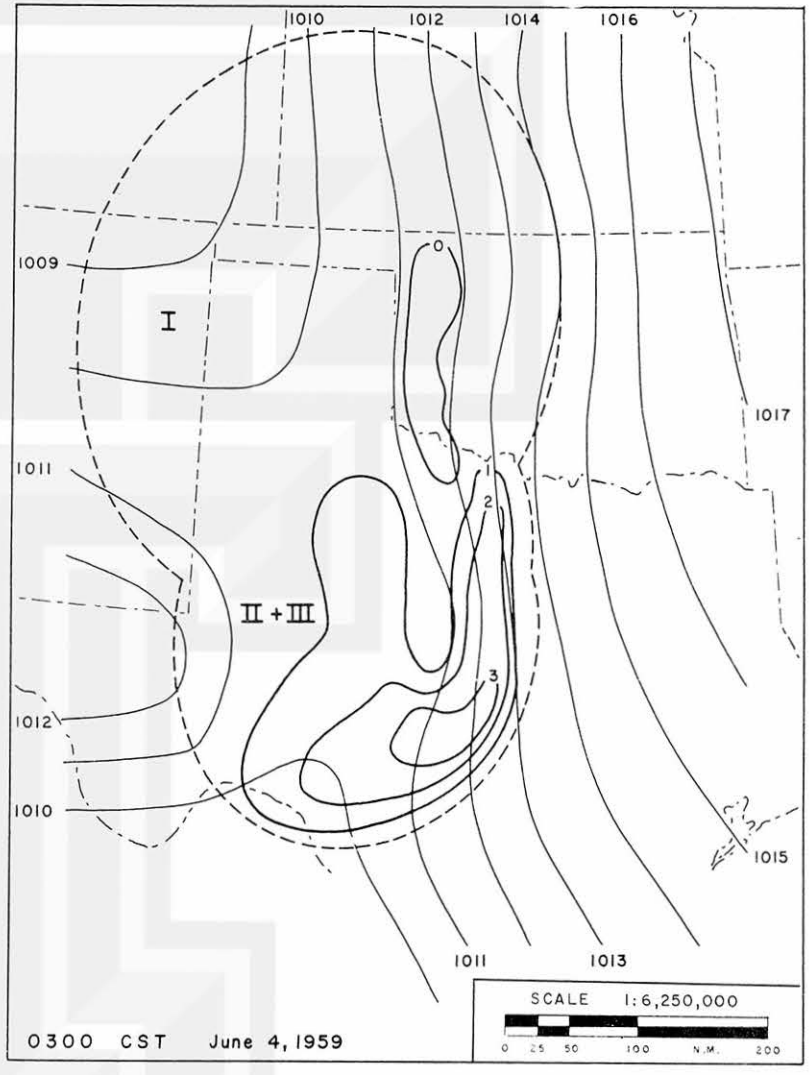

Fig. 15 Hourly excess pressure analysis

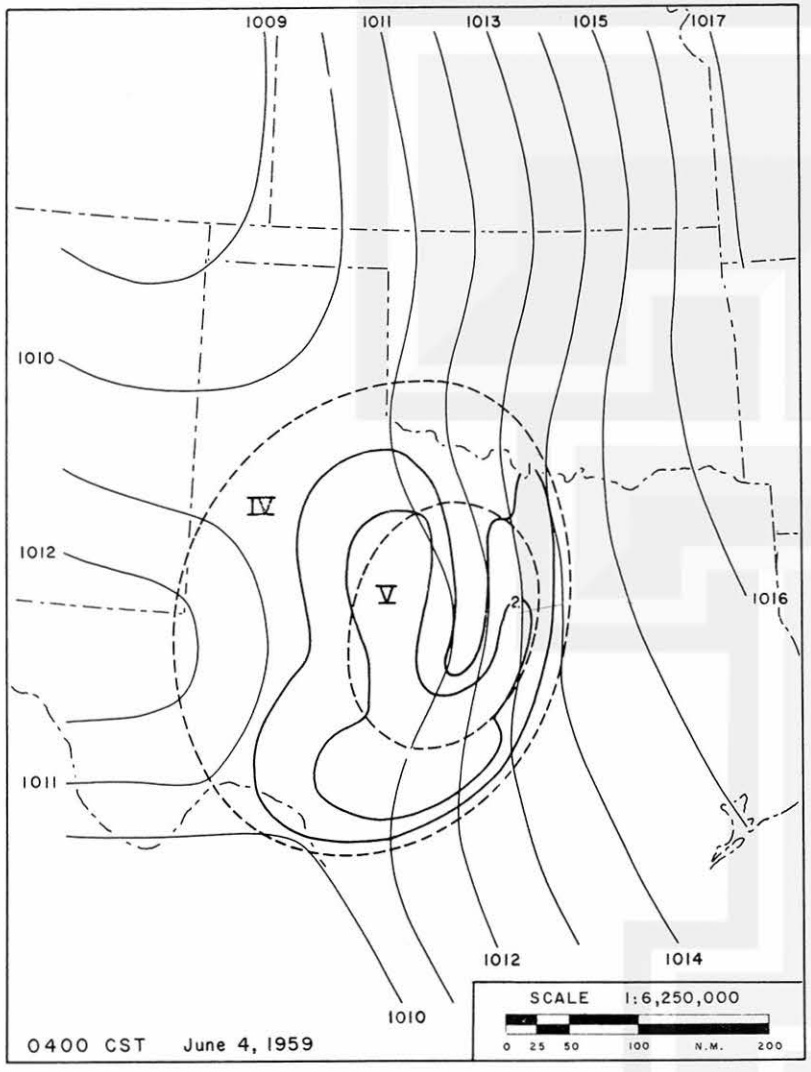

Fig. 16 Hourly excess pressure analysis

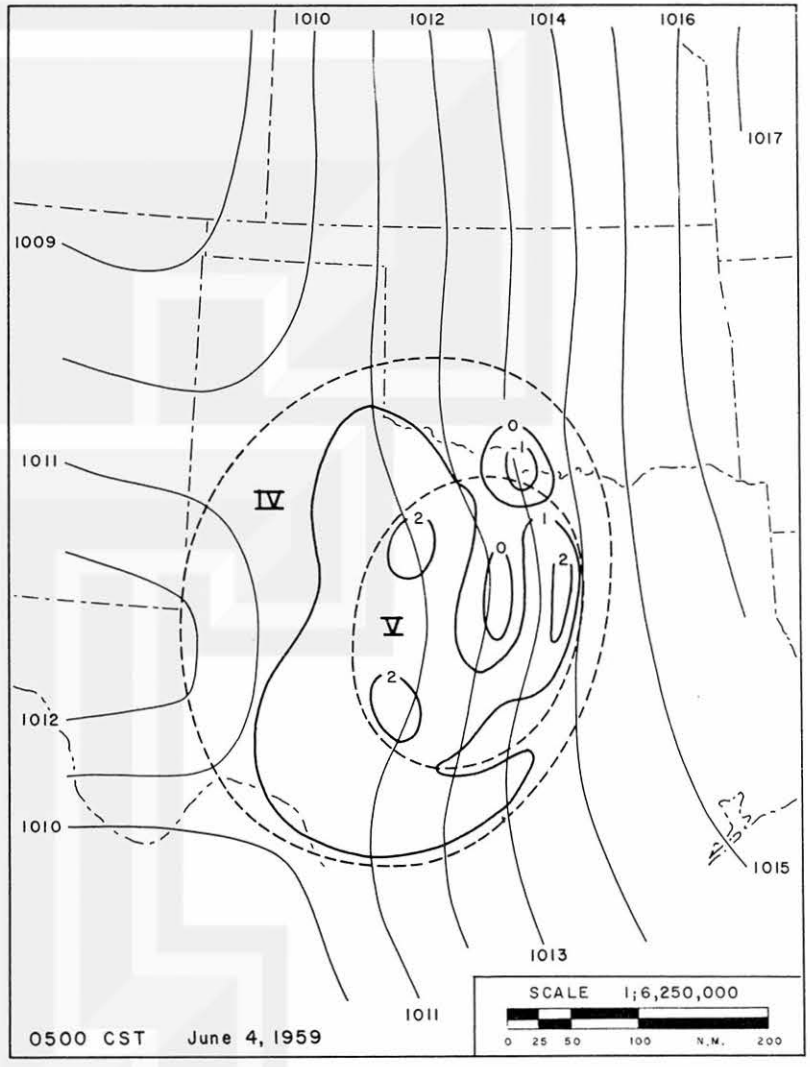

Fig. 17 Hourly excess pressure analysis

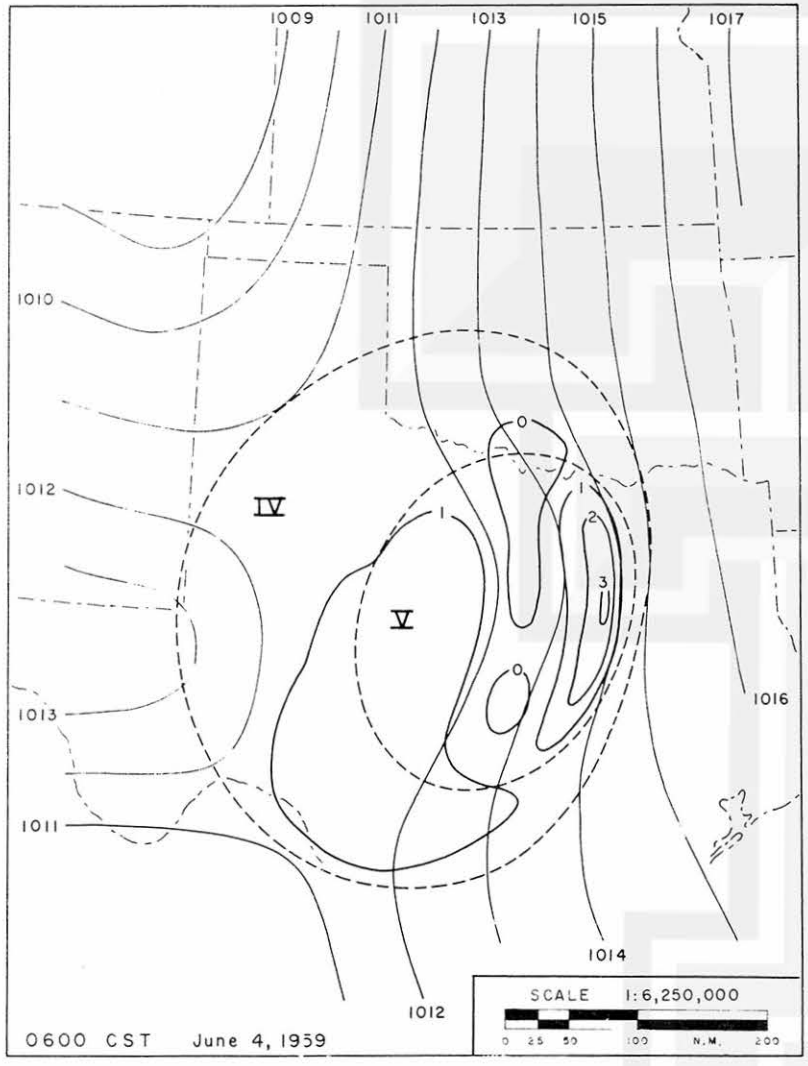

Fig. 18 Hourly excess pressure analysis

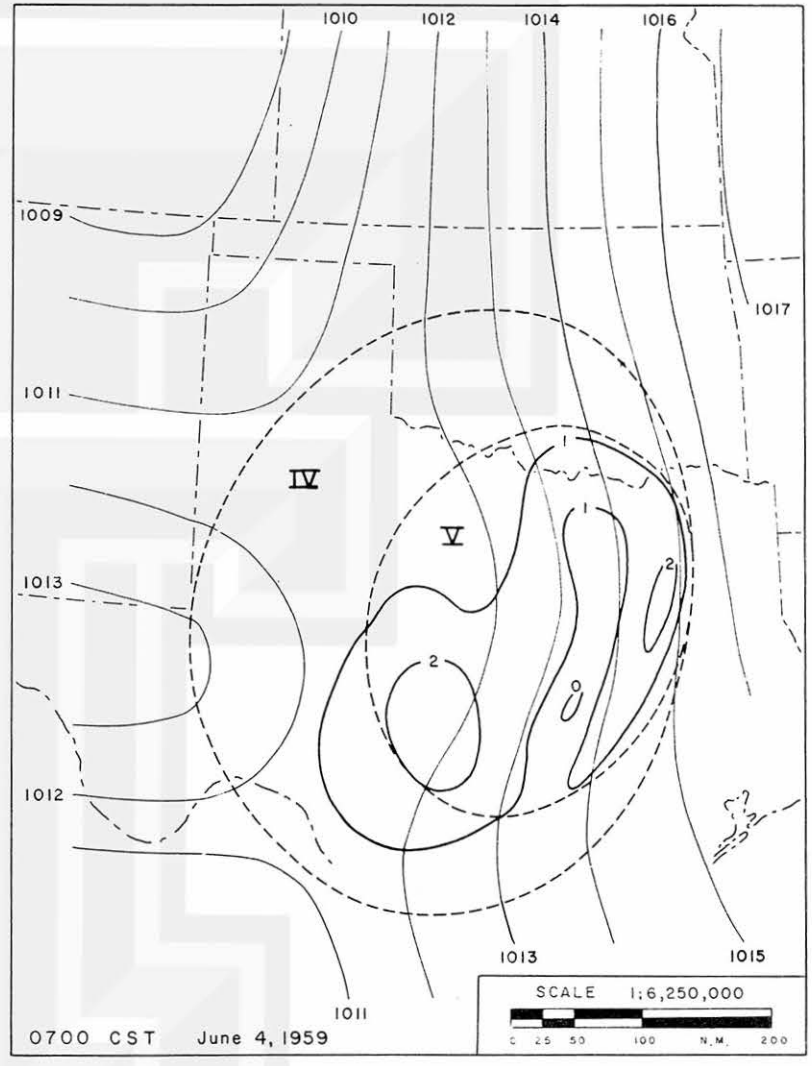

Fig. 19 Hourly excess pressure analysis

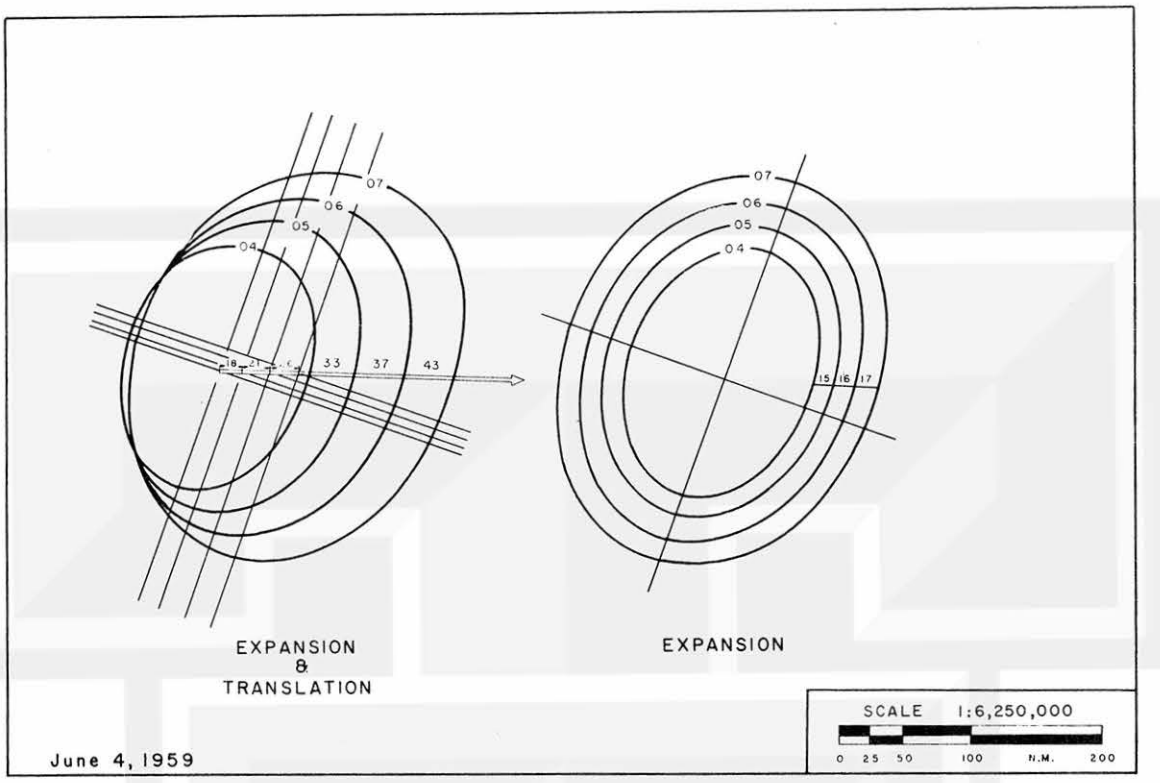

Fig. 20 Expansion and translation of system V

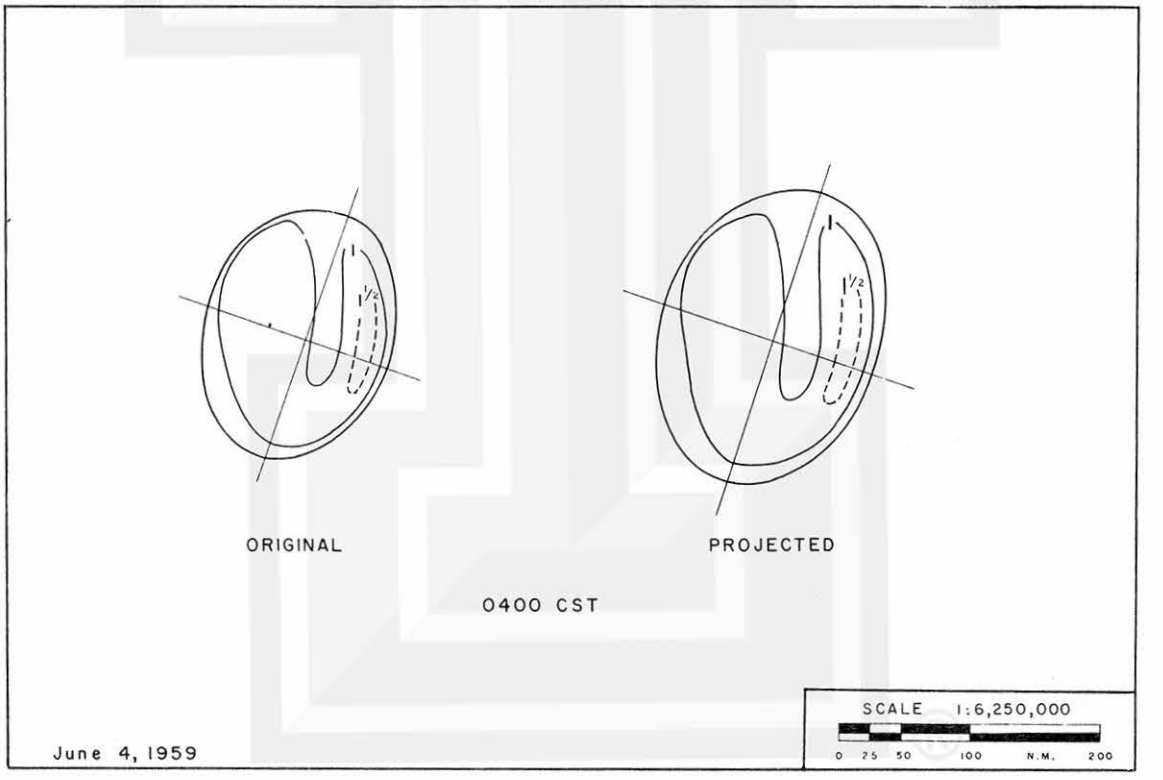

Fig. 21 Excess pressure and areal expansion of system V at 0400 CST

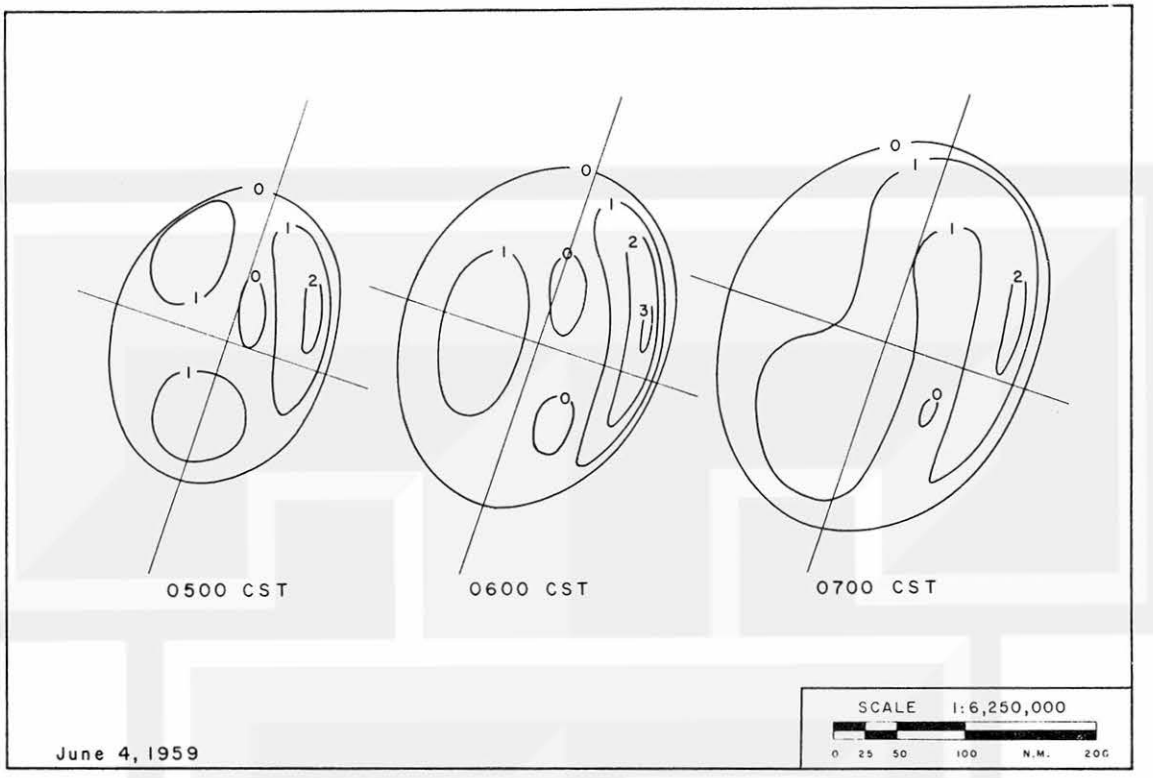

Fig. 22 Excess pressure of system V

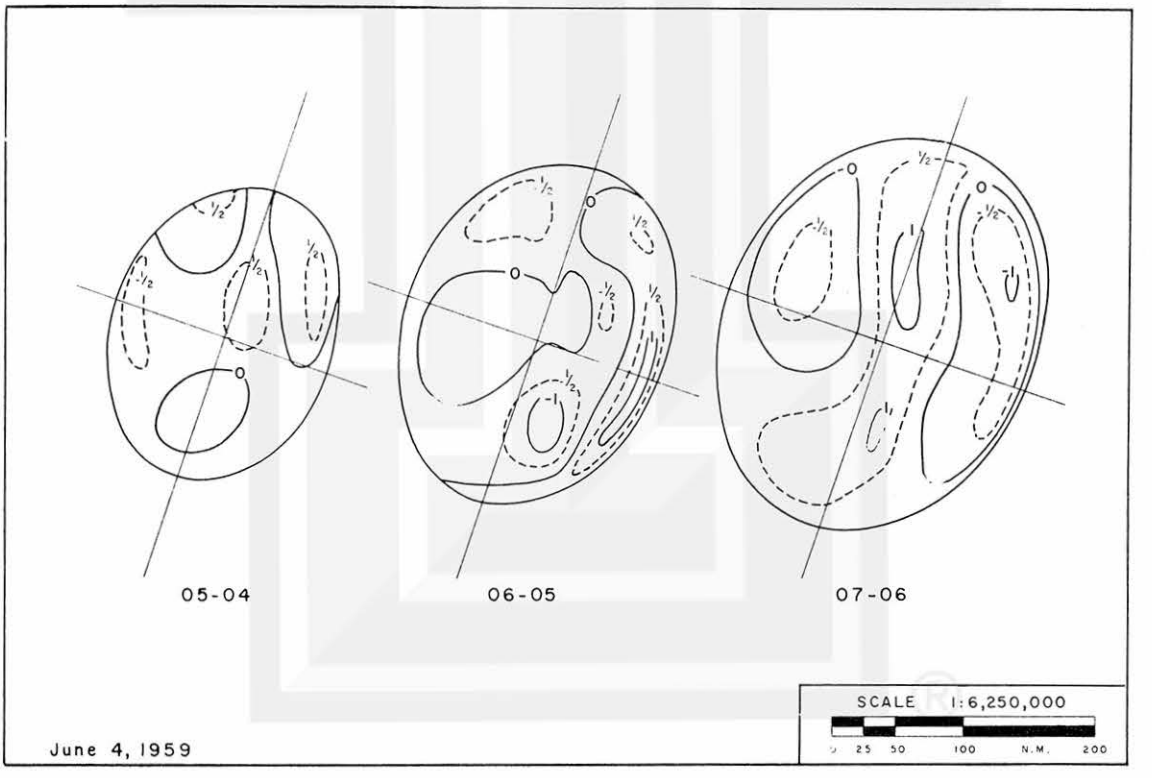

Fig. 23 Hourly change in excess pressure of system V

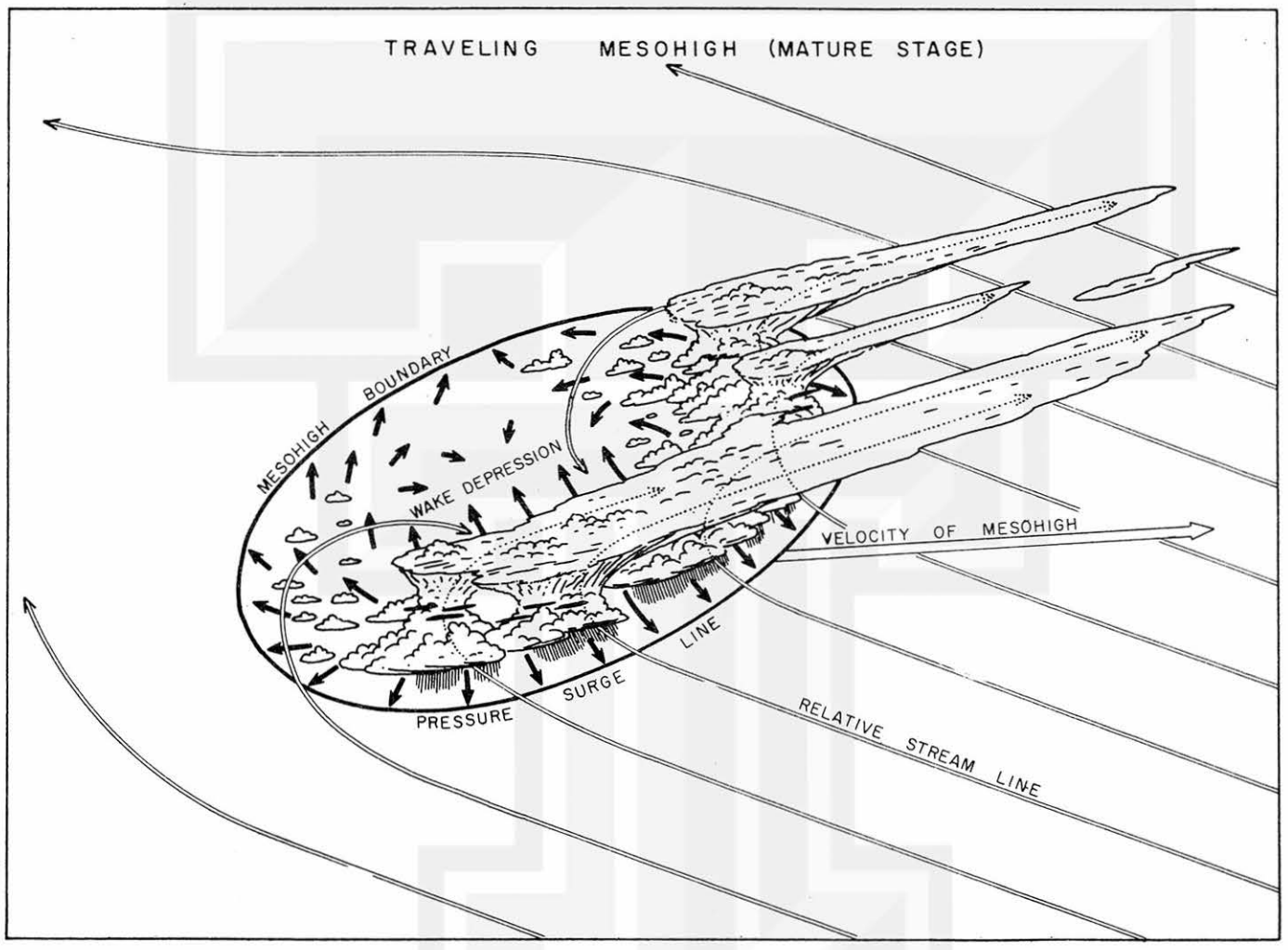

Fig. 24 Model of a traveling mesosystem (after Fujita[6])

MESOMETEOROLOGY PROJECT ----- RESEARCH PAPERS

1. Report on the Chicago Tornado, by Rodger A. Brown and Tetsuya Fujita

2. Index to the NSSP Network, by Tetsuya Fujita

3. Outline of a Technique for Precise Rectification of Satellite Cloud Photographs, by Tetsuya Fujita

4. Horizontal Structure of Mountain Winds, by Henry A. Brown