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Western Region Synoptic Analysis - Problems and Methods

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WESTERN REGION SYNOPTIC ANALYSIS-PROBLEMS AND METHODS

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WESTERN REGION
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WESTERN REGION SYNOPTIC ANALYSIS-PROBLEMS AND METHODS

I. INTRODUCTION

With increasing use of centralized computer products, interest in synoptic analysis has noticeably waned at many field stations in the Western Region. This is especially true with regard to frontal analysis. Although computerized maps do not show fronts as such, there is still a definite need for carrying fronts on surface charts. This is especially true for short-range, detailed forecasts of 1 - 18 hours, which are an integral part of our Western Region small-scale program. Sharp discontinuities in weather elements associated with significant cold fronts must be carefully analyzed and accurately predicted in order to make useful short-range forecasts.

NMC, of course, still produces man-made frontal analyses on surface synoptic charts. However, it has been found by many Western Region forecasters that refinement of facsimile surface frontal analyses west of the Rockies is frequently necessary. These modifications are required because of two general problem areas:

1. Failure of the classical Norwegian frontal model in many cases to adequately portray the synoptic situation as it exists in western United States. This model, originally developed during the first World War, was applicable mainly to the eastern Atlantic Ocean and western Europe. The classic model, especially with regard to warm fronts and occlusions, fails in many respects to fit observed conditions over the western United States.

2. Failure of the fax analysis to consistently show continuity of surface fronts across the rugged terrain of the Western Region.

It is rare indeed that analysts can follow an occluding wave cyclone over the plateau, or even a true warm front. Occlusions moving into the western plateau usually assume characteristics of cold fronts, and the analysis of cold fronts themselves is subject to limitations. A later section of this study will discuss in detail another method of analysis to deal with this problem.

One of the principal difficulties with frontal analyses over western United States is the failure to move cold fronts along with the surface gradient, or, more precisely, with the speed of low-level winds in the cold air-mass normal to the front. Certainly, one of the most fundamental concepts of frontal analysis is good continuity, and analysts should strive to follow this principle.

II. TERRAIN PROBLEMS

Basically, the reason for moving fronts too slowly is lack of obvious surface indications of frontal passages. Lack of indications is, of course, due mostly to local terrain (Figure 1). Drainage winds are especially troublesome in this respect. At locations like Boise and Salt Lake City, which have strong nocturnal southeast drainage winds, correct placement of cold fronts on 0600Z and 1200Z maps is often difficult if surface data alone are considered. Readers are referred to [1] for a description of local effects on synoptic weather patterns, and an example of drainage wind effects on passage of a cold front at Salt Lake City.

Fronts are often held stationary or moved too slowly over the Columbia Basin of eastern Washington and the lower Colorado River Valley in southeastern California and western Arizona (Figure 1) where lee troughs form with strong westerly flow. Continuity is poor as the front is later jumped ahead into the correct position.

The same problem also occurs in the Snake River Valley of eastern Idaho, where channeling of low-level winds obscures frontal passages (Figure 2). A close watch must be kept on hourly reports in these areas for brief showers, temporary wind shifts, and pressure rises as indicators of frontal passages. Note in Figure 3 that wind and weather shortly after a typical frontal passage in southeastern Idaho are nearly the same as before the passage.

In addition to surface indications, a further check on frontal positions can be made by association with short-wave troughs as shown on upper-air charts, preferably at the 500-mb level. Cold fronts in western United States usually lie in the area of positive vorticity advection ahead of a short-wave trough, and frequently lie between the 10 and 12×10^{-5} per second vorticity isopleths, as shown in Figure 4. Cold fronts in locations that do not fit this concept reasonably well should be scrutinized closely as to possible mislocation.

Another problem that arises with frontal positions is difficulty in timing of fronts arriving on the Pacific Coast. Maximum use of satellite pictures, both visual mode and infrared, should be made to help determine frontal locations in the eastern Pacific in order to avoid this type of analysis error (see Figure 5 for example).

III. USE OF RADAR IN ANALYSES

Composites prepared from several radar systems, available on National Fax, are a definite aid in synoptic scale frontal analyses. With the advent of Salt Lake City, Albuquerque, Auburn, and Palmdale ARTC radar capabilities for weather purposes, plus Sacramento, Medford, and Missoula WSR-57 radars (Figure 6), it is now usually possible to pinpoint frontal locations in western United States rather well when there is sufficient moisture present for precipitation and echo formation. For example, the echo extending from southern Montana to northern Utah (Figure 7) is obviously helpful in locating a cold front. One difficulty, of course, is the fact that many cold fronts are dry; and when moisture is present, precipitation tends to persist along windward slopes of mountains and be absent along leeward slopes--even with the front itself. This can, of course, lead to a false impression with regard to the frontal location. In Figures 8a and 8b, a band of precipitation detected by Sacramento radar is associated with a cold front as it moves across California. However, as the front moves east of the Sierra Nevada (Figures 8c and 8d), the precipitation band remains over the mountains, with little or no precipitation accompanying the front.

IV. SUMMER ANALYSIS PROBLEMS

There are some physical conditions operating in the Western Region that result in developments seldom observed in the rest of the United States. For example, the Pacific Ocean in spring and summer is a source region for a cool, moist air mass. The "Marine Push" described by Dickey and Larson [2] is one phenomenon resulting from the presence of this air mass. In this case, cool marine air dams up against the western slopes of the Cascade and/or coast range (Figure 9, top portion) and when the cool air attains a sufficient depth (lower portion of figure), along with development of a thermal trough over interior Oregon and Washington, it spills into coastal and interior valleys. Strong westerly winds and violent thunderstorms often accompany this marine push, which can be a true frontogenesis. An analysis of a marine push, prepared by the Fire-Weather Unit at Salem, Oregon, is shown in Figures 10a - 10d and is discussed below.

At 0600 PDT September 7, 1965 (Figure 10a), the surface map (isobars drawn at a 1-mb interval) shows a high over the interior of Oregon and Washington, with a trough along the immediate coast. The easterly flow has brought dry air to the coast range, Willamette Valley, and Oregon Cascades. At 1300 PDT (Figure 10b), the thermal trough has shifted eastward to the Willamette Valley. The flow on the coast is now light onshore. By 1900 PDT (Figure 10c), the thermal trough has intensified markedly and a strong push of marine air into the Willamette Valley and Puget Sound area is commencing. The thermal trough is also well developed over southeastern Washington.

By 0600 PDT September 8 (Figure 10d), the trough over southeastern Washington has intensified further, while the eastern lobe of the Pacific high has pushed into western Washington and western Oregon, where marine air now fills the valleys.

At 1300 PDT September 8 (Figure 10e), the thermal trough over eastern Washington is quite intense, and marine air is now pushing through the Columbia Gorge and spilling through passes in the Cascades. Temperatures in the Willamette Valley and Puget Sound area are about 10 degrees cooler than on the previous afternoon. At this stage, frontogenesis can be introduced in the trough east of the Cascades.

In the above case, the marine push appeared to have been triggered by a weak short-wave trough moving from Alaska southeastward across British Columbia. The 500-mb charts (not shown) also had a slow-moving trough extending from western Montana to central California, with a strong ridge over the Gulf of Alaska. More often, however, the marine push coincides with arrival of a weak front moving into coastal Washington and Oregon from the eastern Pacific Ocean. In these situations, continuity should be maintained on the front. An example of such a synoptic situation will be given later. To a lesser extent, and more on the mesoscale, "marine pushes" are also observed in coastal California. However, here the air aloft is sufficiently dry so that thunderstorms usually do not develop and, also, the cool marine air fails to cross the Sierra Nevada. Thus, the phenomena have more the characteristics of a strong sea breeze, and a cold front is usually not carried on the analysis. For other small-scale analysis examples, see [3].

Fronts moving through the Pacific Northwest in summer frequently cause analysts considerable difficulty. This is due to the normally strong thickness gradient that exists between the plateau and the northwest coast. Figure 11 shows normal 850-mb isotherms for July. From southern Nevada to the northwestern tip of Washington, there is about an 18°C. temperature difference. It is obvious that there will be difficulty following a front through this thermal field; but there are some techniques that can be helpful, and these are demonstrated in the example for June 26 - 28, 1967.

The surface chart for 1200Z June 26 is shown in Figure 12. Plotted data are taken from the NMC fax chart. The normal isobaric pattern is present with a ridge off the California and Oregon coasts and a trough over the plateau. The fax analysis carried no fronts near the West Coast, nor did the previous 0000Z and 0600Z charts. Continuous rain reported on Vancouver Island, however, indicates a frontal system is probably approaching the coast. This rain commenced during the past 6 hours.

The 500-mb vorticity chart for the same time (Figure 13) shows a short-wave trough near 132° W. with significant PVA into the British Columbia and Washington coasts as shown by the stippling. A short-wave trough as pronounced as this is usually a good indicator that a surface front is either present or soon likely to develop at a distance equal to about 5° latitude east of the short-wave trough. This would indicate a likely position for the front near 125 W., or just off the coast at 1200Z. Thus it is important to critically examine the vorticity chart even during summer.

The 850-mb chart for 1200Z on the 26th (Figure 14) shows the normal isotherm concentration between the plateau and northwest coast with a 9°C. temperature difference between Boise and Quillayute, Washington. This gradient can be compared with the normal gradient (Figure 11). The 850-mb chart shows this summer temperature gradient better than the 1000 - 500-mb thickness lines, as much of the thermal contrast is concentrated in the lower layers due to marine influences. However, in winter when there are strong inversions near the surface over the plateau region, either the 1000 - 500-mb thickness lines or 700-mb isotherms are better for delineating the thermal field over western United States.

Six hours later, at 1800Z June 26 (Figure 15), rain has spread southward onto the Washington coast. Pressures are rising west of the Cascades and falling to the east. The thermal discontinuity across the mountains is sharp, with temperatures in the 80s to the east and 50s and 60s to the west. There is a pronounced thermal low over eastern Washington. The front should be placed as shown in the figure. The fax analysis did not indicate this front.

By 0000Z June 27 (Figure 16), continuity is good, with the frontal zone now located over eastern Washington and central Oregon. Since the normal 3-hour pressure change at this time is a fall of 1 to 1-1/2 mbs, the front can be placed ahead of some stations with falling pressure. The fax charts still carried no surface front. The thermal trough extends from southeastern Washington through southwestern Idaho to northwestern Utah. The ridge is building into the northwest coast.

The 500-mb barotropic vorticity chart for 0000Z on the 27th, Figure 17, shows the short-wave trough located over western Washington and western Oregon. This position agrees quite well with the position indicated for the front on the surface map, that is, approximately 5 degrees west of the frontal position.

At 850 mbs (Figure 18) isotherms are very strongly packed northwest of the front. There has been a marked increase in packing over Oregon and Washington during the 24-hour span, with a 19°C. temperature difference between Boise and Quillayute, compared to only 9 degrees 24 hours earlier. Note the contrast as compared with the normal temperature gradient (Figure 11). Twenty-four hour temperature changes have been entered above the 850-mb temperatures in order to show the cooling behind and warming ahead of the front.

By 0600Z June 27 (Figure 19), Boise reported .03 with a thundershower, and the front can be placed just to the east of this station. The front is well marked north of the Canadian border, but elsewhere it is difficult to place because of nocturnal effects. However, the front should be moved forward on the basis of continuity.

The 1200Z surface map (Figure 20) indicates a position for the front through eastern Idaho, where there had been showers with marked pressure rises; but placement elsewhere at this time of the morning (5 a.m. local time) is again difficult, and reliance must be placed principally on 850-mb contours and isotherms. The surface fax chart carried a trough near the indicated frontal position.

The 500-mb vorticity chart for 1200Z on the 27th is shown in Figure 21. A position equivalent to 5 degrees of latitude ahead of the short-wave trough would agree well with the surface and 850-mb positions. On the latter chart (Figure 22), the front extends from western Montana through central Idaho to northeastern Nevada. Strong cold advection is indicated over the northern portion of the region.

The front can be followed a little better on the 1800Z surface chart (Figure 23) as the day progresses and observations become more representative. A wind shift at Lewistown (LWT), Montana, plus several showers and check tendencies, will help place the front. The front is also easily located on the map for 0000Z on the 28th (Figure 24). The fax analysis still did not carry the front at this time.

The 500-mb vorticity chart for 0000Z (Figure 25) shows that the short-wave trough has moved into Idaho and western Nevada. This strongly supports the frontal position determined from the 850 mb (Figure 26) and surface chart (Figure 24). When a relationship between an upper trough and surface front as good as demonstrated here can be established and maintained, the front should be indicated on the surface map.

At 850-mb (Figure 26) the wind at Salt Lake City shifted from southerly to northwesterly, although the 24-hour temperature change has not yet indicated cooling. Good cold advection is indicated behind the front, and Boise shows a 10-degree temperature drop in 24 hours.

At 0600Z (not shown) the front was located from near the Montana-Dakota border through eastern Wyoming to central Utah. Considerable shower and thunderstorm activity had developed back of the front. The fax analysis introduced the northern portion of the front at this time. By 1200Z the front had moved mostly out of the Western Region.

Maximum temperatures behind this front dropped 10 to 20 degrees as it moved across the northwestern states on June 26 - 28 (Figure 27). Locations of the cold front at 1800Z for June 26, 27, and 28 are indicated on the charts. Thus, the front was certainly worth picking up and carrying through the region as an aid to temperature forecasting.

Analysis problems such as described above occur frequently in summer. Other recent case histories have been documented in Western Region Technical Attachments 70-25 and 71-31. These are included in the appendixes for convenience. Comments were received from the field on #71-31 to the effect that examination of teletype sequence reports (not available in WRH at the time the Technical Attachment was prepared) indicated that the cold front was past Stampede Pass, Yakima, The Dalles, Bend, and Medford at 0000Z June 23 (Figure 1 in Technical Attachment).

This would give better continuity on movement of the front from Figure 1 to Figure 3.

V. AN EXAMPLE OF ANALYSIS PROBLEMS IN ARIZONA AND SOUTHERN CALIFORNIA

The next series of maps illustrate difficulties that frequently arise with frontal analyses over southern California and Arizona. With a strong westerly flow, there is a problem associated with the lee trough in the lower Colorado River Valley--analysts tend to hold fronts back instead of moving them along with the flow. Frontal passages are quite difficult to discern in this area. However, some guidelines can be provided which will assist in the analysis.

Figure 28 shows surface conditions at 0000Z April 10, 1967. The fax analysis showed a cold front extending from eastern Washington to northwestern California. However, very little precipitation is associated with the front. The 500-mb chart for the same time (Figure 29) shows a deep trough just off the Pacific Coast.

The surface map for 1200Z (Figure 30) shows considerable deepening over Nevada. The fax analysis had dropped the front; however, there is sufficient evidence to carry it on continuity. Precipitation is developing over the northern and western portions of the region. Note the trough extending southward from Nevada along the lower Colorado River Valley. Another trough is forming off the California coast.

Twelve hours later, at 0000Z on the 11th (Figure 31), the low is still present over Nevada with the trough extending southward to the Gulf of Baja, California. The fax analysis reintroduced the front on this map as a stationary front in this trough. However, continuity from intermediate maps for the past 12 hours would indicate the front to be much farther east. A trough in the isobars over northern Utah, along with a weak wind shift and difference in pressure tendencies in southern Idaho, determines the position for the front, which is indicated as weak and decreasing. The front cannot remain stationary in the indicated fax position because of the gradient. Rain is falling in northern and central California as the California trough deepens and moves southeastward.

The 500-mb chart for 0000Z (Figure 32) shows a short-wave trough over southern Nevada and southwestern Arizona. This trough supports the position of the cold front a little farther to the east, and suggests that the front may be worth carrying for a while longer. A closed low has formed over the northern California coast. This low has plunged south-southeastward in the past 12 hours, as shown by the arrow.

At 0900Z (Figure 33) the fax analysis still carried the front in the lee trough along the lower Colorado River. Continuity and weak surface indications again place remnants of the front much farther to the east, over western New Mexico and southwestern Colorado. The trough that was off the coast at 0000Z has moved inland over southern California and intensified. This trough line was carried by the fax analysis. Note the large area of precipitation over central and southern California associated with this trough.

At 1800Z (Figure 34) the fax analysis carried the front through central Utah and Arizona, whereas continuity would place it over central Colorado and New Mexico. The southern California trough has moved southeastward and intensified. Note the strong temperature contrast across the trough line. This trough was indicated on the fax analysis. However, this could now be considered cold frontogenesis, and has become the most important synoptic feature.

The ESSA satellite photo for approximately the same time (Figure 35) clearly shows the double frontal structure. There is a band of cloudiness across central New Mexico, extending down into old Mexico. This cloud band is associated with the easternmost dissipating front. Another solid bank of cloudiness extends from Nevada through southern California, thence southwestward over the ocean. This cloud band is associated with the intensifying westernmost cold front. The fax cold front is located in a clear area between the two cloud bands.

Six hours later, at 0000Z, April 12 (Figure 36), considerable cloudiness and some thundershowers are shown to be associated with remnants of the easternmost system, over eastern New Mexico and Texas Panhandle. Some substantial precipitation amounts were recorded in the six-hour period.

The westernmost system is now a strong cold front. Note the sharp wind shifts, strong temperature contrasts, and weather. The fax analysis carried the front over central Arizona, in nearly the same position as on the map six hours earlier. It is evident that the front was still west of Phoenix and Prescott at this time.

The final surface map of the series, for 0600Z April 21 (Figure 37), shows a strong cold front in eastern Arizona. The actual frontal position now coincides with the fax-analyzed position. Moderate-to-heavy snow is falling over northwestern Arizona, and snow was reported at Tucson within six hours after map time. Substantial amounts of precipitation fell in southern Arizona.

In summary, frontal analysis over the mountainous Western Region is often quite difficult. The above examples were shown not merely to fault previous errors in analysis, but rather to point out methods whereby future analyses may be improved.

VI. THE TROWAL

An analysis concept that has found some favor in Canada and northern sections of western United States is the trowal. This has been described by W. Godson [4, 5] of the Canadian Meteorological Service, and also by Jacobson and Rozett [6]. This section is based on the Jacobson-Rozett paper. Mr. Jacobson contributed materially to development of the original trowal concept.

The term "TROWAL" was introduced by the Canadian Meteorological Service in the late 1940s and is a contraction of "Trough of Warm Air Aloft". However, the concept was used in the Seattle FAWS Unit before 1945.

One of the reasons for introducing the Trowal concept was problems with the occluded front. Fundamentally, the occlusion process involves three air masses of differing densities (Figure 38). The density difference must be sufficient to establish and maintain a strong thickness or potential-temperature gradient on the cold air side of the frontal surfaces, as shown in the schematic diagrams of warm- and cold-type occlusions (Figures 39, 40). The dashed lines are 1000 - 500-mb thickness isopleths. Occlusions entering the West Coast in fall and winter tend to be the warm type, as the ocean is warmer than the land. In spring, cold-type occlusions predominate, as the water is colder than the land. Problems arise in synoptic practice when the required surface air-mass contrasts are absent, as in the so-called neutral occlusion (Figure 41). Whatever the origin of the system, the meteorologist is frequently faced with a cloud mass observable from both the surface and weather satellite that progresses across the terrain in as predictable a manner as a cold front, but without any significant surface temperature contrast. We are accustomed to calling these cloud systems neutral or indeterminate occlusions, yet these upper systems are sometimes followed within 200 - 300 miles by easily recognizable surface cold fronts. This double structure is shown by satellite photographs and tends to confuse meteorologists.

A common winter synoptic sequence appearing on surface analyses in the Pacific Northwest is the following (Figure 42): A warm-type occlusion moves onshore from the eastern Pacific, preceded by a cold front aloft; the warm occlusion is changed by the analyst to an indeterminate occlusion east of the Cascades, and the cold front aloft dropped. For a time, the surface frontal position as analyzed vacillates between the occlusion and the cold front aloft, finally being jumped ahead east of the Rockies into the surface trough as a cold front. This poor continuity leads to obvious difficulties in forecasting frontal weather.

VII. DEVELOPMENT OF THE TROWAL

A trowal is a symmetrical trough-shaped frontal surface aloft which slopes upward into the colder air northward along its longitudinal axis (Figure 43). Frontal positions at 500, 700, and 850 mbs projected onto a horizontal surface indicate the depth of cold air north of the wave. The locus of wave crests at the various upper levels, shown by the dashed line, marks the trowal. The upper portion of the figure shows a vertical cross-section along line AB of the lower portion. The trowal is located on the surface by the downward projection of the bottom of the trough of warm air. It is distinguished from warm, cold, or occluded fronts in that the frontal discontinuity does not have contact with the earth's surface. It differs from upper warm or cold fronts in its symmetry.

At this early stage (Figure 43), it is not useful to analyze the trowal as a separate entity. However, the trowal increases in length, height, and intensity in proportion to the growth of the surface wave (see Figure 44 for a well-developed trowal). At this and later stages of development, it is useful to analyze the trowal on synoptic charts.

Satellite pictures over ocean areas have indicated how a chain of events in wave development may lead to trowal formation. Cloudiness associated with positive vorticity advection has a typical "comma-shaped" appearance on satellite photos. As the comma cloud approaches a stable wave on a front, a so-called "instant" occlusion is formed. This is shown schematically in Figure 45 taken from [7]. The trowal would be indicated north of the wave in Figure 45D instead of the occlusion. An example of this development, also taken from [7], is shown in Figures 46 and 47. Figure 46 shows NMC surface analysis for 0000Z April 8, 1970, with a flat wave near 35° N 160° W. Twenty-four hours later, Figure 47, a well-developed occlusion is shown off the West Coast. The satellite pictures corresponding to these two charts are shown in Figures 48 and 49. They indicate that a comma cloud, associated with positive vorticity advection, overtook the wave on the front, leading to an apparent fully developed ("instant") occlusion. The situation at 2200Z April 8 could more appropriately be analyzed with a trowal northward from the wave crest through the thickness ridge.

On the surface chart the trowal is not very distinct. It may often be located by changes from large to lesser pressure falls, or even to small rises. Wind shifts are only temporary and temperature contrasts are usually lacking with the trowal passage.

VIII. TROWAL CLOUDS

The first indication of the approach of a trowal in the Pacific Northwest is an increasing shield of altostratus (Figure 50), although on some occasions cirrus may appear first, followed by altostratus at a lower level. The altostratus thickens as the pressure falls, and there may be some steady precipitation. As soon as the trowal passes, the middle cloudiness will move eastward and there may be a few brief showers behind the trowal.

Cloudiness characteristic of trowals is less prominent east of the Continental Divide in Montana, as only higher clouds are usually present, although, on occasion, sufficient precipitation may fall to give ceilings near 5,000 feet in the lower unstable air mass. The main feature of such a trowal passage may be some light precipitation and cloudiness which develop in the lower cold air.

If the structure is conspicuously asymetrical, it should not be analyzed as a trowal. When temperatures aloft are significantly warmer ahead of as compared to behind the warm-air tongue, the system should be analyzed as an upper cold front (Figure 51). Ahead of the front, steady pressure falls and continuous light precipitation may be noted; behind the upper front, small rises and showers. A reversal of temperatures relative to the warm tongue would produce an upper warm front (Figure 52) with large pressure falls and steady precipitation ahead of the front, and with smaller falls and intermittent precipitation behind the front.

On adiabatic charts, trowals appear as frontal inversions, i.e., humidity is high in and above the inversion (Figure 53). These inversions are normally above the 700-mb level. The air mass above the inversion is usually convectively unstable. When viewed on thickness charts, the trowal appears as a moving ridge of warmer temperatures (Figure 54).

Cold air behind cold fronts entering the Pacific Northwest coastal area may occasionally be too shallow to cross the Cascades. Such cases are usually associated with frontal waves having a frequency of less than 24 hours. When rapidly moving fronts do cross the mountains, the trowal becomes and continues to be the most important feature east of the Cascades and Rockies. Strongest surface winds along the eastern slopes of the Rockies usually occur ahead of the cold front and near the position of the trowal.

A north-south trowal can trigger waves on already existing surface fronts which are oriented in an east-west direction, as well as initiate the southward movement of Arctic or Canadian cold fronts (Figure 55). These cold fronts generally move southward east of the Divide after the trowal has passed. Occasionally Arctic fronts will move southward into Montana before the trowal arrives; in this case, Arctic fronts are generally less intense and plunge southward for a shorter distance than average, since they later move eastward under the influence of the trowal.

A trowal approaching a deepening lee trough may lose its symmetry and become an upper cold front. In that case the unstable characteristics of an upper cold front are taken on by the trowal.

IX. SYNOPTIC EXAMPLES OF TROWAL ANALYSIS

One of the best methods of analyzing and following continuity of trowals is by means of cross sections. Forecasters at Great Falls

WSFO followed this procedure for many years. An example of an analysis of a trowal moving across the Pacific Northwest in early December 1967, analyzed at Great Falls, is given in Figures 56 to 63. Fax continuity on a surface occlusion during this period was not consistent (see Figure 56). Times of frontal passage at Spokane (GEG) and Walla Walla (ALW) and a Canadian station are shown. Note the big jump from 1800Z to 2100Z.

On the cross section from Quillayute to Bismarck for 0000Z December 2 (Figure 57), a trowal is shown near the coast. The warmest air aloft, as shown by potential temperature isotherms (isentropes, solid lines) was near or just inside the coast. On cross sections such as these, the axis of the trowal is usually nearly vertical. When westerly winds increase rapidly with height, the trowal may tilt slightly toward the east with increasing elevation. The surface fax analysis at this time (Figure 58) showed an occluded front near the coast.

The fax analysis at 1200Z December 2 (Figure 59) showed an occlusion through central Washington. On the cross section for this time (Figure 60), the trowal is located between Spokane and Great Falls. Note that the field of potential temperature is nearly symmetrical about the vertical axis, with isentropes almost parallel to the frontal surface. (Due to factors such as radiosonde temperature errors, there are small time and space variations in potential temperature along the trowal.) Cold air domes on either side of the trowal are of similar height. Except at low levels, warming will take place over a station until the trowal passes; and cooling thereafter. Considering the cross section and the APT satellite picture for 1800Z (Figure 61), it would have been better to indicate a cold front in central Washington and a trowal over western Montana and Idaho on the surface analysis.

By 0000Z December 3 (Figure 62), the trowal is near Glasgow, Montana. At this time, the fax analysis (Figure 63A), jumped the occlusion from a position in eastern Washington to a position much farther east and close to the trowal position (Figure 63B). The trowal was becoming the more important discontinuity; a perhaps better analysis would have been to carry both trowal and cold front eastward, dissipating the cold front over northern Idaho about 0000Z, as indicated in Figure 63B.

A more recent example of a synoptic situation that could be analyzed with a trowal occurred on January 5 - 7, 1972. The thickness ridge near 135°W in Figure 64 for 1200Z January 5 moved inland to Alberta and western Montana by 0000Z January 6 (Figure 65). The front on the fax analysis was moved more slowly to British Columbia and appeared to have little relationship to the thickness lines. A trowal (heavily-dashed line) could be carried in the thickness ridge, moving to near the Montana-Dakota border by 1200Z January 6 (Figure 66), where the trowal is weakening. Another trowal is entering the West Coast on this chart and has moved into British Columbia and Alberta by 0000Z January 7 (Figure 67). Note that on these charts the cold front has been drawn nearly perpendicular to the thickness lines. A trowal analysis would be preferred in this case.

A final example is shown for November 3 - 4, 1971 (Figures 68 - 70). The fax frontal analysis was quite complicated and lacked continuity over the northwest--a trowal analysis would have been simpler and would also explain adequately the weather that occurred. It would have been better to indicate a trowal (dashed line) in the moving thickness ridge on all three charts, with a cold front following the trowal on Figures 69 and 70, in the approximate position shown by the fax analysis over Washington and Oregon. Cloudy skies and scattered light snow were reported over eastern Washington, northern Idaho, and Montana, well ahead of the fax-analyzed surface frontal position.

X. CONCLUSION

The trowal is presented as an analysis concept that has proved useful to explain the sequence of weather events in the Pacific Northwest under certain conditions. Forecasters at WSFOs in the northwestern portion of the Western Region are encouraged to try analyzing the trowal on either locally prepared maps or facsimile charts, in order to ascertain usefulness of this concept for forecasting in their areas of responsibility.

XI. REFERENCES

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[2] DICKEY, W. W., and L. B. LARSON. The Marine Push. Unpublished manuscript, 1964.

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[4] GODSON, W. L. The Structure of North American Weather Systems. Centenary Proceedings, Royal Meteorological Society, 1950.

[5] GODSON, W. L. The Synoptic Properties of Frontal Surfaces. QJRMS 77:633 - 653 (1951).

[6] JACOBSON, ARTHUR, and ARTHUR ROZETT, JR. The Trowal. Unpuplished manuscript, National Weather Service Forecast Office, Great Falls, Montana, August 1969.

[7] Western Region Technical Attachment No. 70-19, Satellite Pictures versus Models, May 19, 1970.

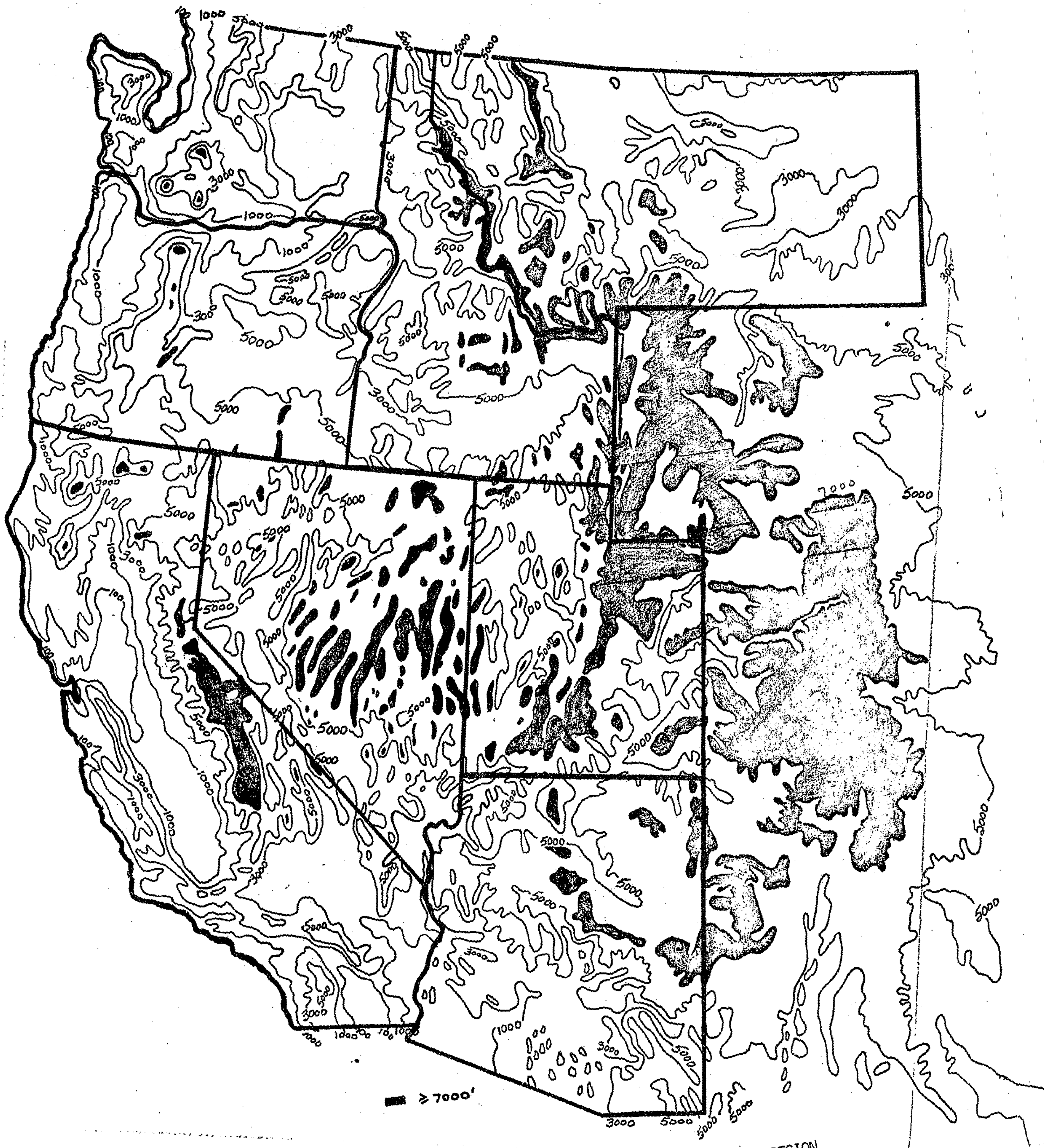


FIGURE 1. TOPOGRAPHY OF WESTERN REGION.

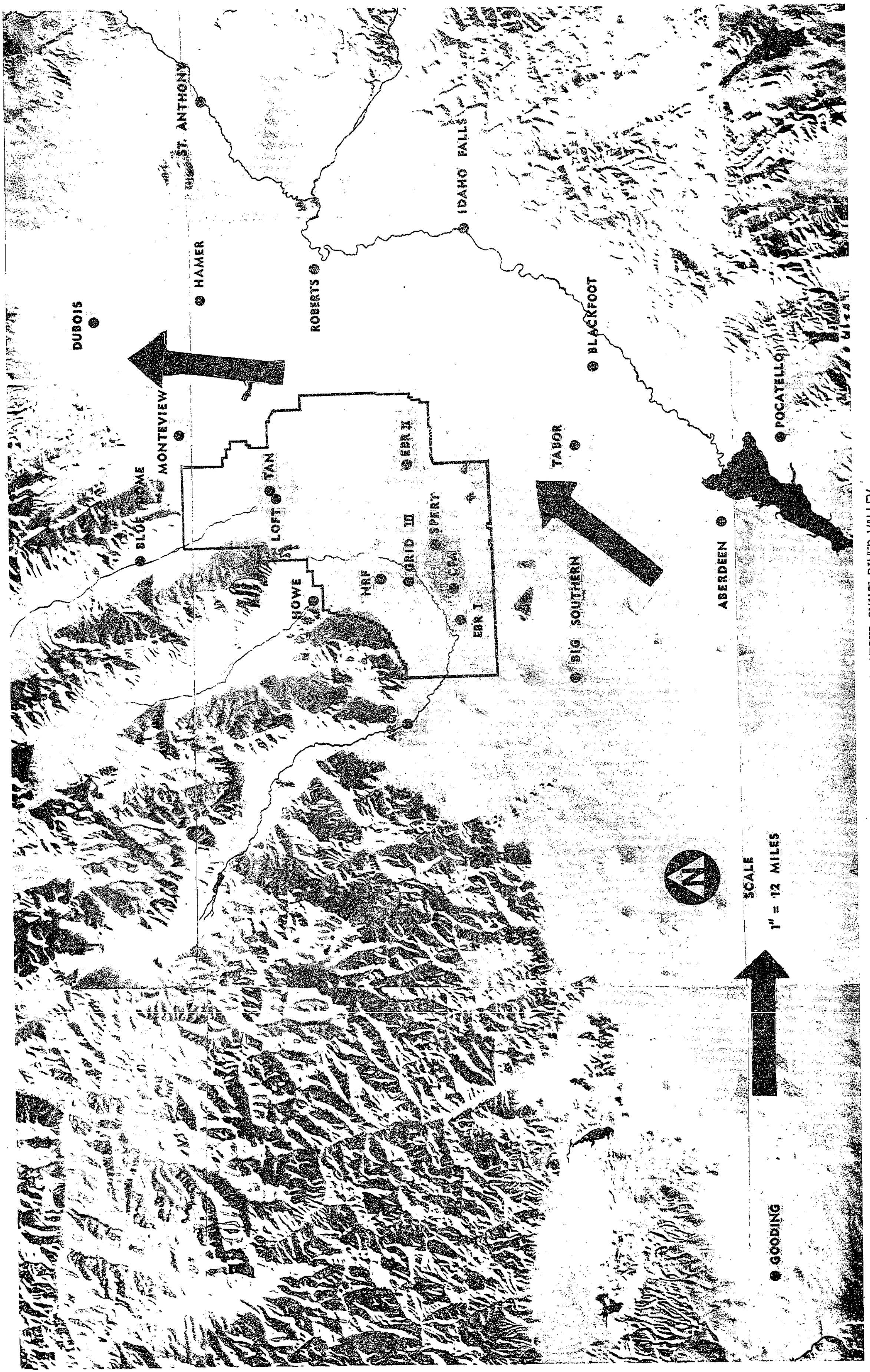


FIGURE 2. CHANNELING OF WINDS IN UPPER SNAKE RIVER VALLEY.

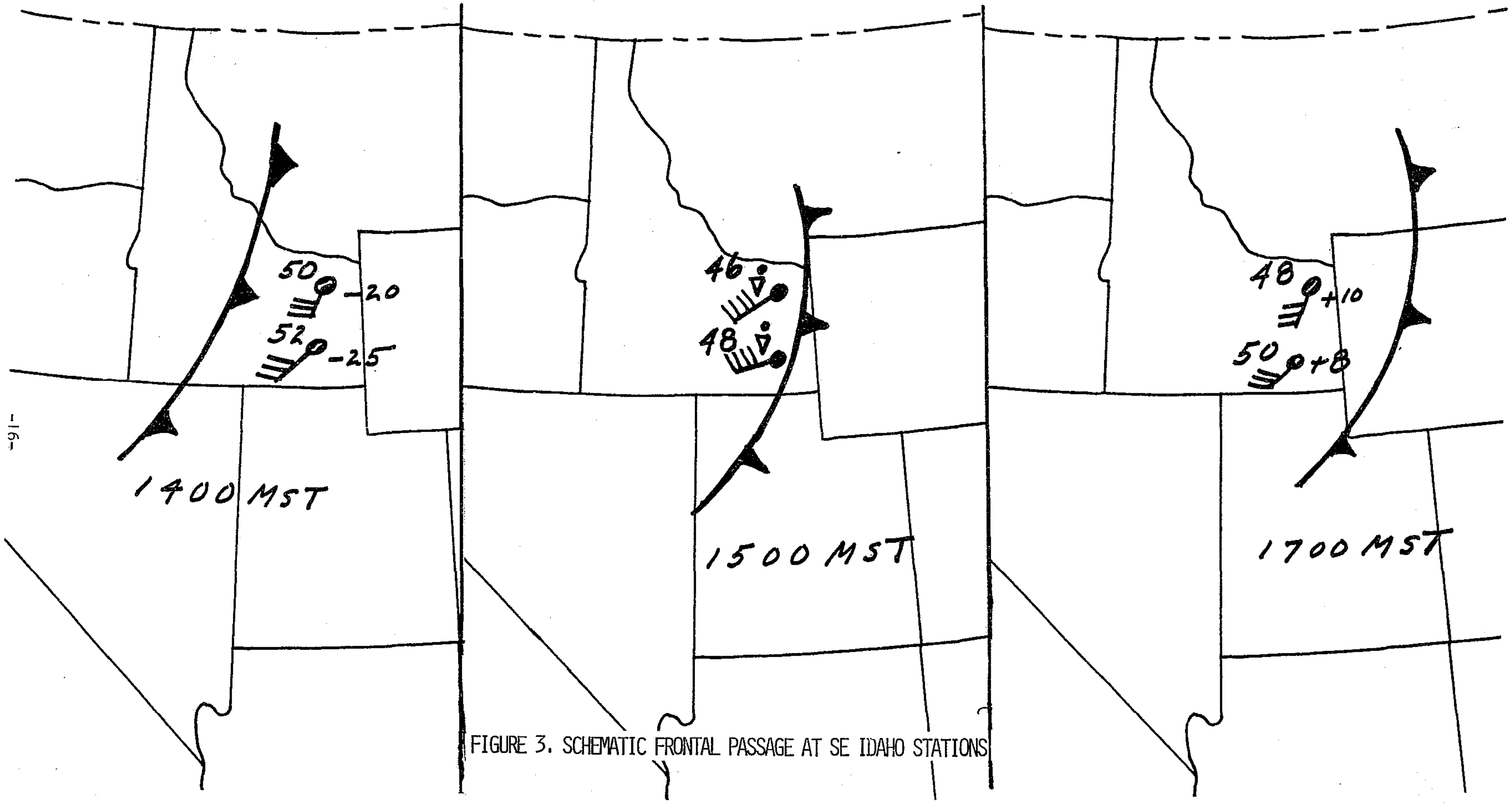


FIGURE 3. SCHEMATIC FRONTAL PASSAGE AT SE IDAHO STATIONS

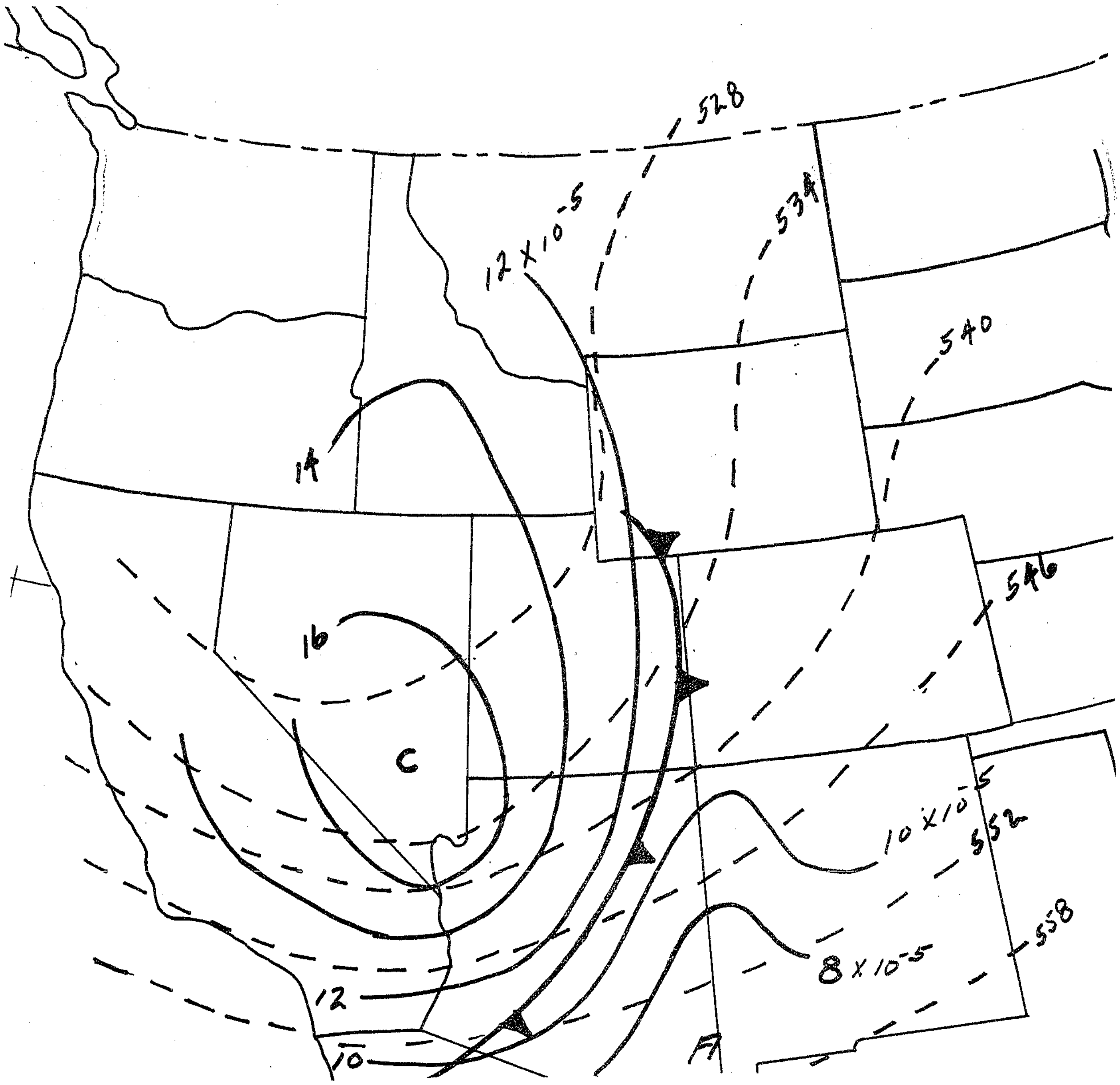


FIGURE 4. RELATIONSHIP OF COLD FRONT TO VORTICITY ISOPLETHS 12Z MARCH 2, 1965.

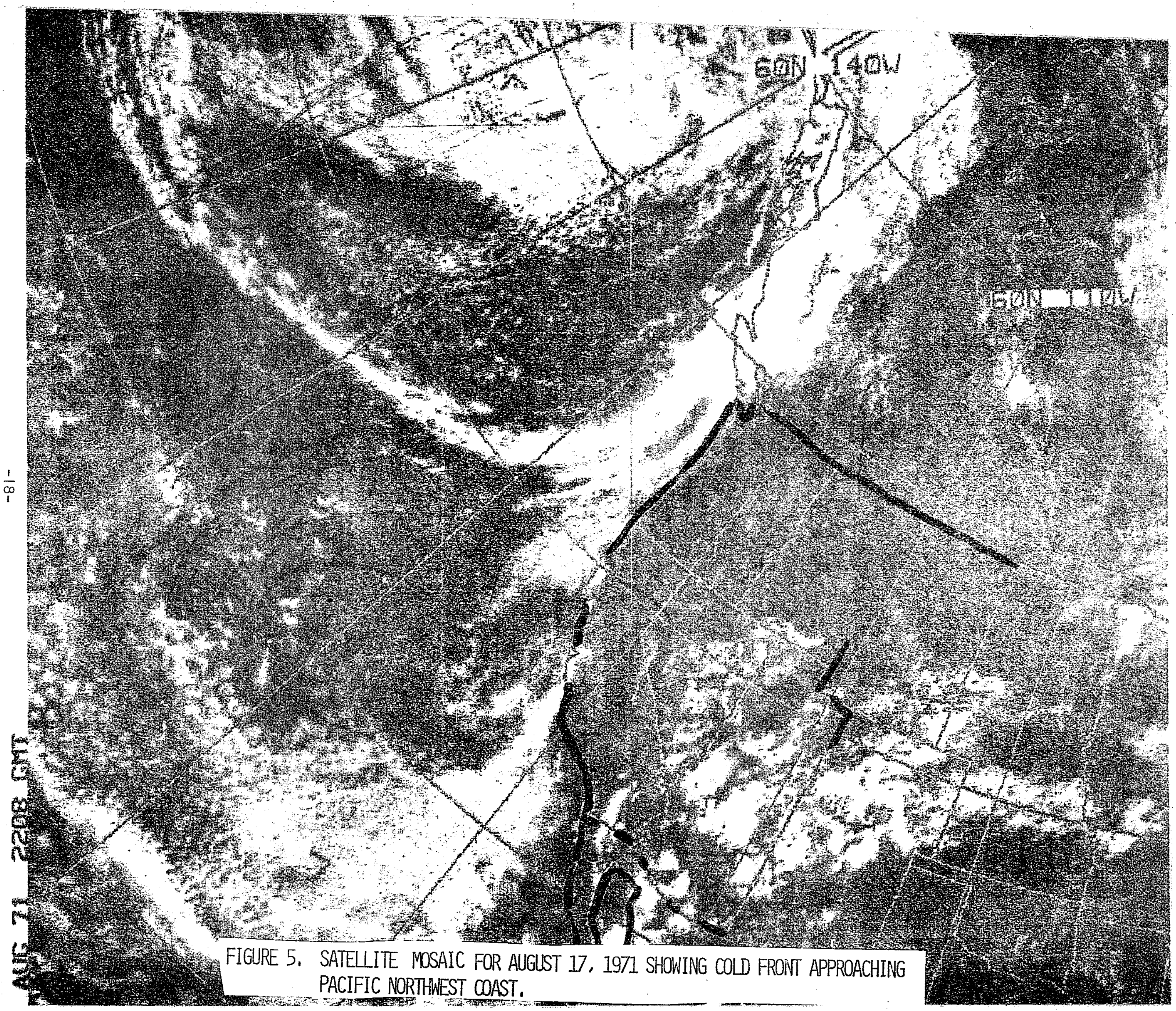


FIGURE 5. SATELLITE MOSAIC FOR AUGUST 17, 1971 SHOWING COLD FRONT APPROACHING PACIFIC NORTHWEST COAST.

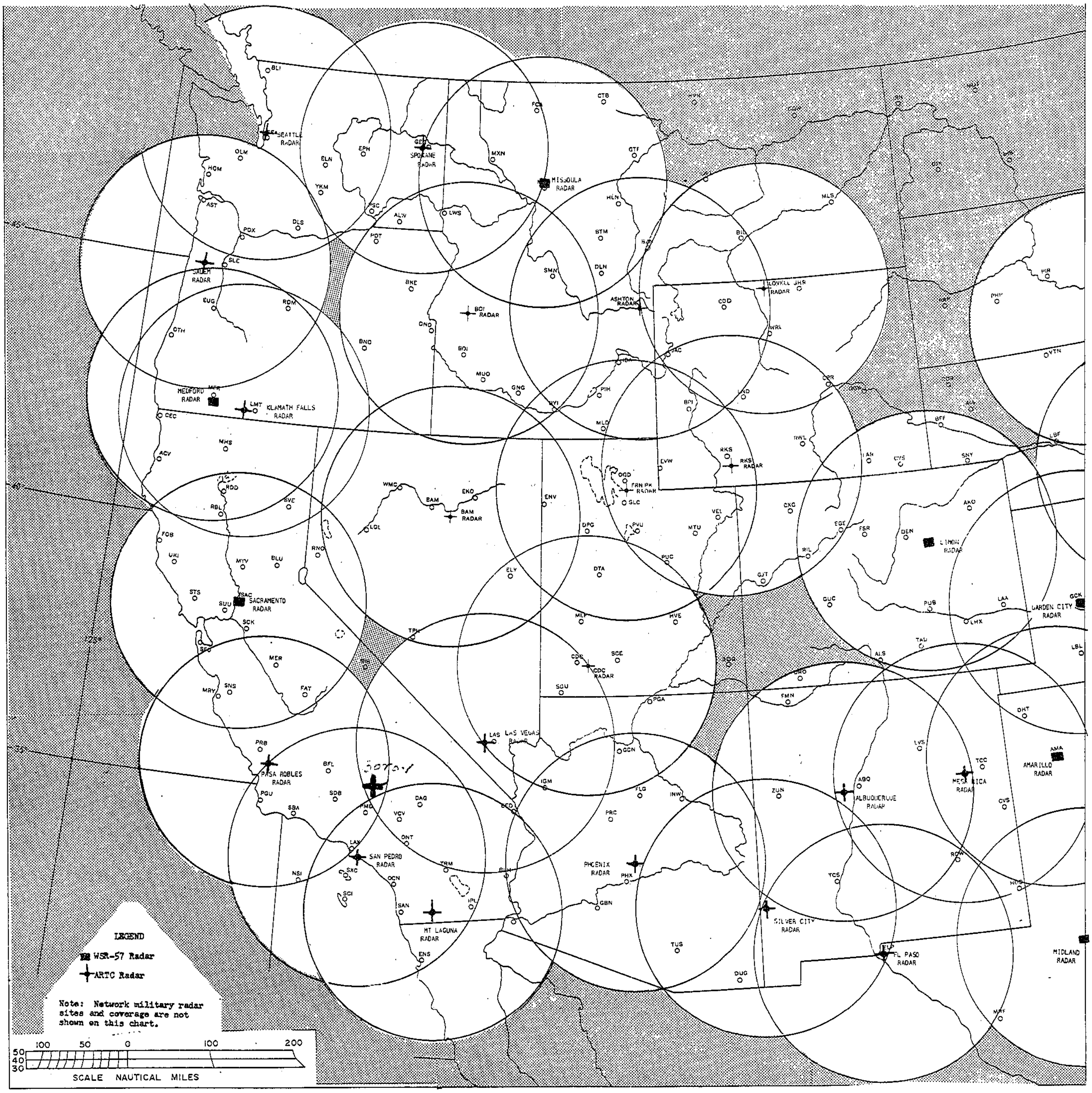


FIGURE 6. COMBINED ARTC-NWS RADAR WEATHER COVERAGE OVER WESTERN UNITED STATES.

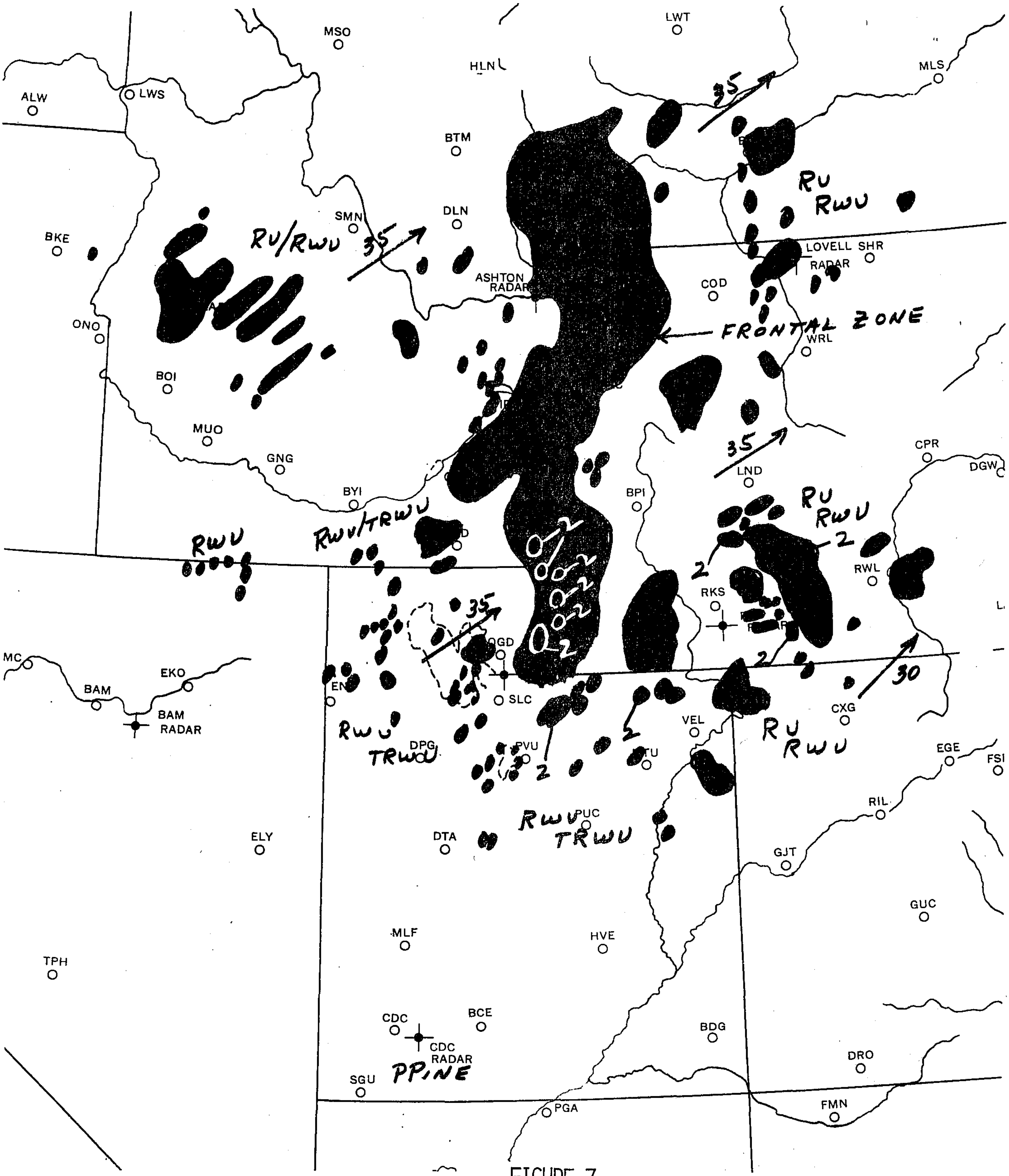


FIGURE 7.

Composite Radar Echo Chart, 1745 MST 9/30/67. All observations from seven radar systems remoted to SLC ARTC Center are included. The number 2 is used to identify moderate to strong echoes observed when a radar system is in CP Mode.

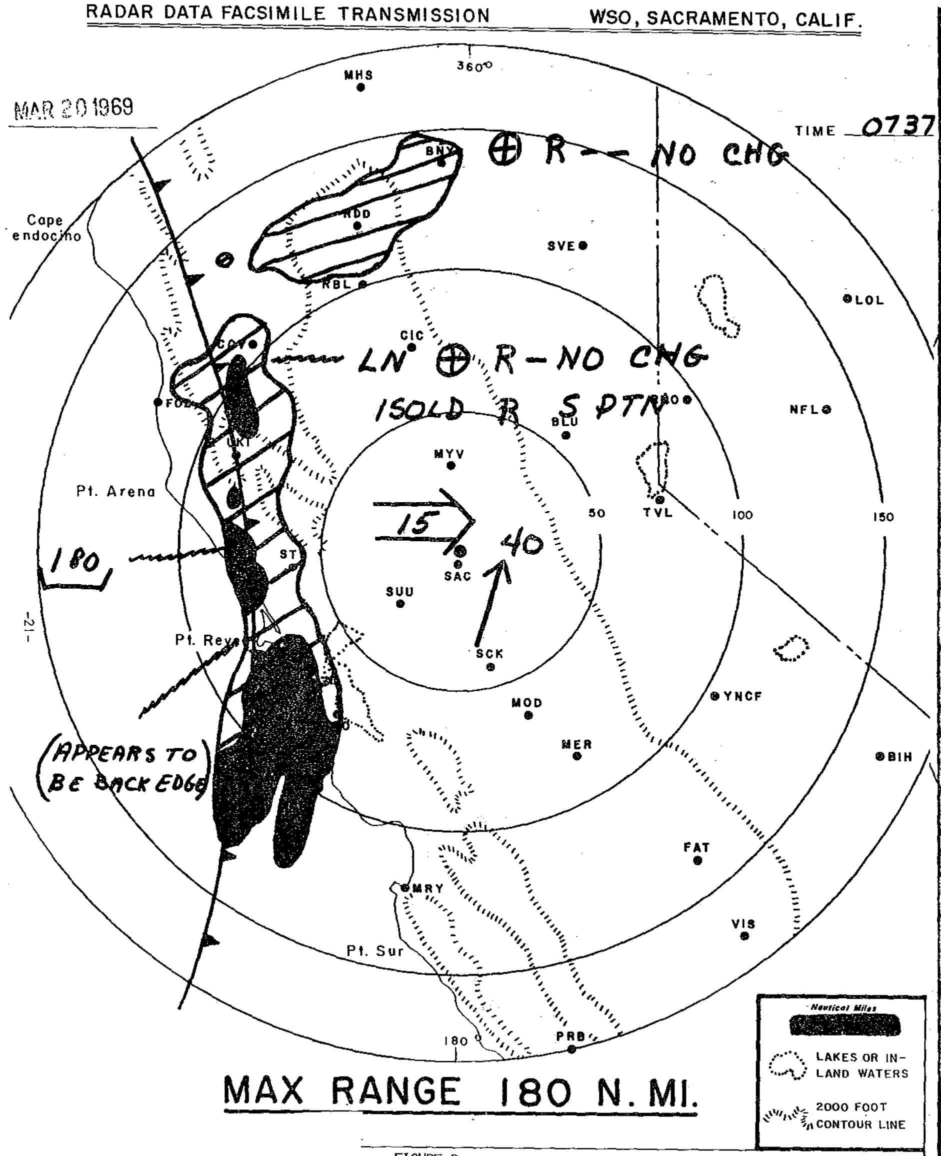


FIGURE 8A.

SACRAMENTO WSO RADARSCOPE OVERLAY 0737 PST MARCH 20, 1969.

USCOMM-ESSA-DC

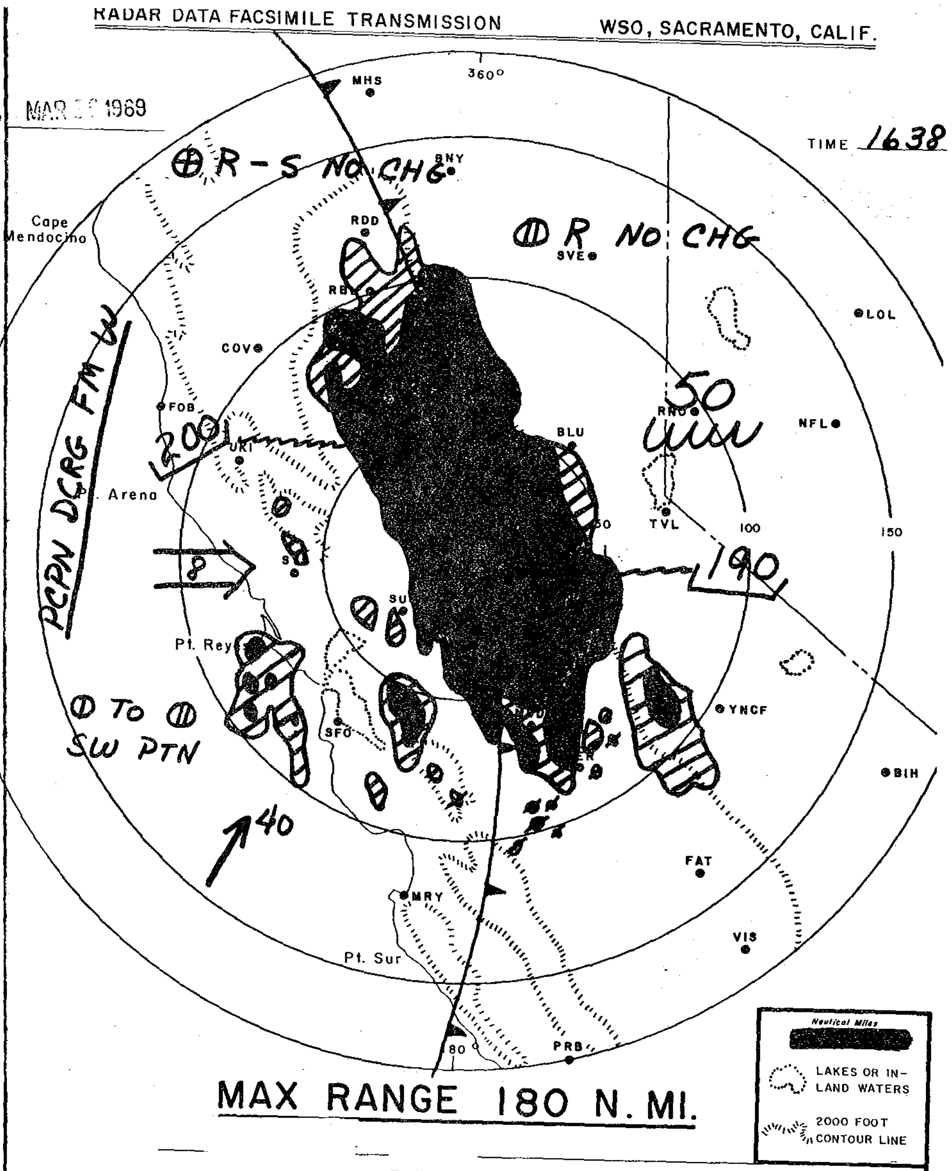


FIGURE 8B.

SACRAMENTO WSO RADARSCOPE OVERLAY 1638 PST MARCH 20, 1969.

USCOMM-ESSA-DC

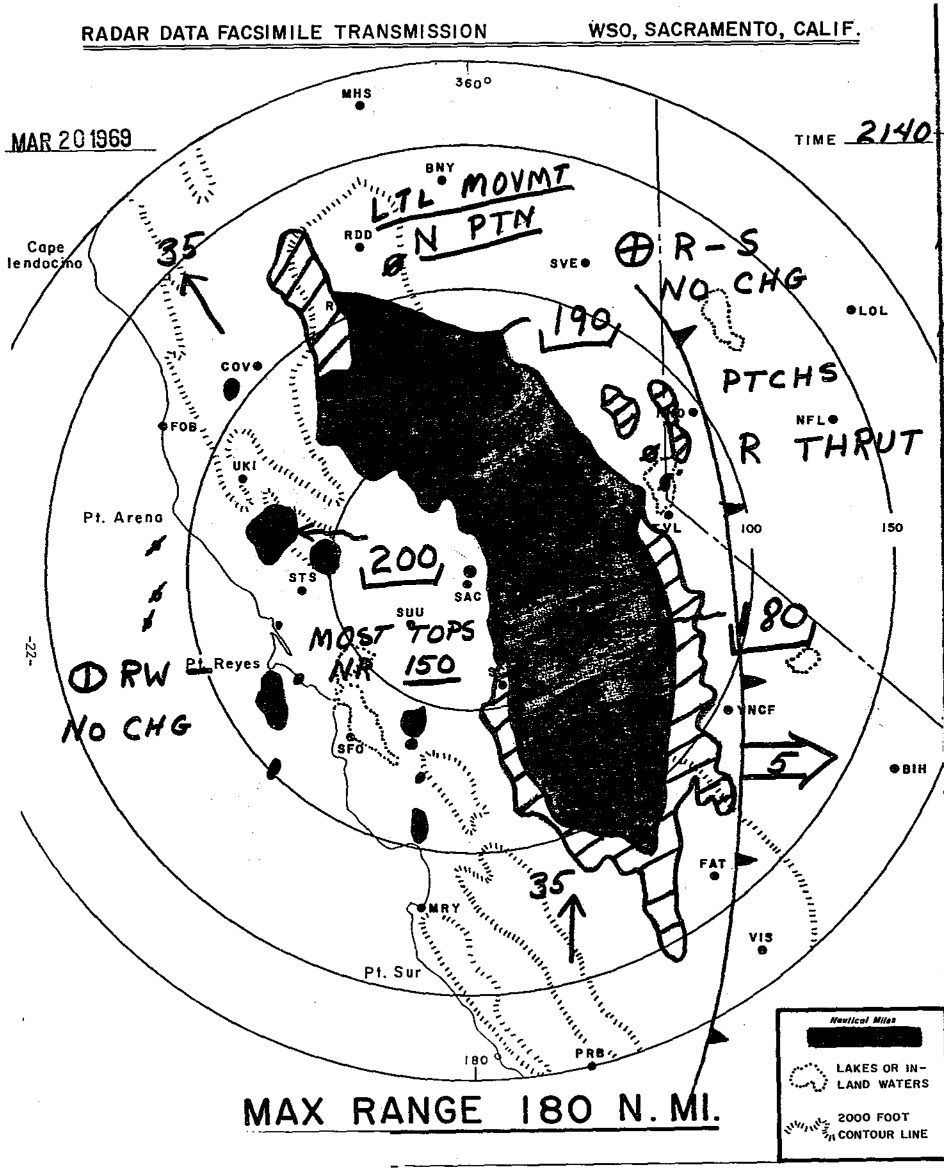


FIGURE 8c.
SACRAMENTO WSO RADARSCOPE OVERLAY 2140 PST MARCH 20, 1969.

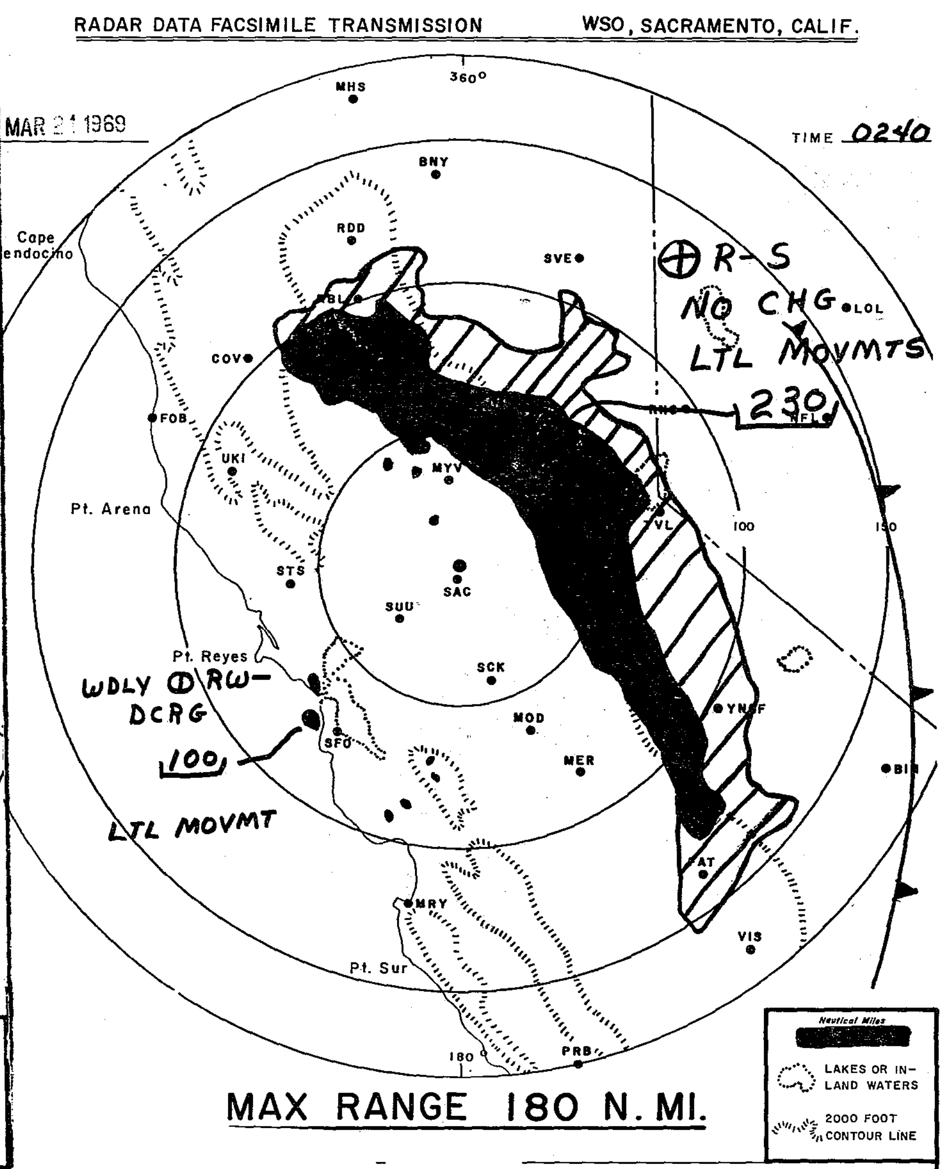


FIGURE 8D.
SACRAMENTO WSO RADARSCOPE OVERLAY 0240 PST MARCH 21, 1969.

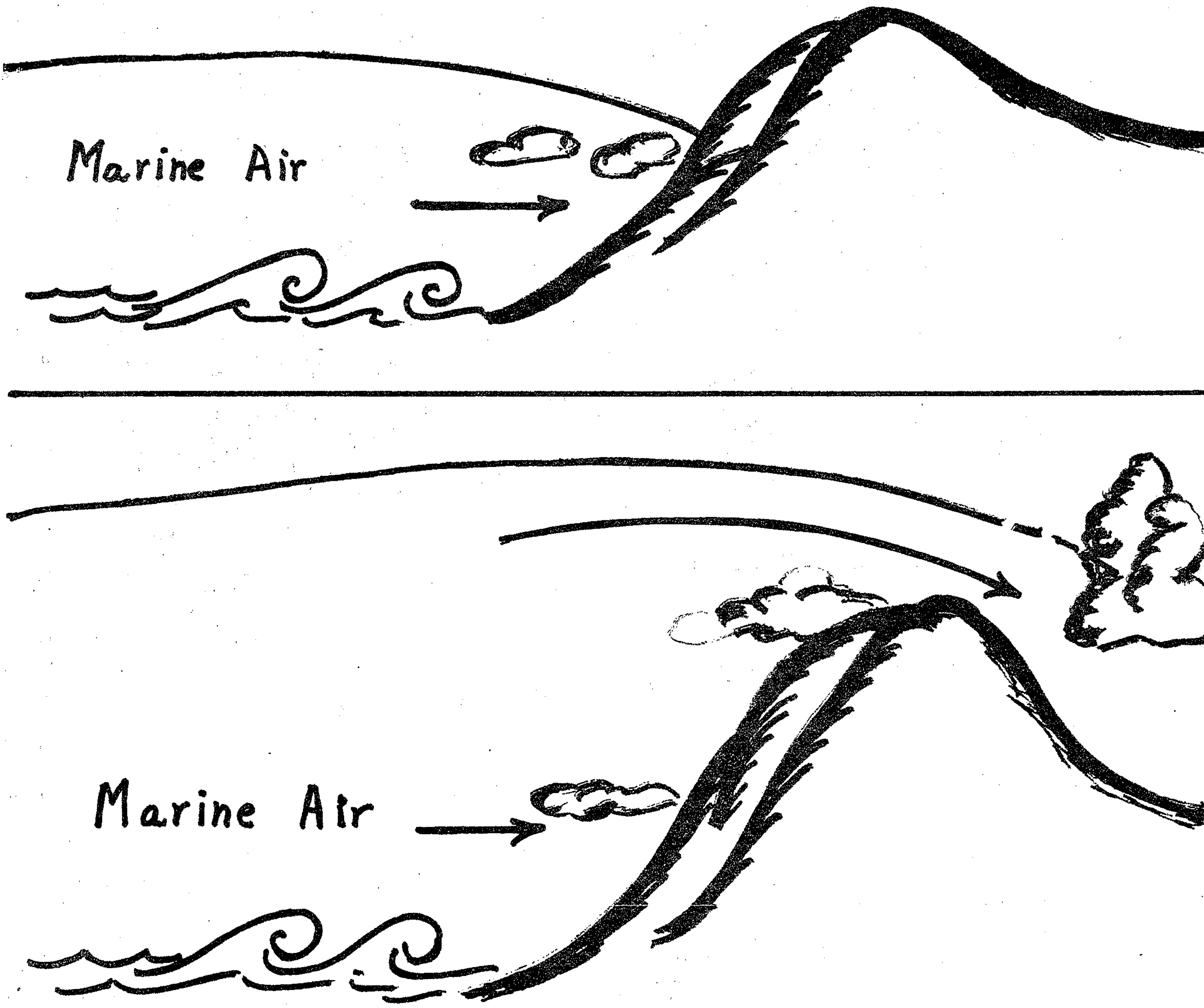


FIGURE 9. MARINE AIR SPILLING OVER COAST RANGE.

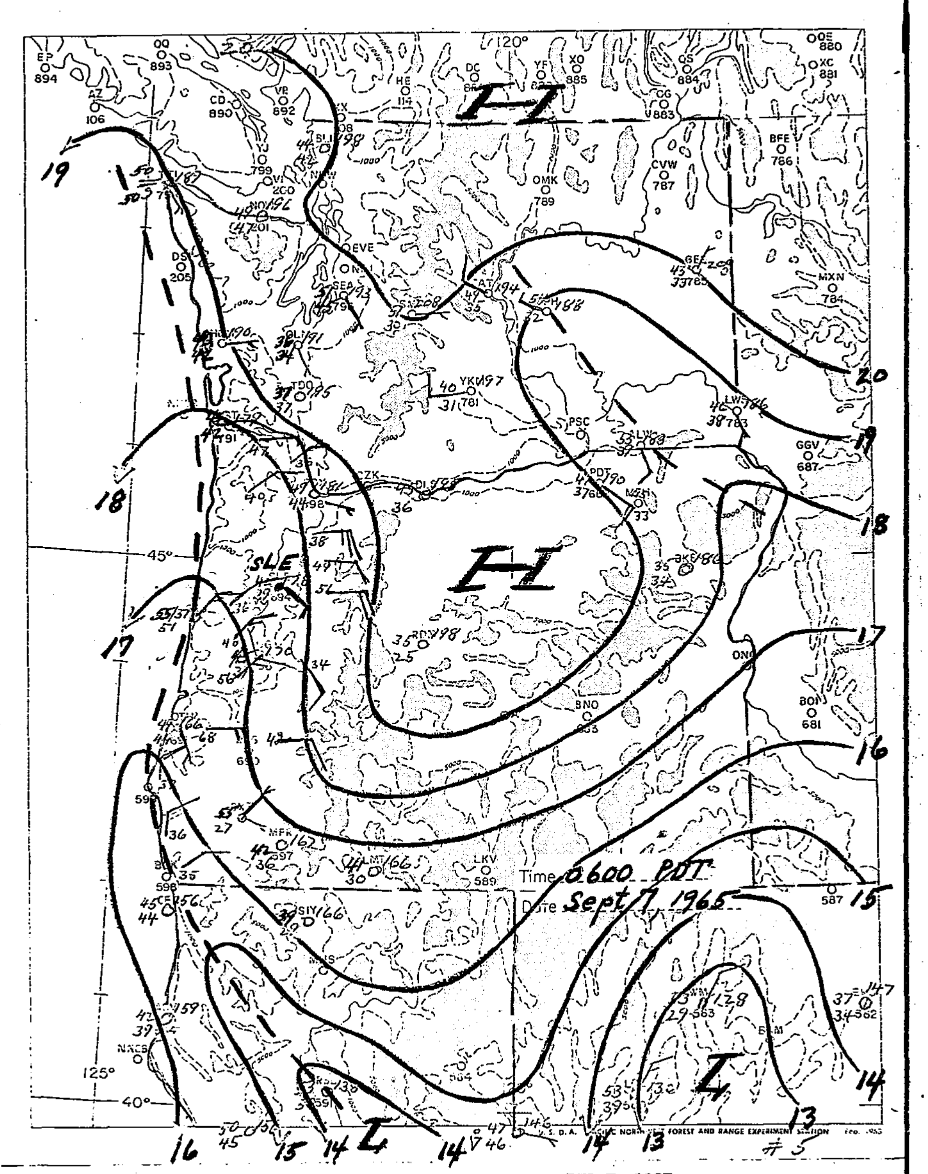


FIGURE 10A. SURFACE CHART, 0600 PDT SEPTEMBER 7, 1965.

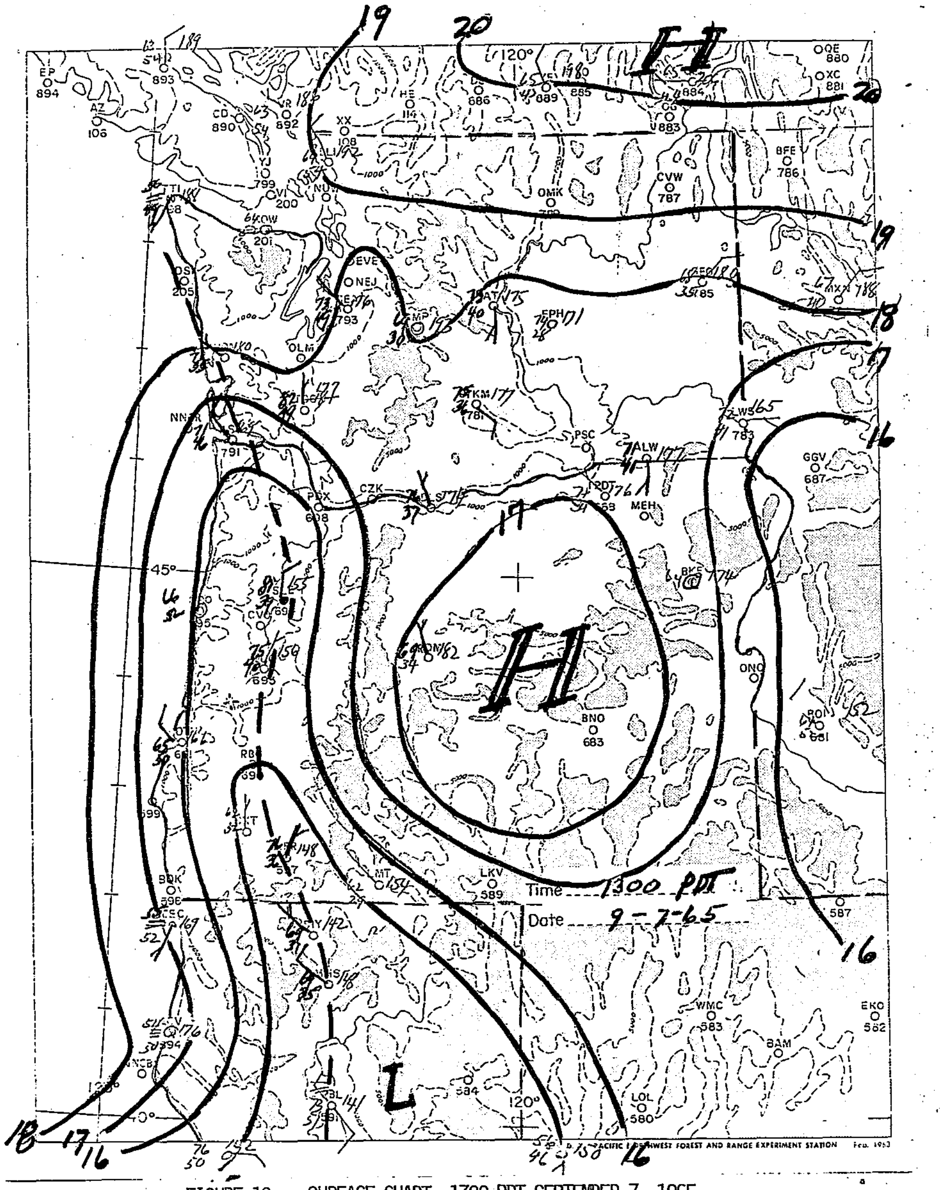


FIGURE 10B. SURFACE CHART, 1300 PDT SEPTEMBER 7, 1965.

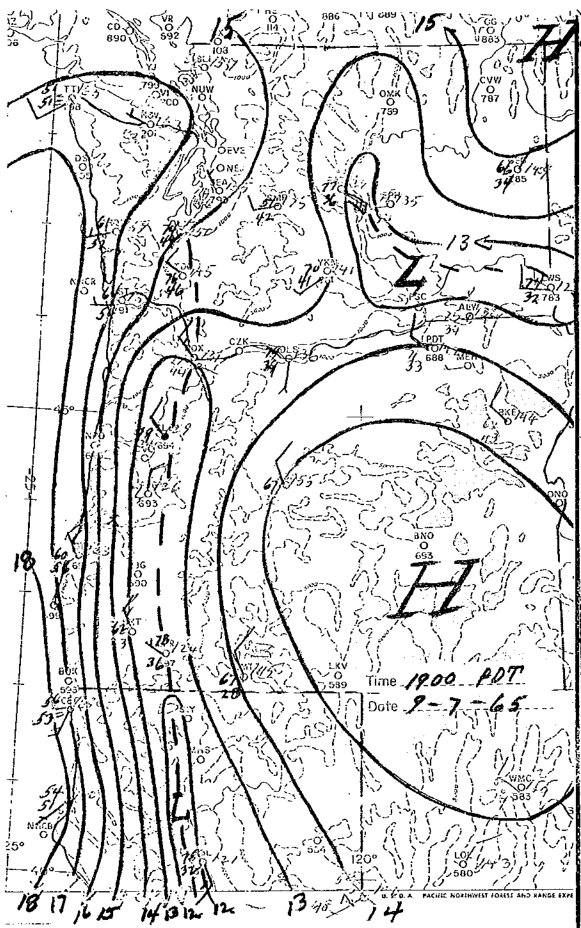


FIGURE 10c. SURFACE CHART, 1900 PDT SEPTEMBER 7, 1965.

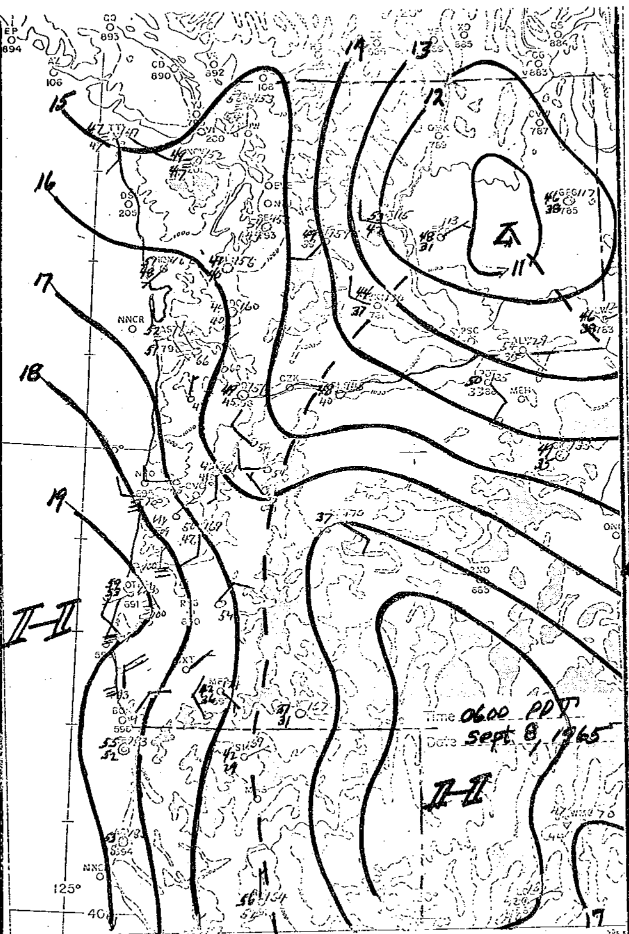


FIGURE 10d. SURFACE CHART, 0600 PDT SEPTEMBER 8, 1965.

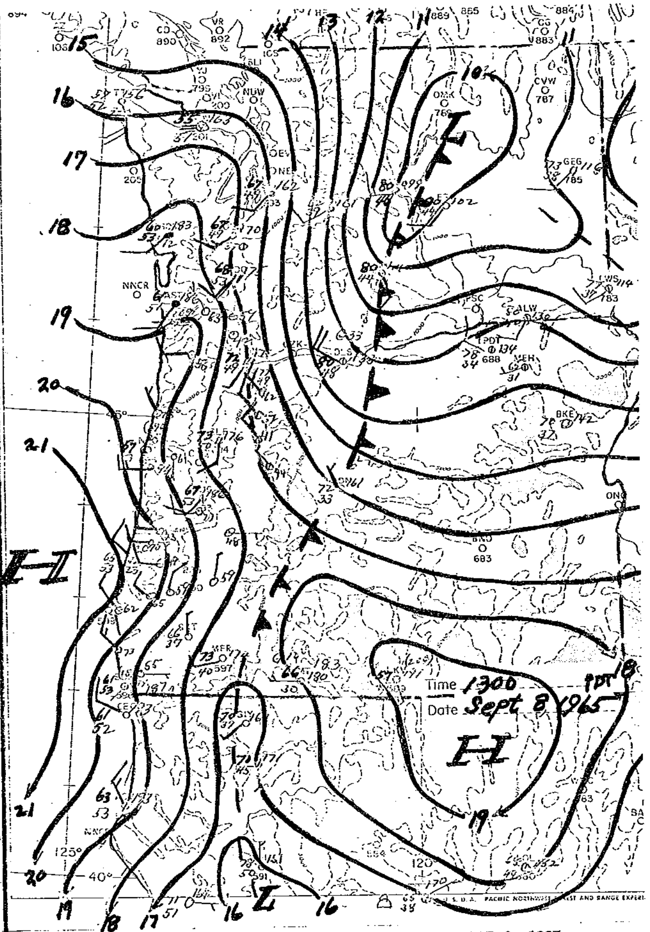


FIGURE 10e. SURFACE CHART, 1300 PDT SEPTEMBER 8, 1965.

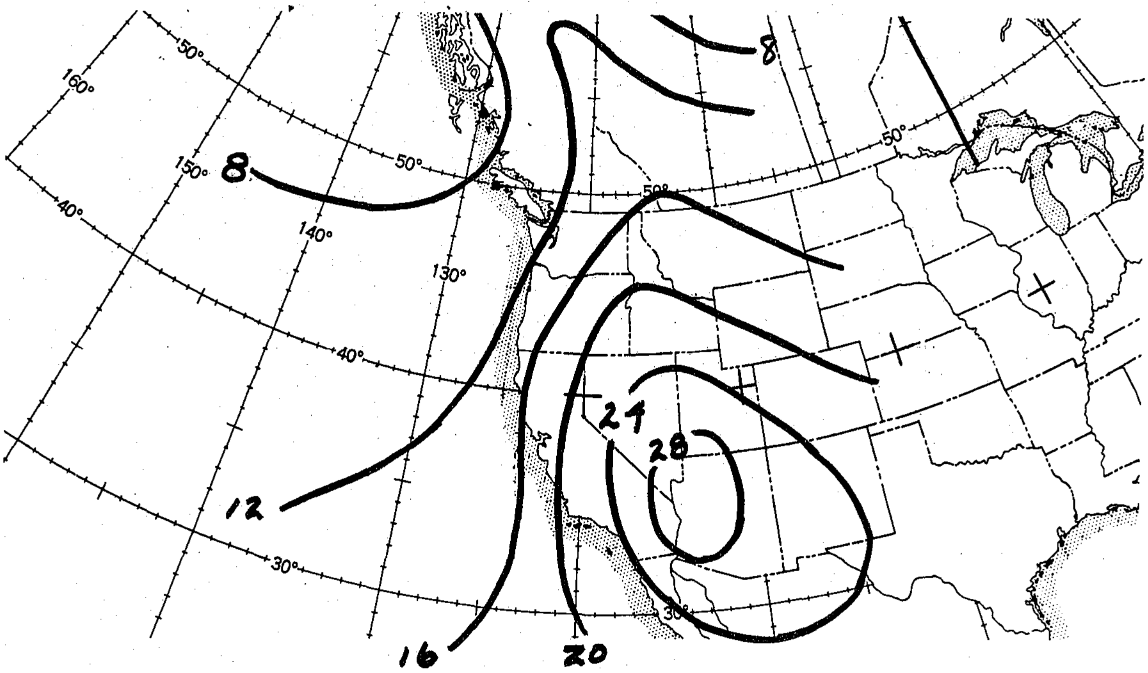


FIGURE 11. NORMAL 850-MB ISOTHERMS, JULY.

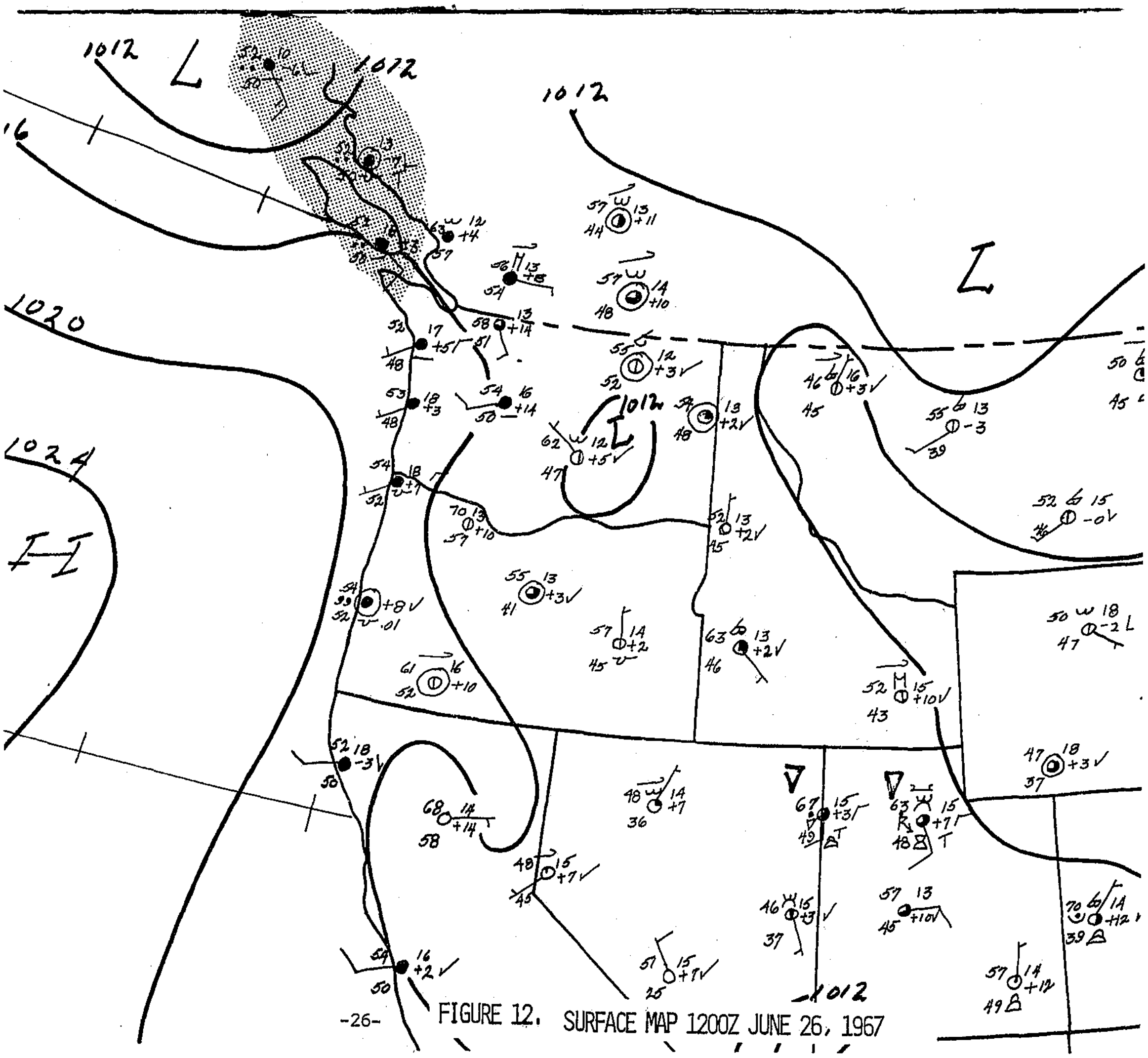


FIGURE 12. SURFACE MAP 1200Z JUNE 26, 1967

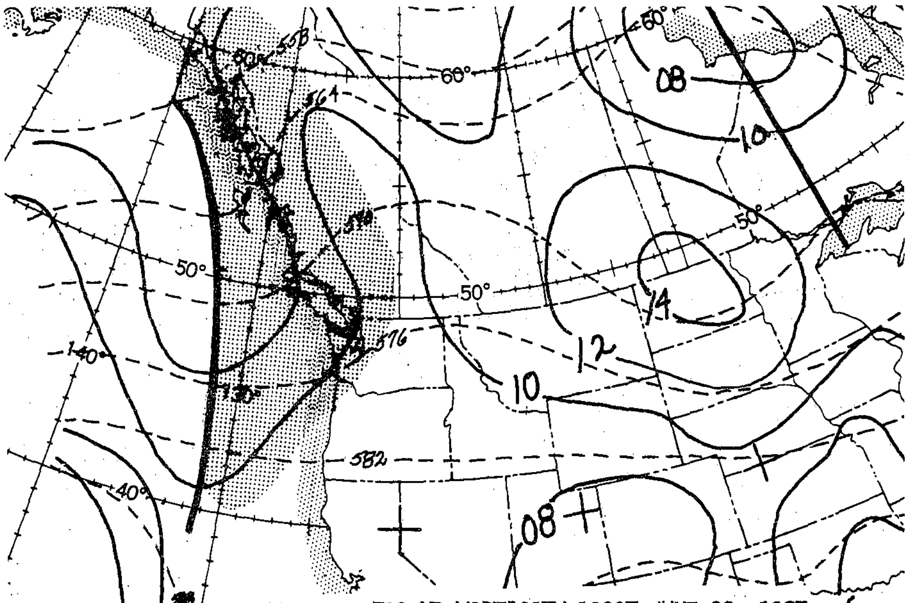


FIGURE 13. 500-MB VORTICITY 1200Z JUNE 26, 1967

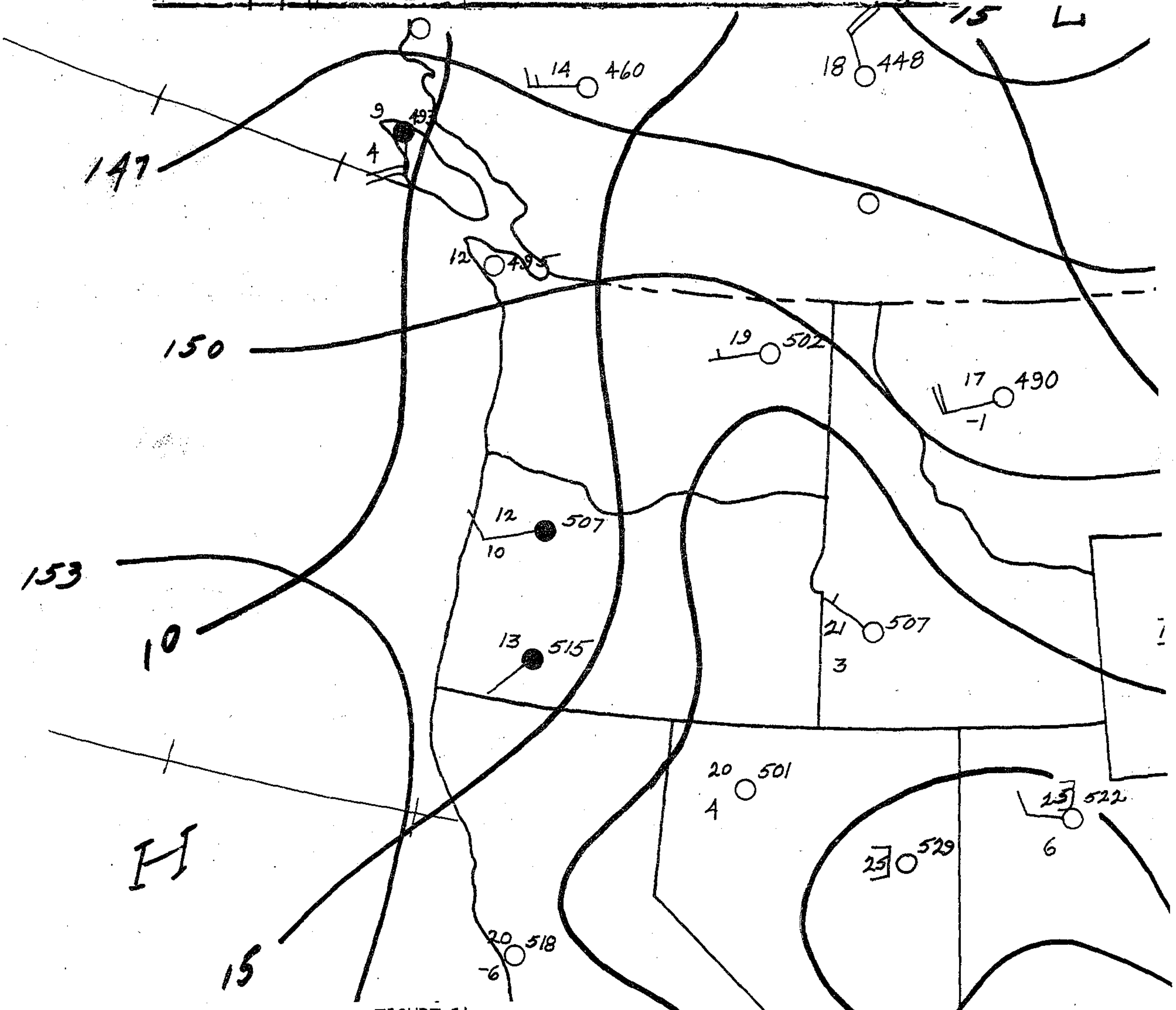


FIGURE 14.

850-MB CHART 1200Z JUNE 26, 1967

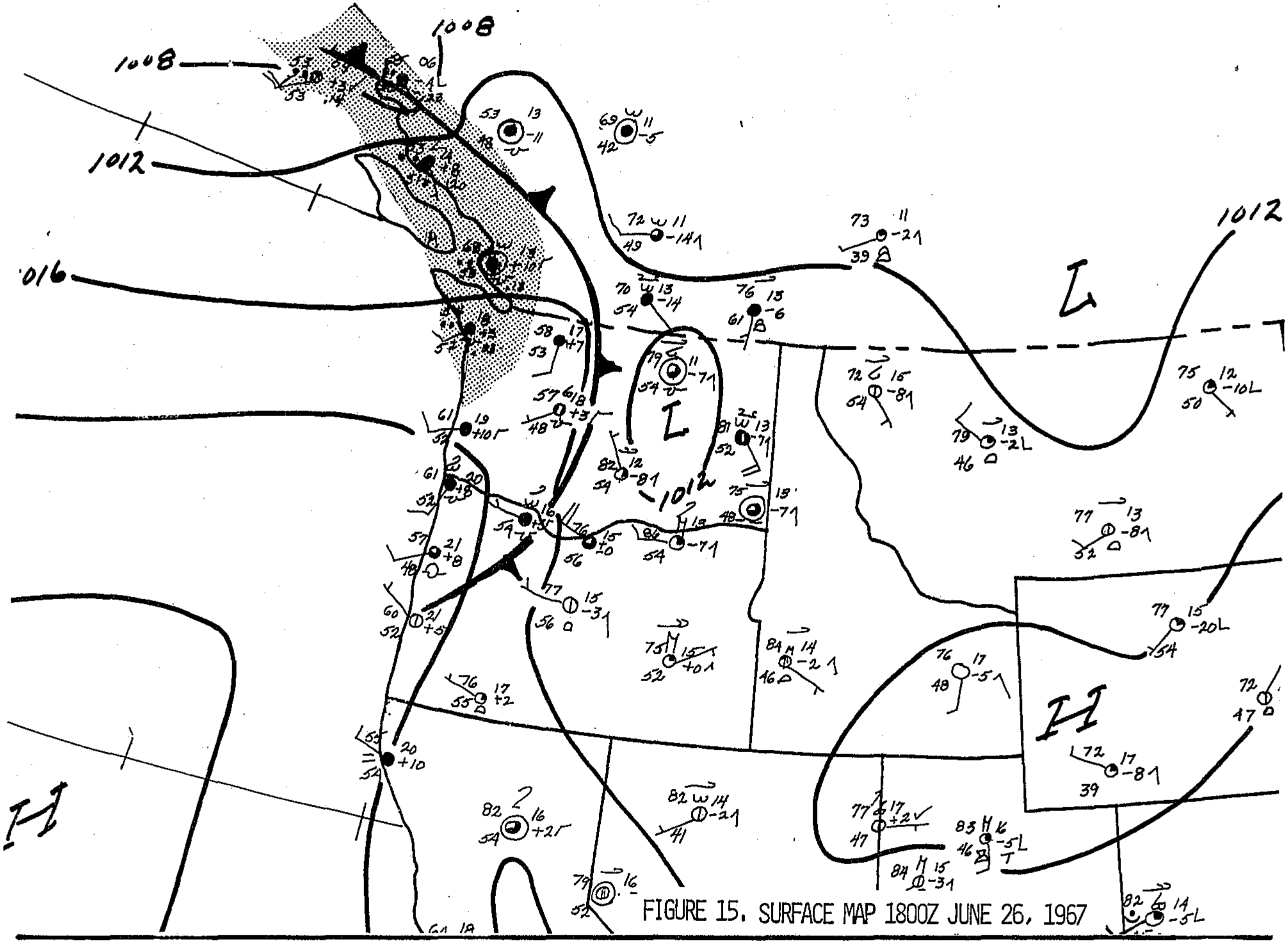


FIGURE 15. SURFACE MAP 1800Z JUNE 26, 1967

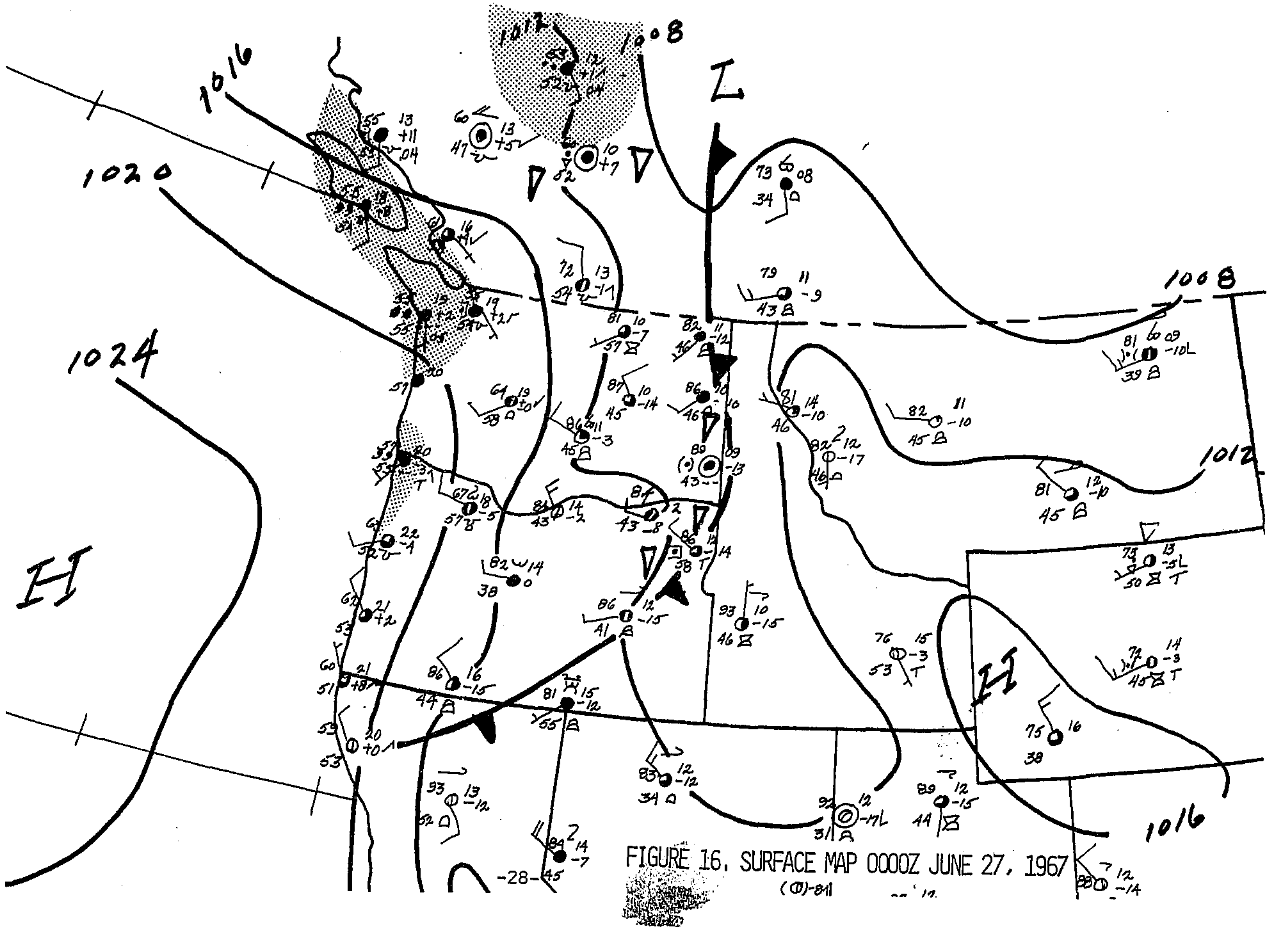


FIGURE 16. SURFACE MAP 0000Z JUNE 27, 1967

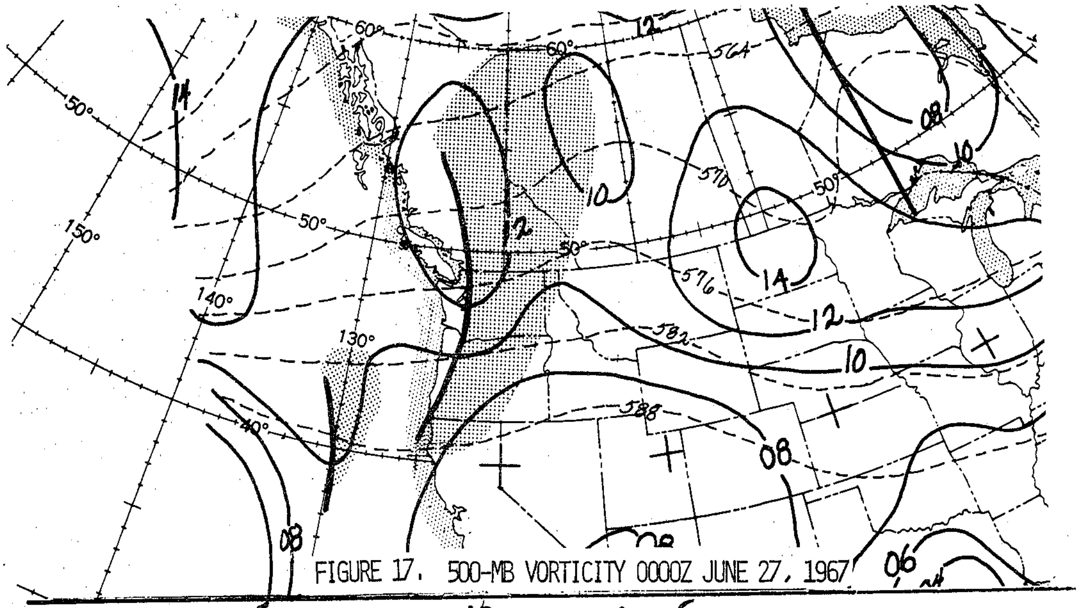


FIGURE 17. 500-MB VORTICITY 0000Z JUNE 27, 1967

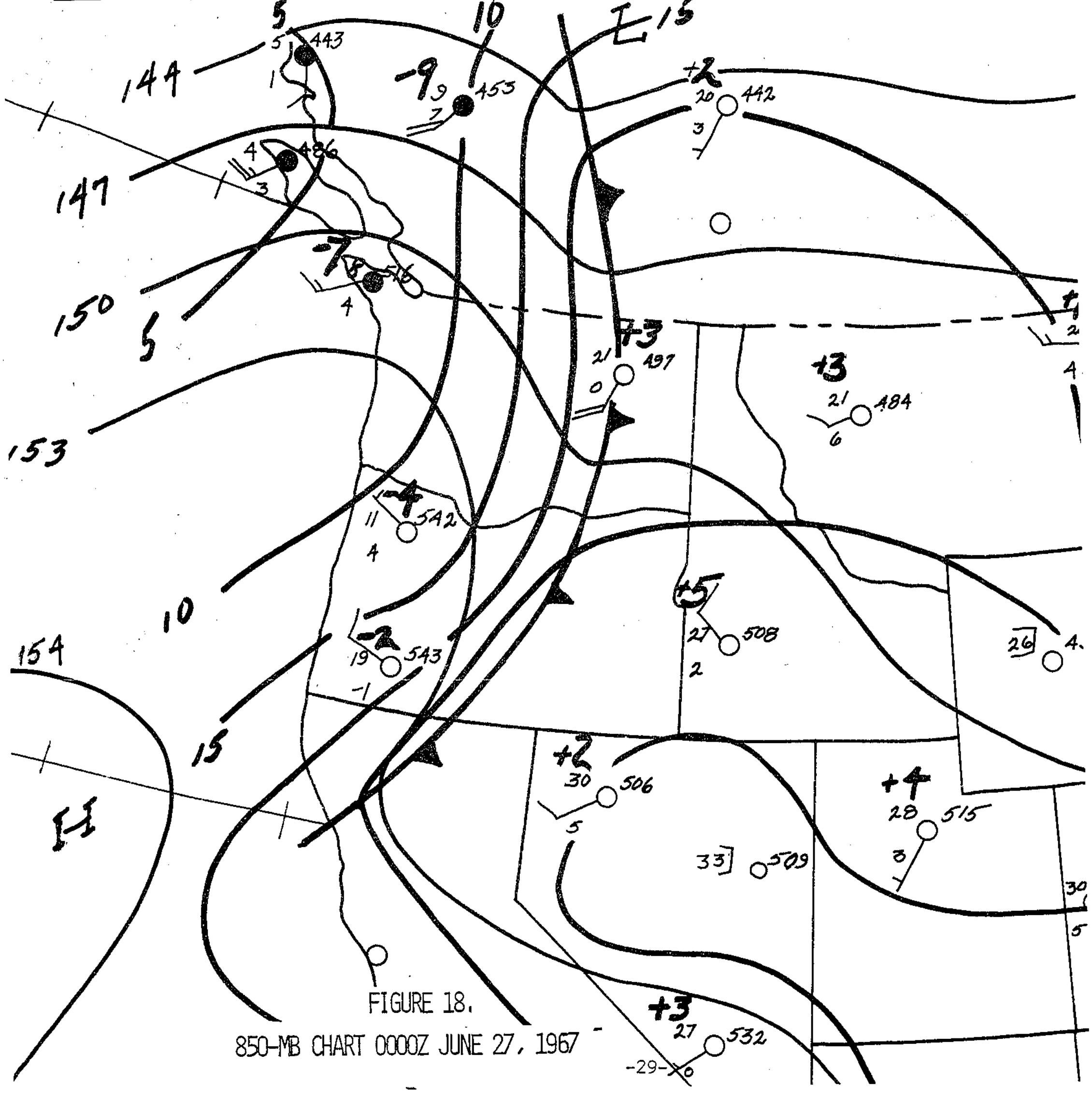


FIGURE 18.
850-MB CHART 0000Z JUNE 27, 1967

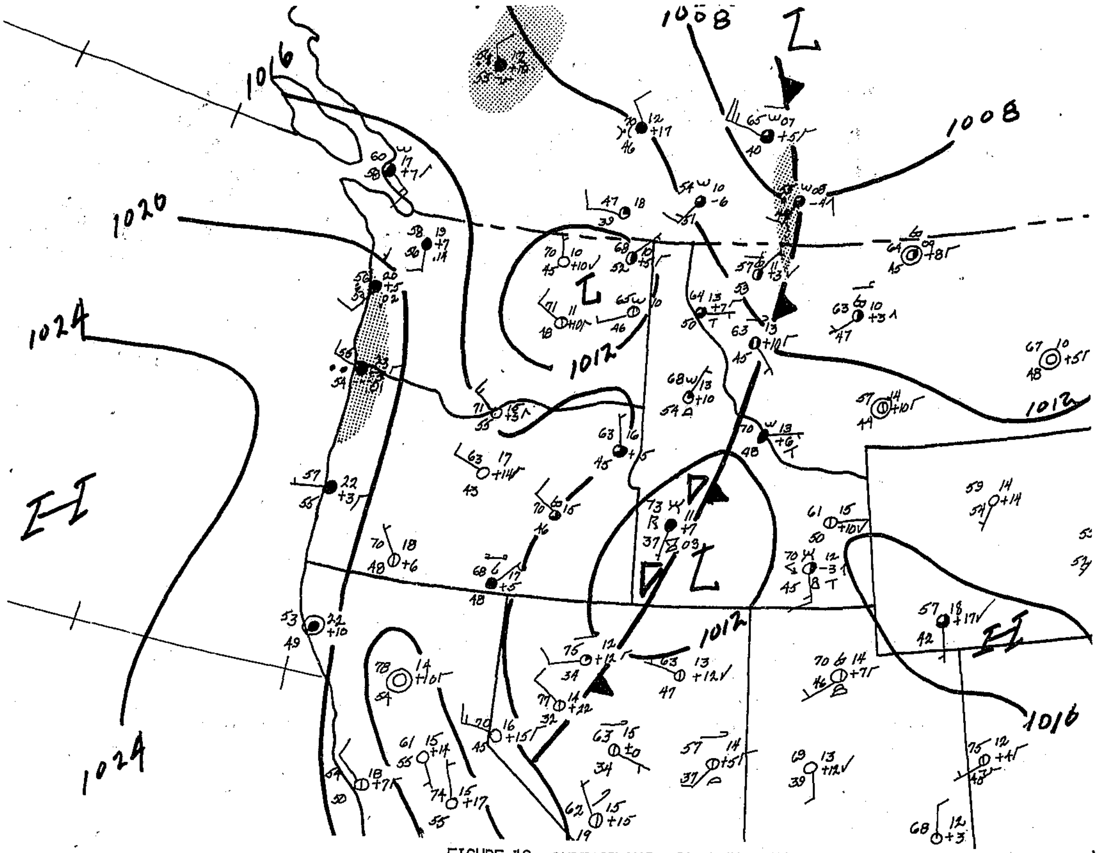


FIGURE 19. SURFACE MAP 0600Z JUNE 27, 1967

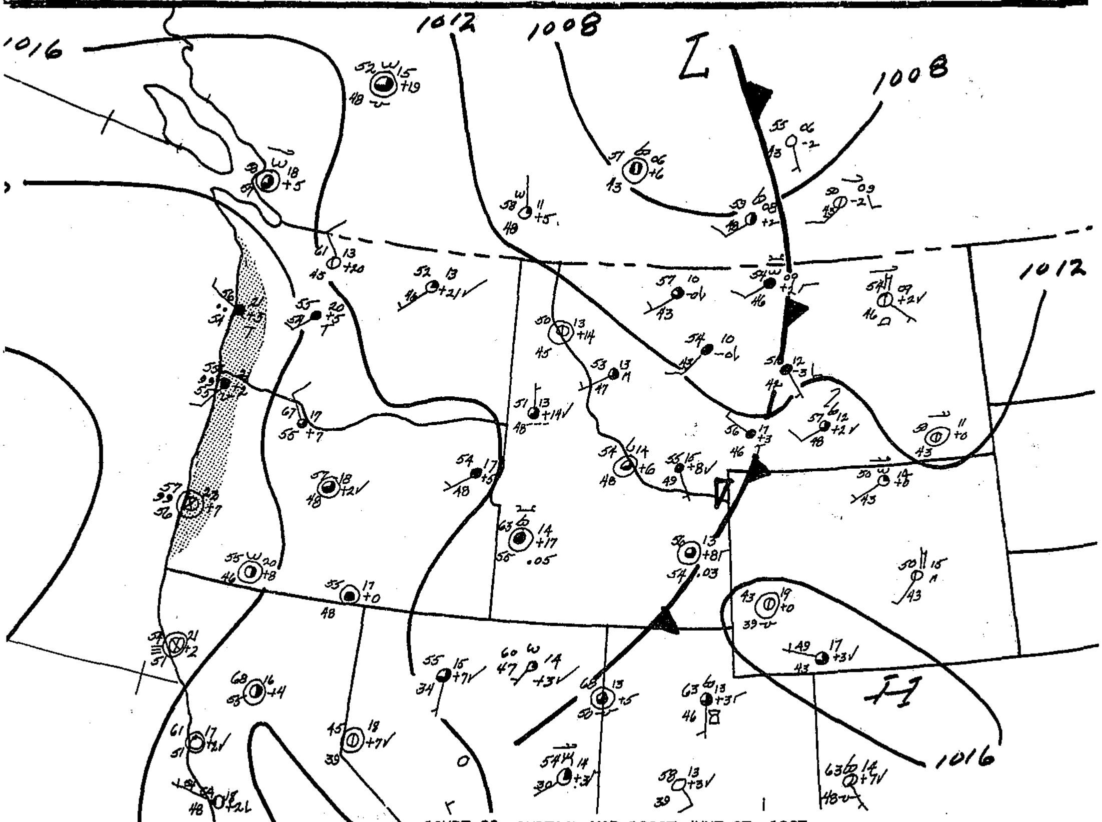


FIGURE 20. SURFACE MAP 1200Z JUNE 27, 1967

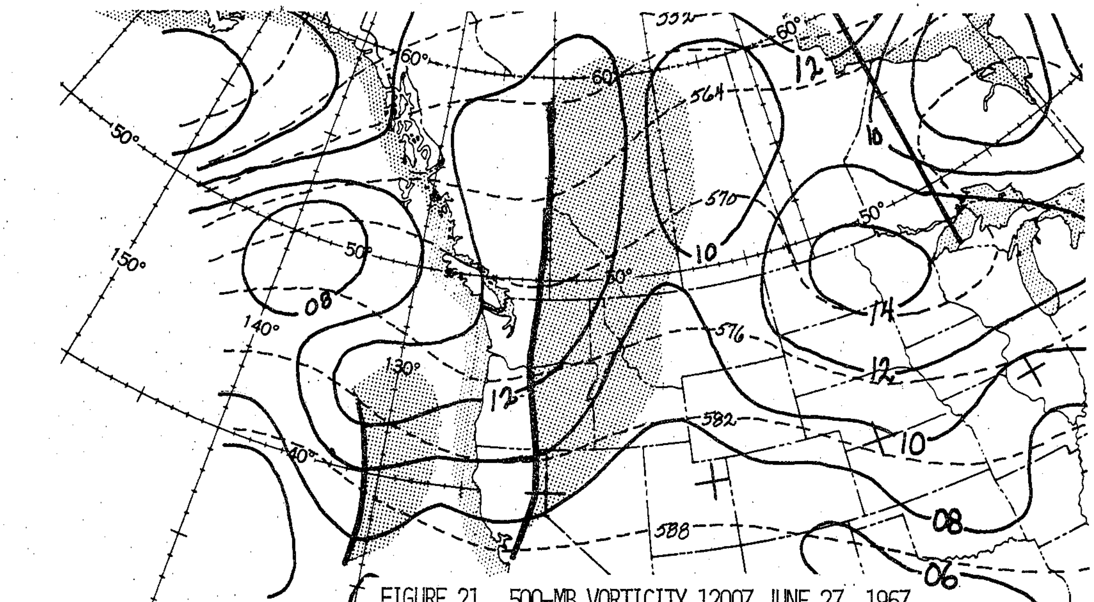


FIGURE 21. 500-MB VORTICITY 1200Z JUNE 27, 1967

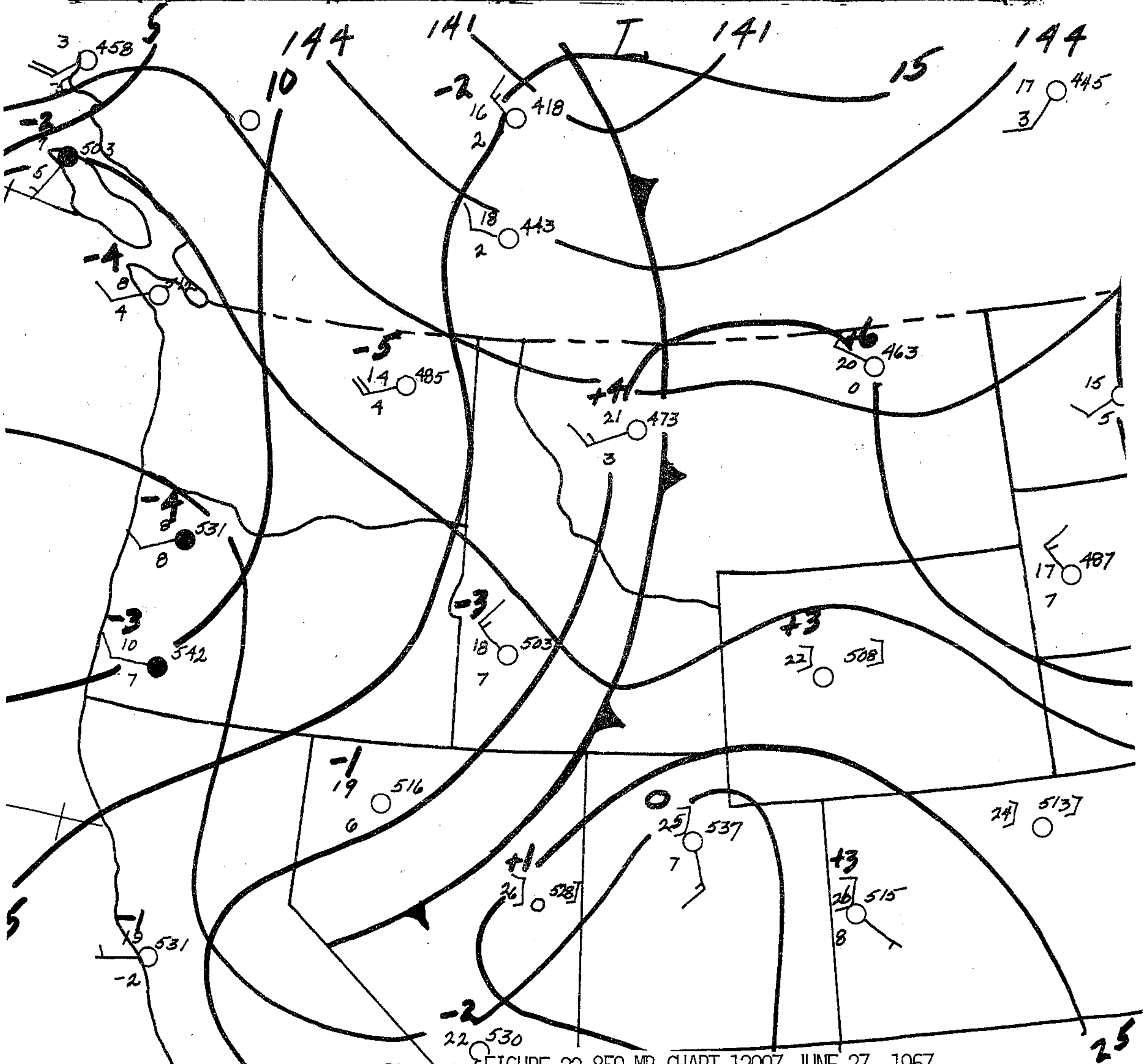


FIGURE 22. 850-MB CHART 1200Z JUNE 27, 1967

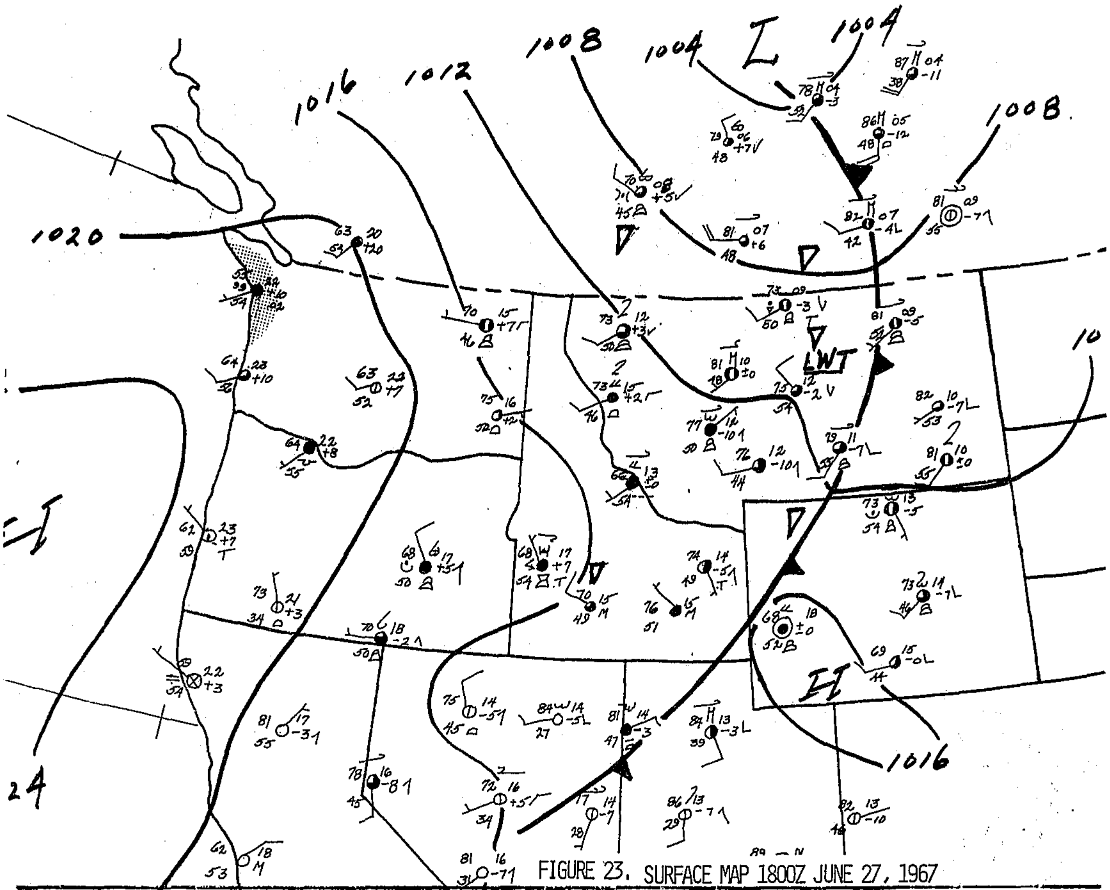


FIGURE 23. SURFACE MAP 1800Z JUNE 27, 1967

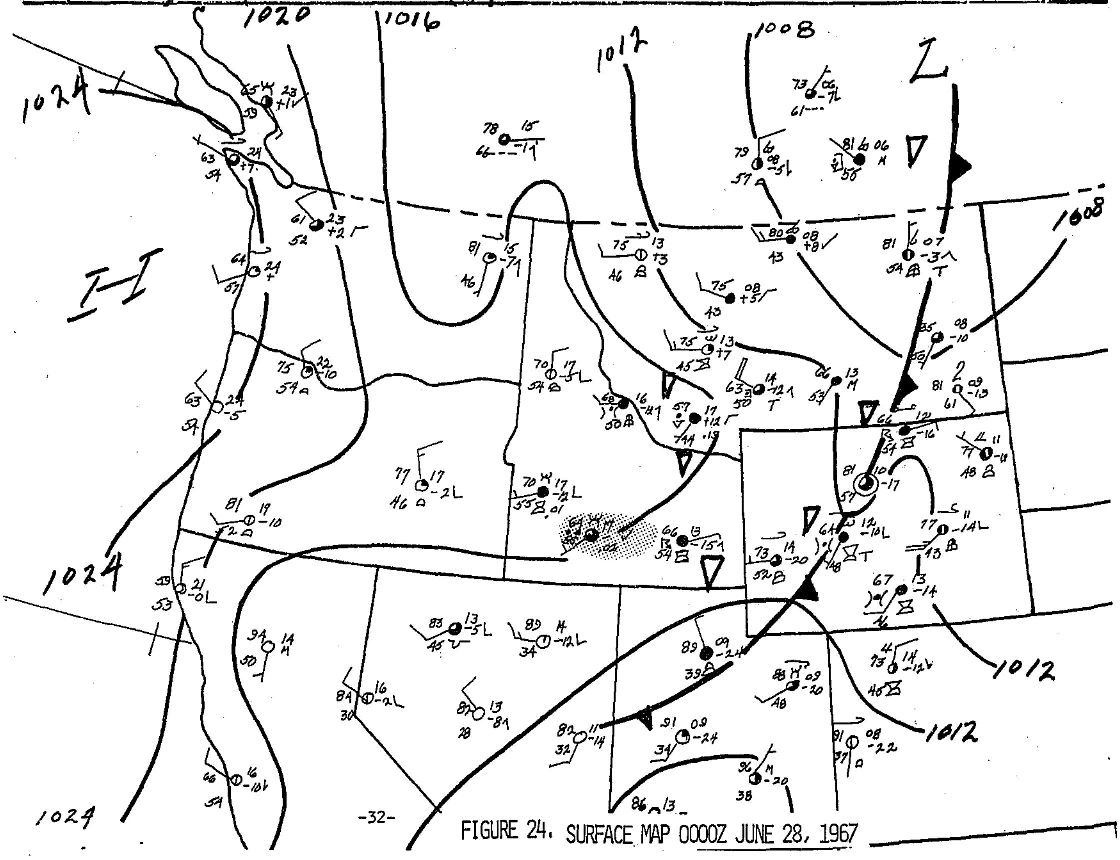


FIGURE 24. SURFACE MAP 0000Z JUNE 28, 1967

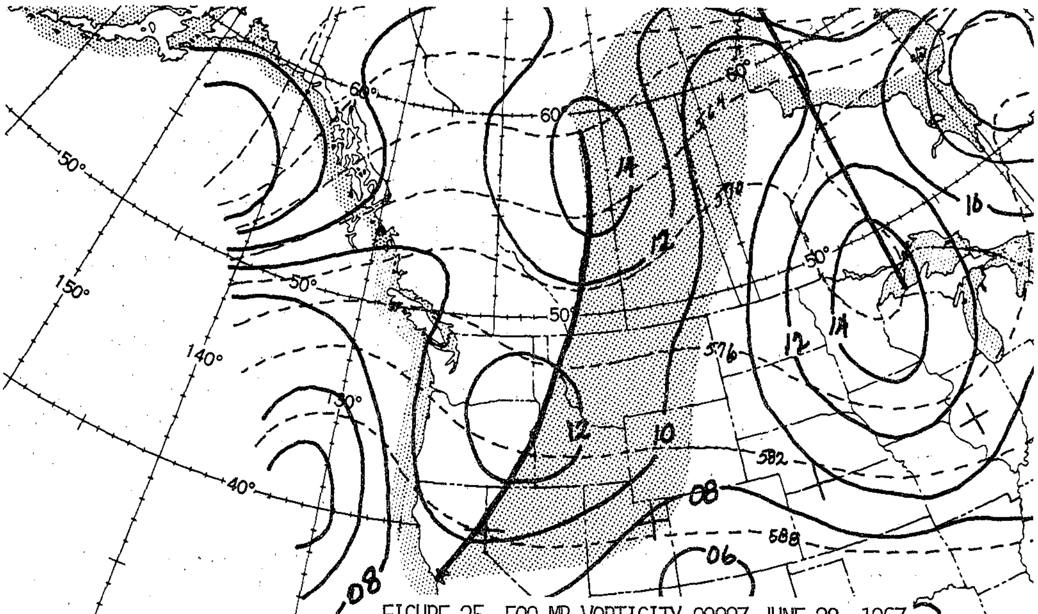


FIGURE 25. 500-MB VORTICITY 0000Z JUNE 28, 1967

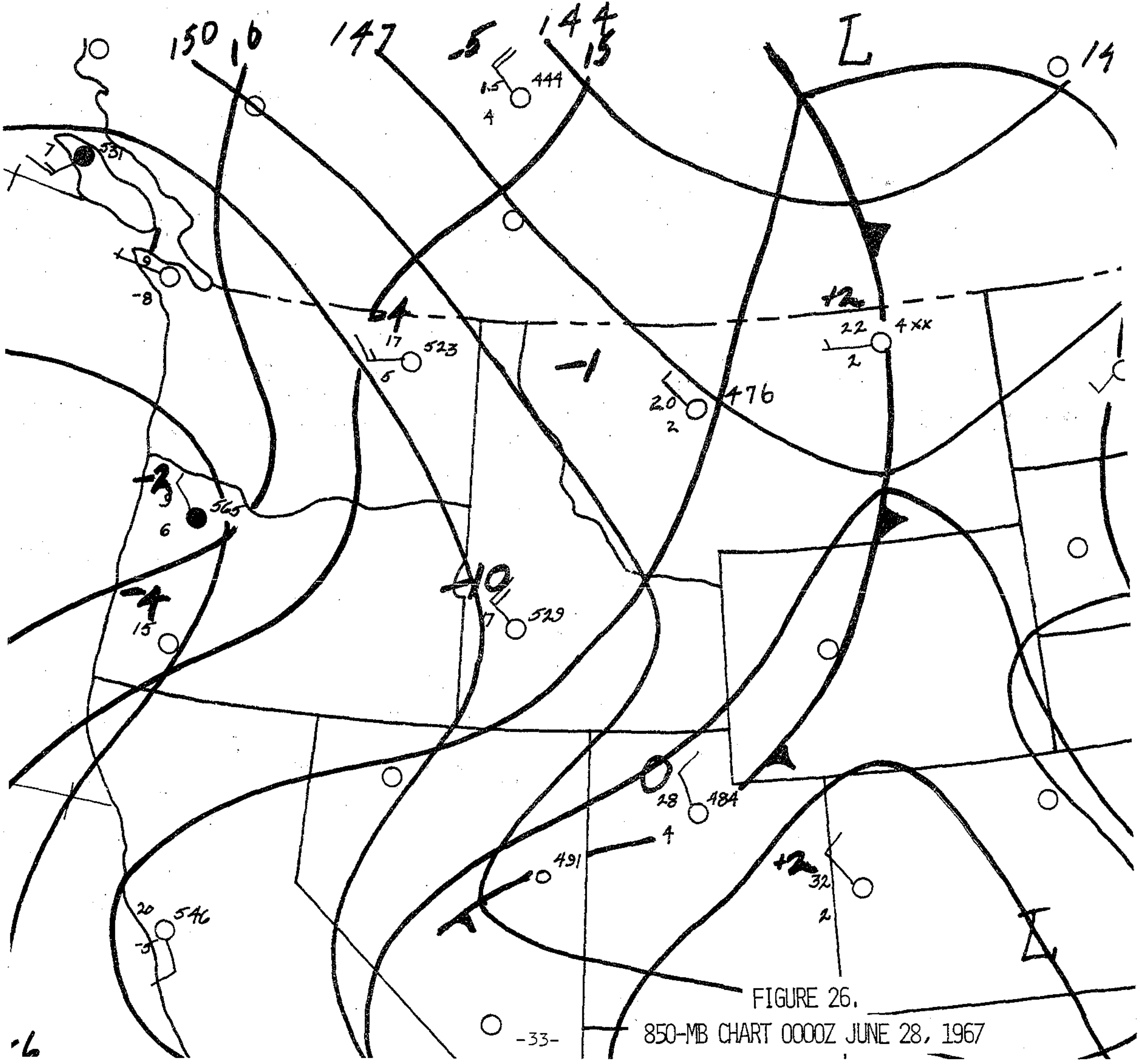


FIGURE 26. 850-MB CHART 0000Z JUNE 28, 1967

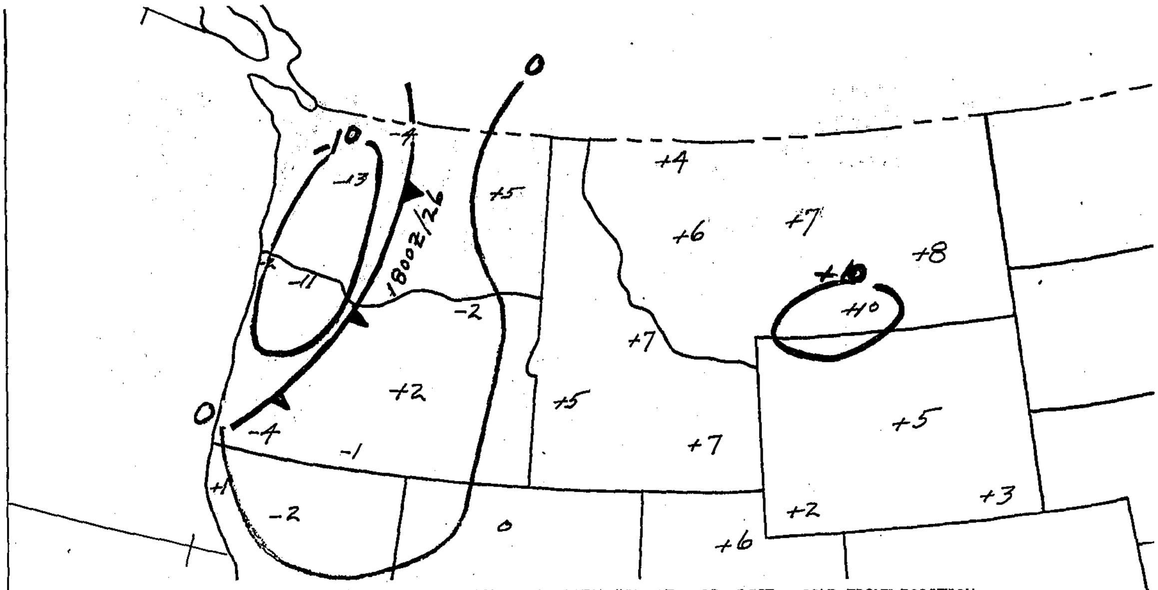


FIGURE 27A. CHANGE IN MAXIMUM TEMPERATURE JUNE 25 - 26, 1967. COLD FRONT POSITION IS FOR 1800Z JUNE 26.

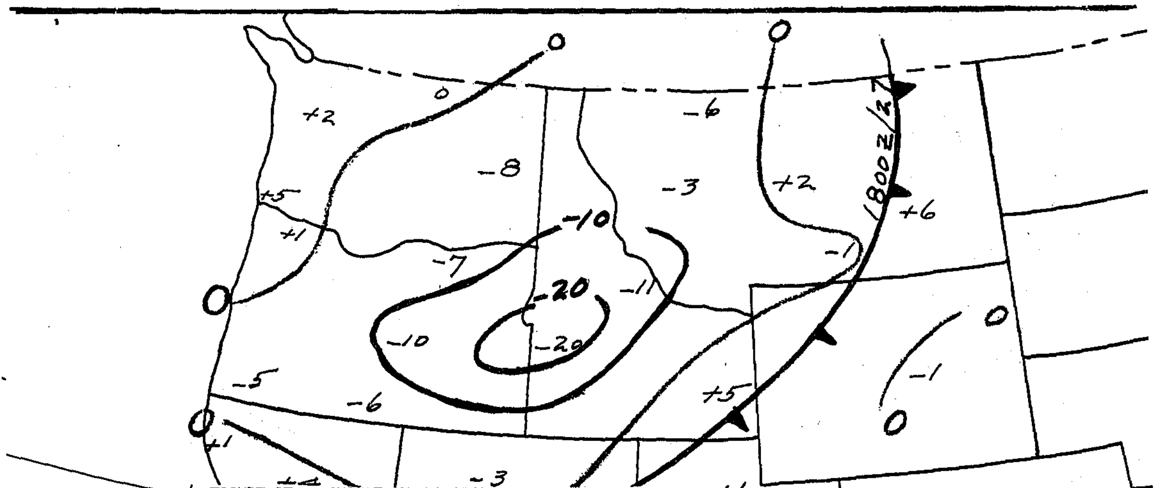


FIGURE 27B. CHANGE IN MAXIMUM TEMPERATURE JUNE 26 - 27, 1967. COLD FRONT POSITION IS FOR 1800Z JUNE 27.

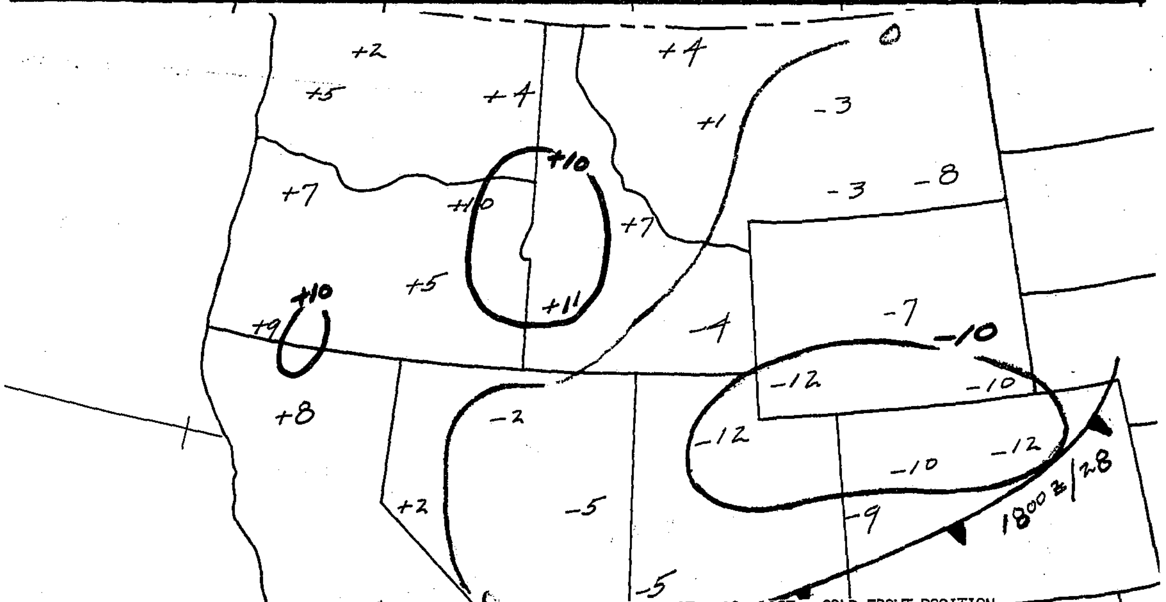


FIGURE 27C. CHANGE IN MAXIMUM TEMPERATURE JUNE 27 - 28, 1967. COLD FRONT POSITION IS FOR 1800Z JUNE 28.

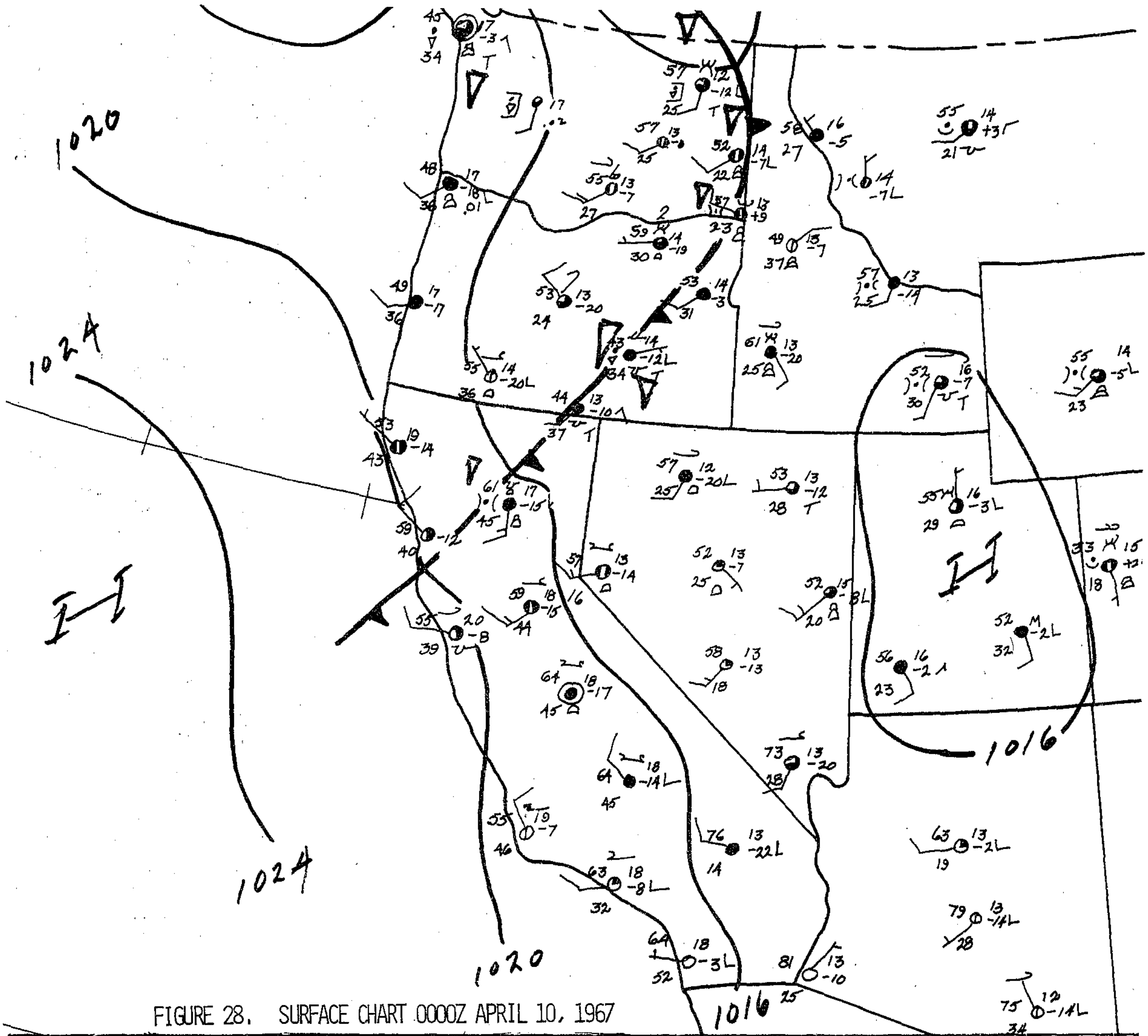


FIGURE 28. SURFACE CHART 0000Z APRIL 10, 1967

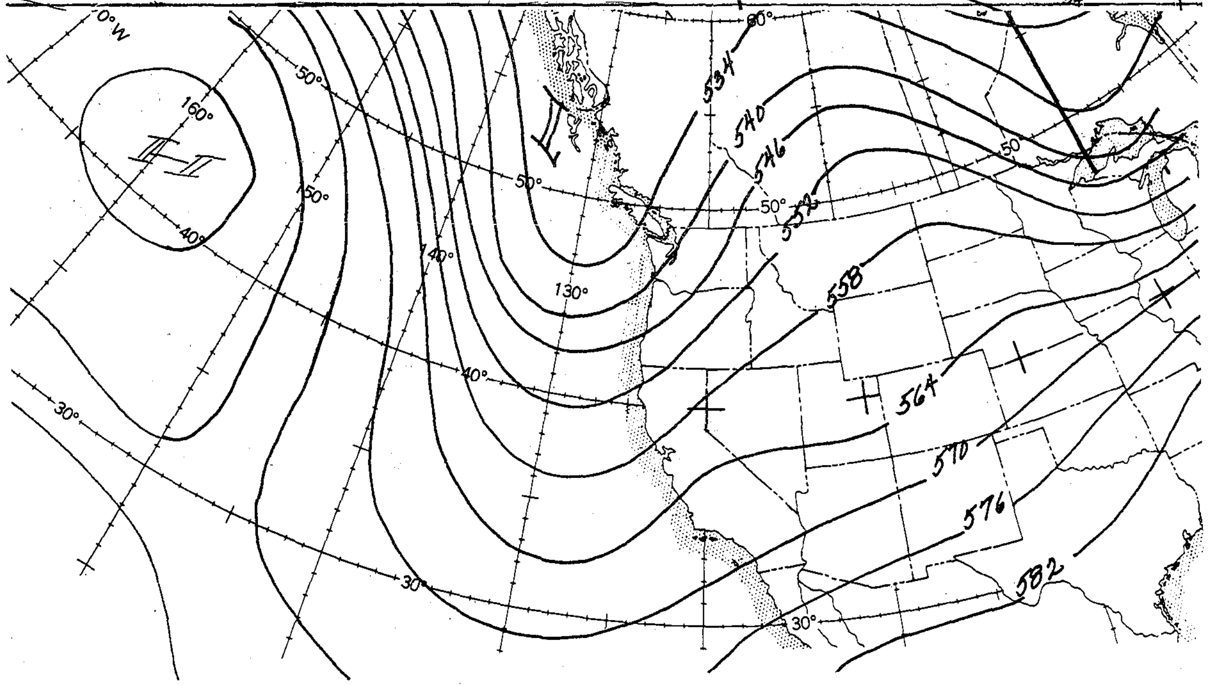


FIGURE 29. 500-MB ANALYSIS, 0000Z APRIL 10, 1967.

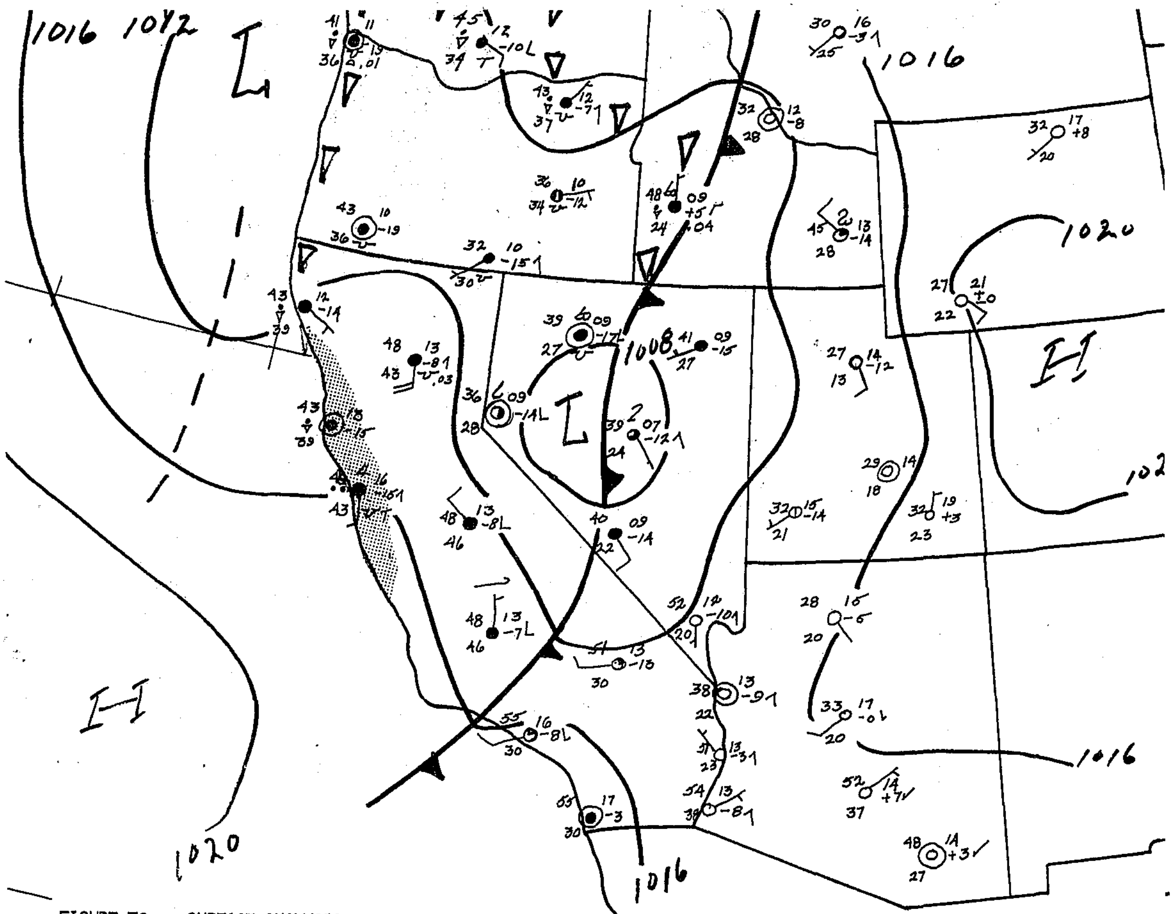


FIGURE 30. SURFACE ANALYSIS, 1200Z APRIL 10, 1967.

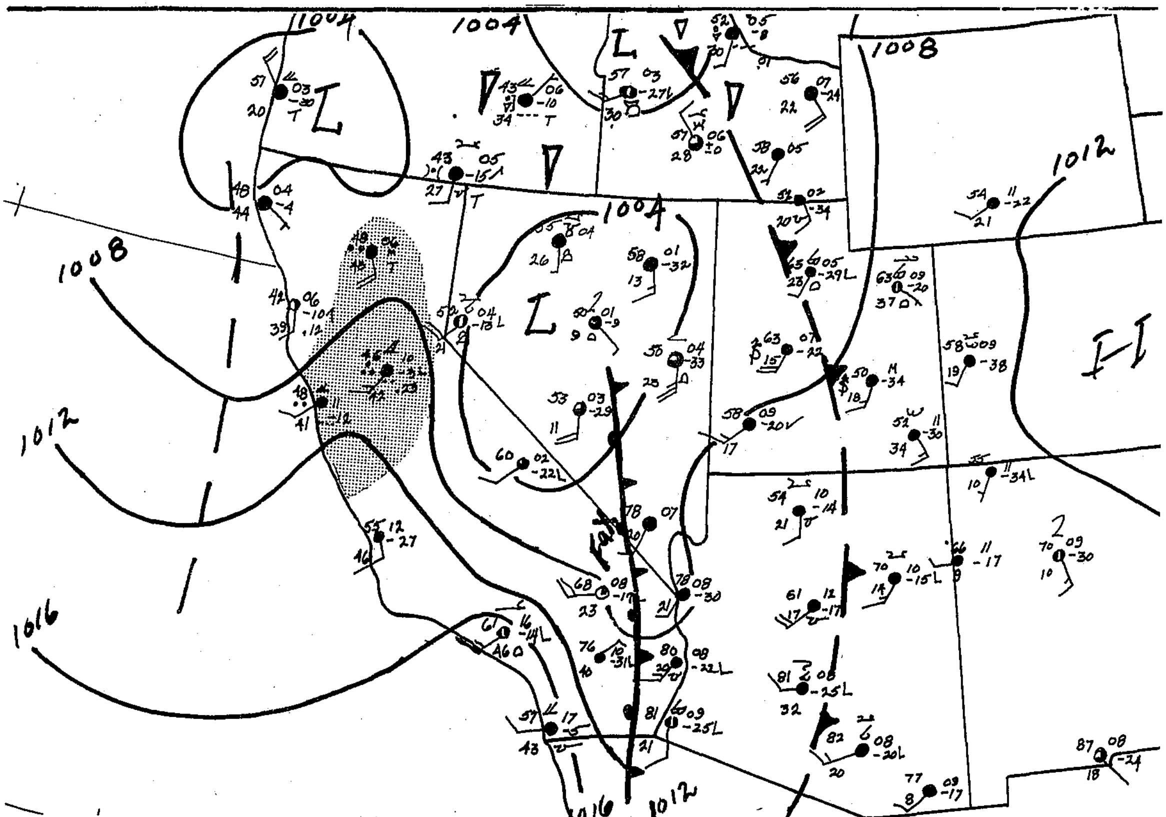


FIGURE 31. SURFACE ANALYSIS, 0000Z APRIL 11, 1967.

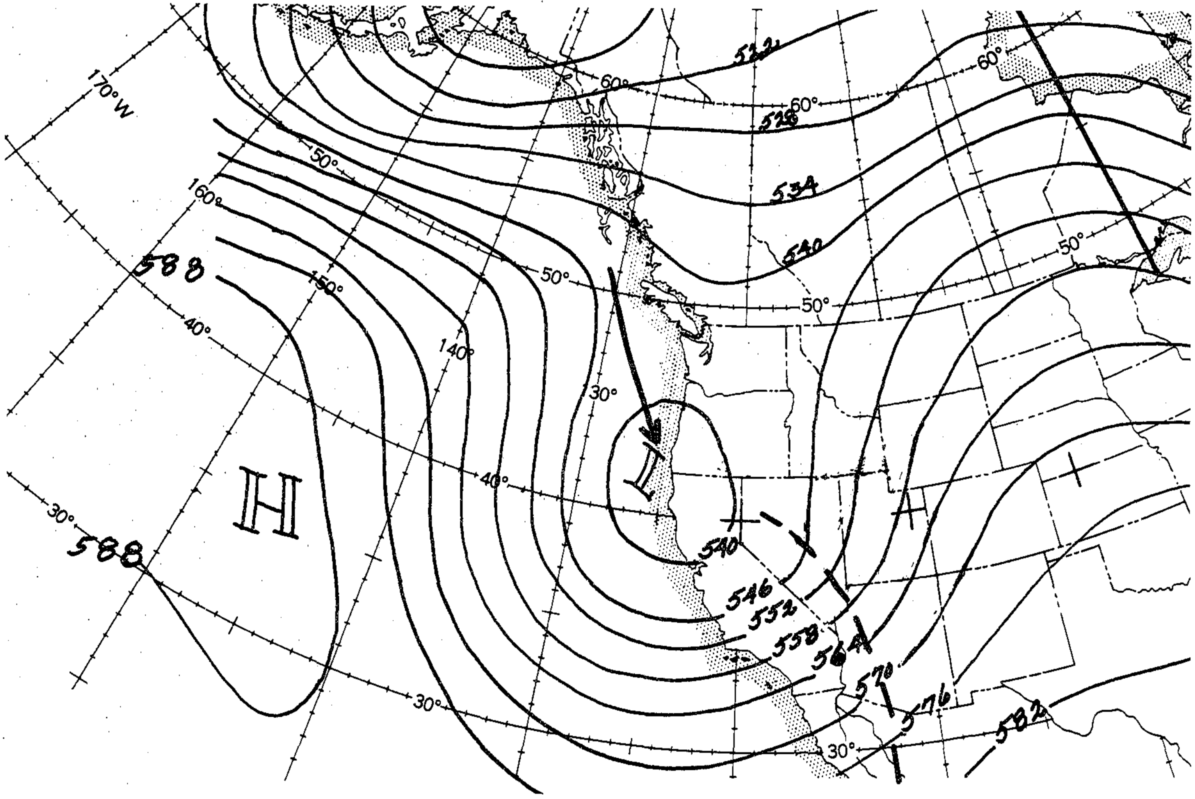


FIGURE 32. 500-MB CHART 0000Z APRIL 11, 1967

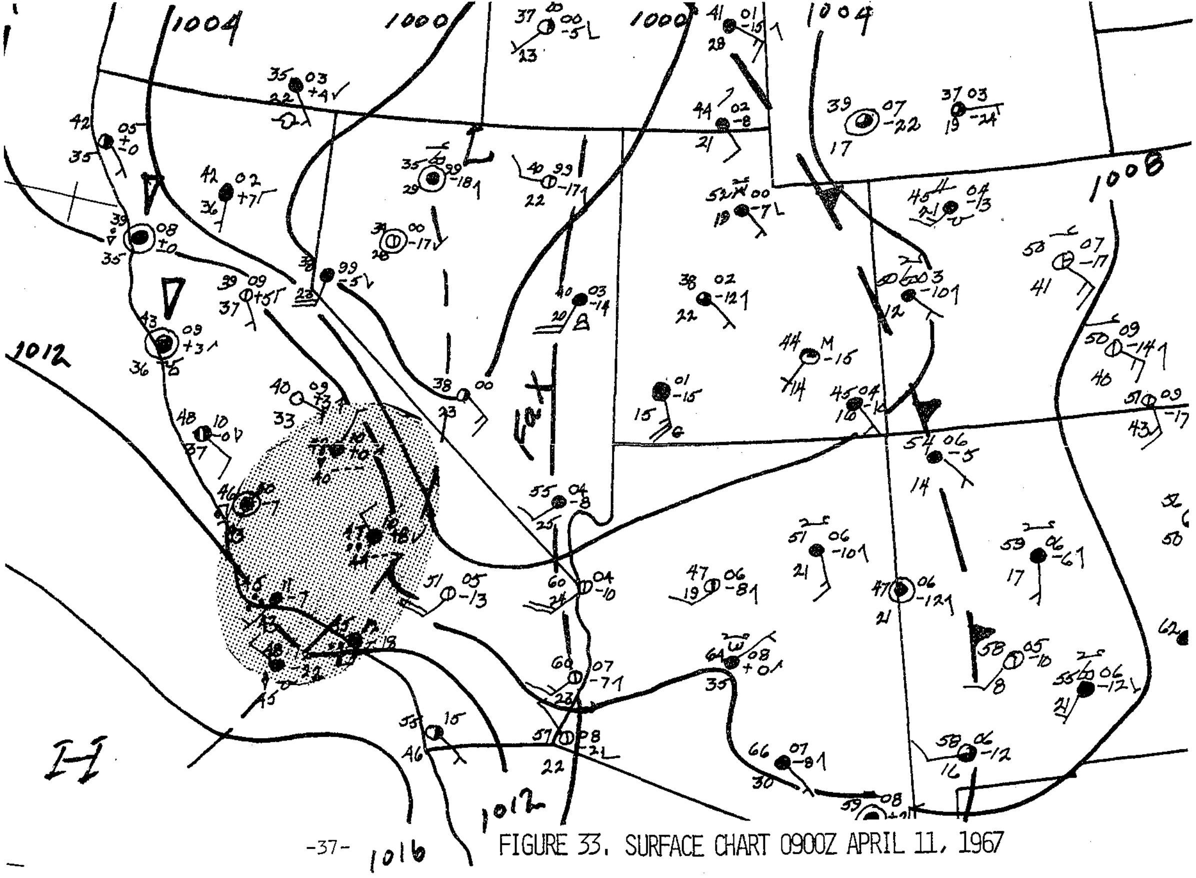


FIGURE 33. SURFACE CHART 0900Z APRIL 11, 1967

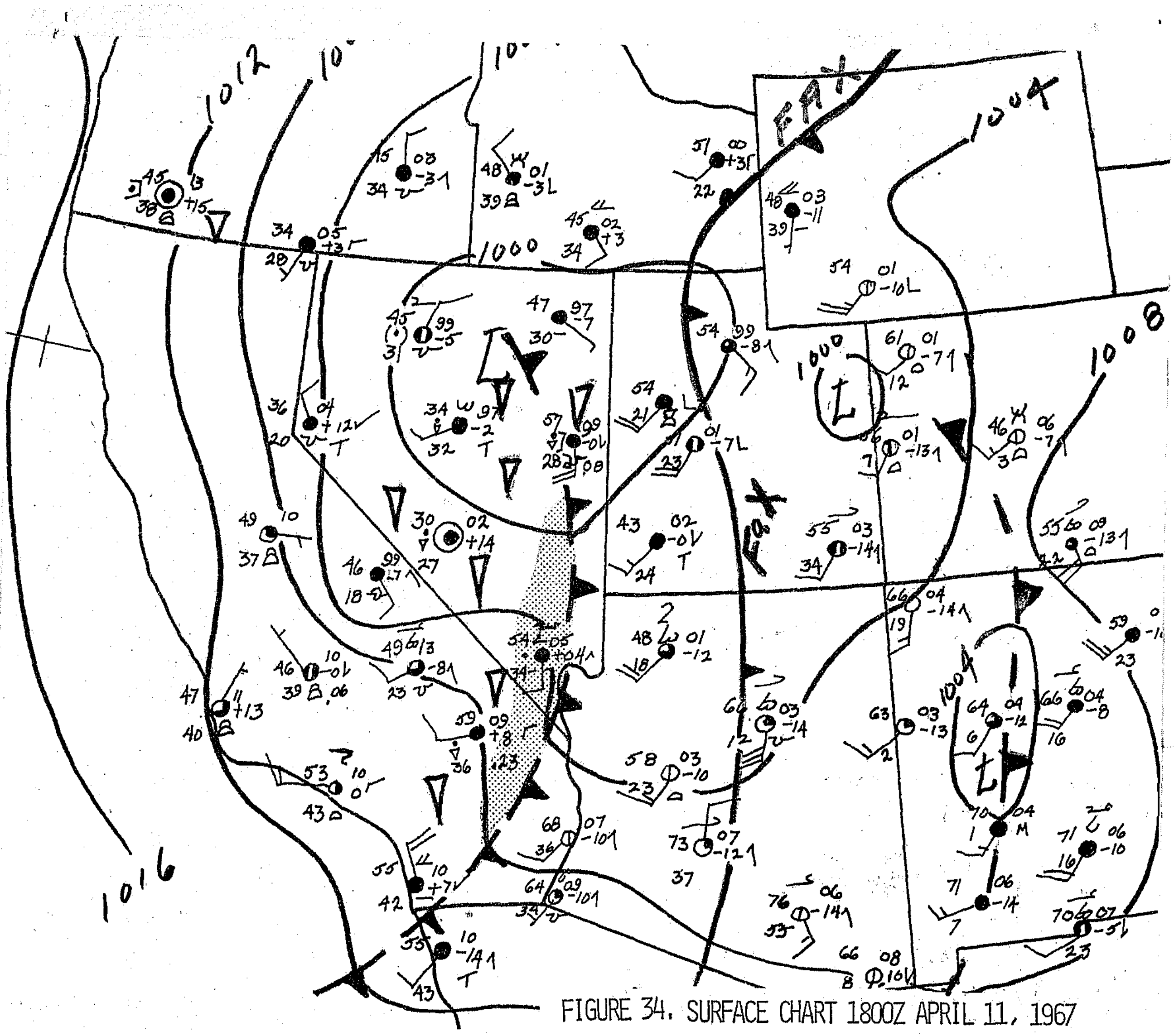


FIGURE 34. SURFACE CHART 1800Z APRIL 11, 1967

FIGURE 35. ESSA 3 SATELLITE PICTURE, 2137Z APRIL 11, 1967.

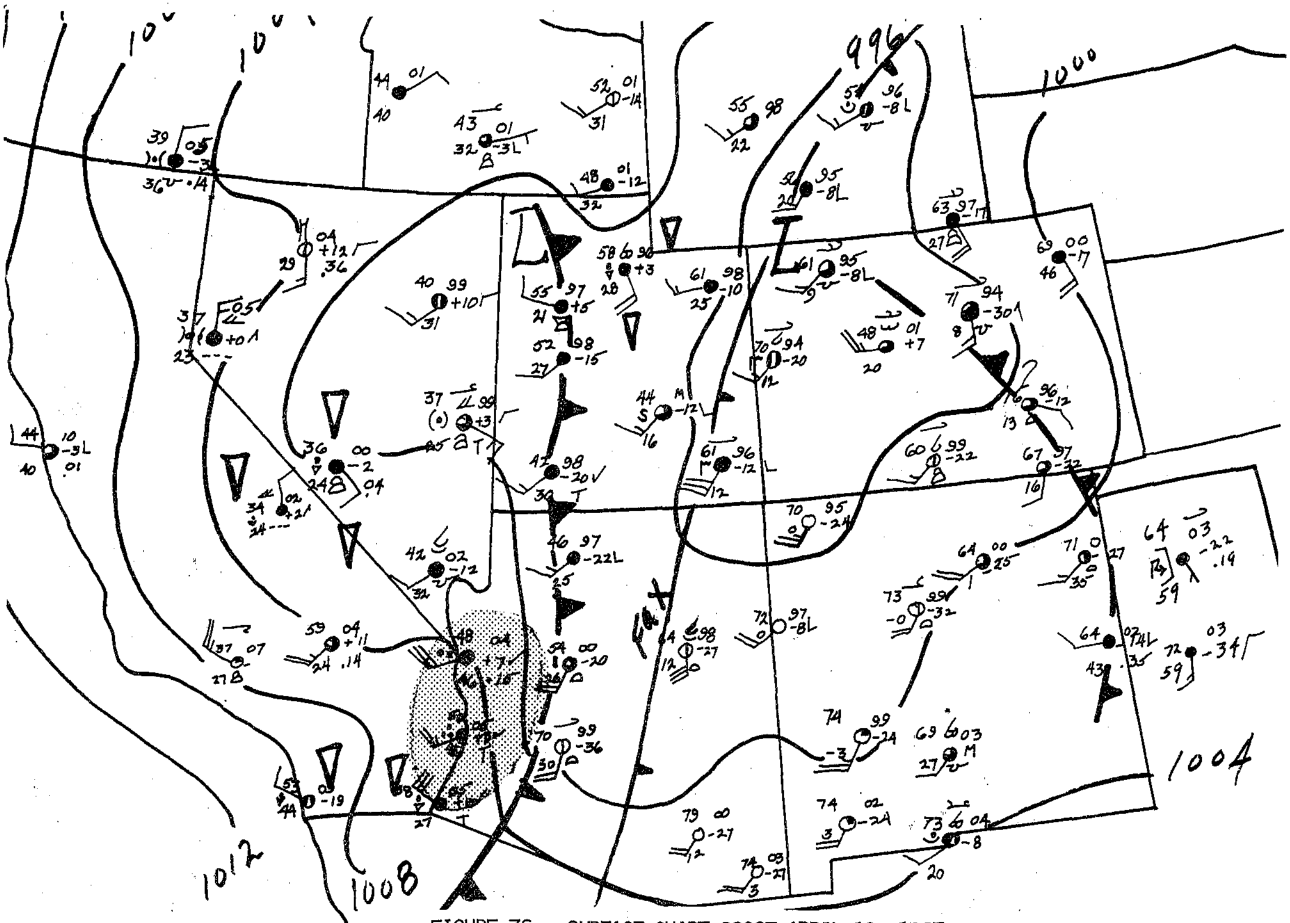


FIGURE 36. SURFACE CHART 0000Z APRIL 12, 1967

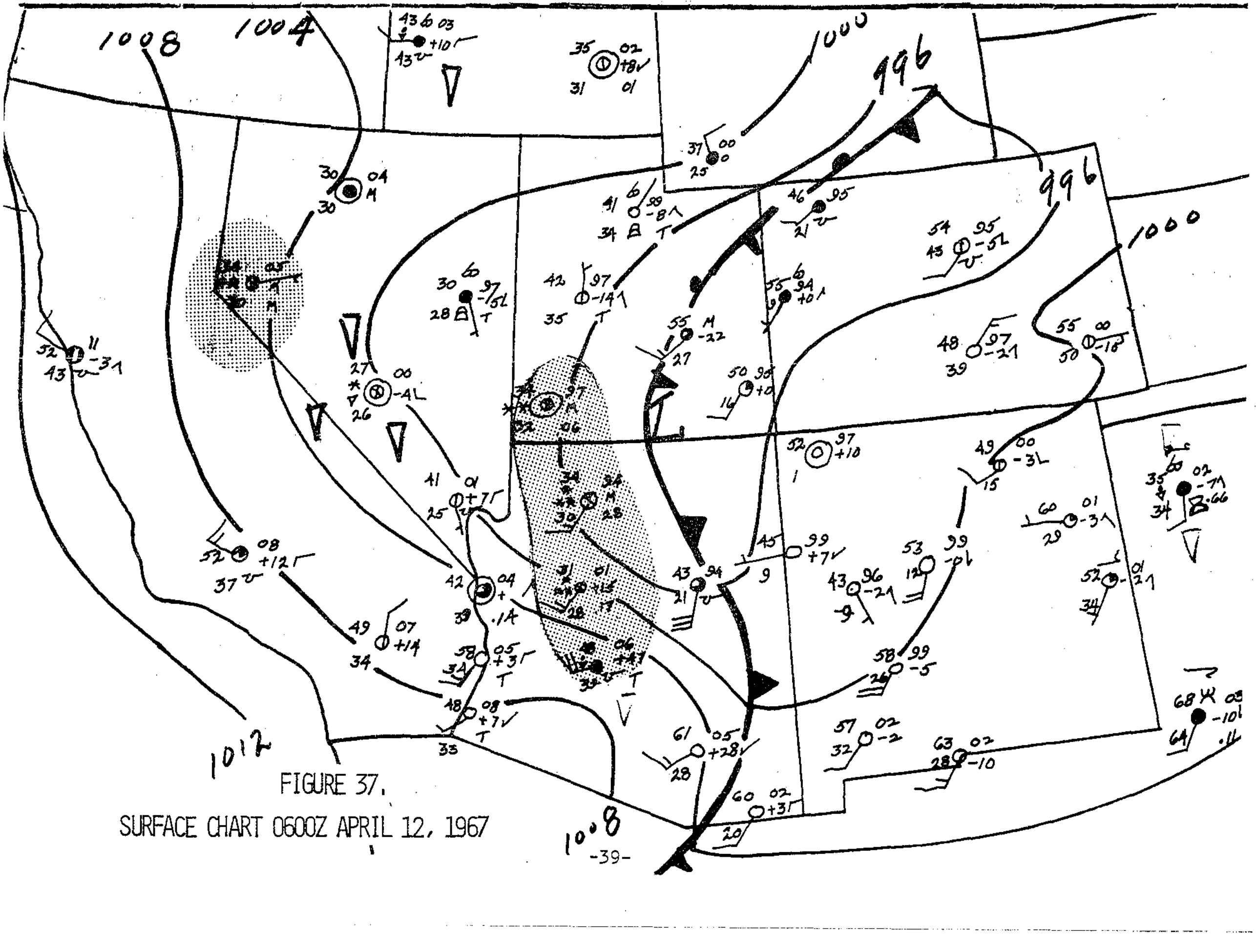
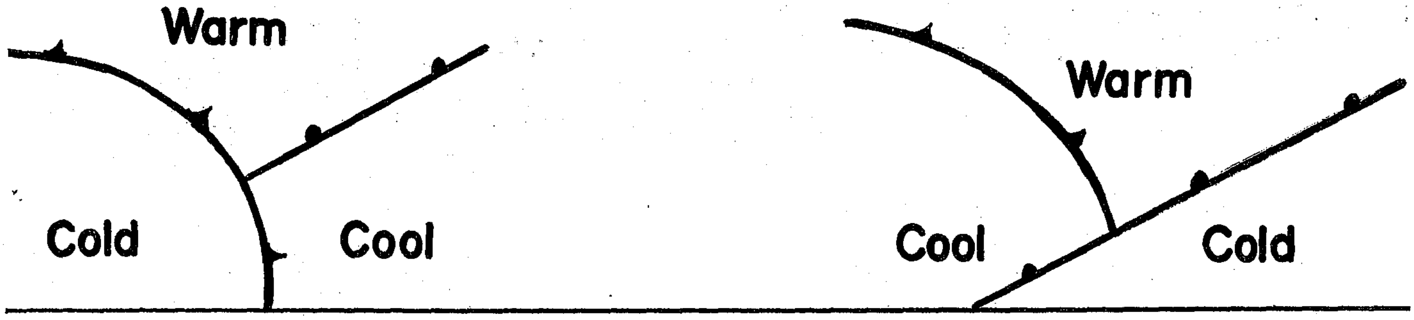


FIGURE 37.
SURFACE CHART 0600Z APRIL 12, 1967



Cold Occlusion

Warm Occlusion

FIGURE 38. WARM AND COLD TYPE OCCLUSIONS.

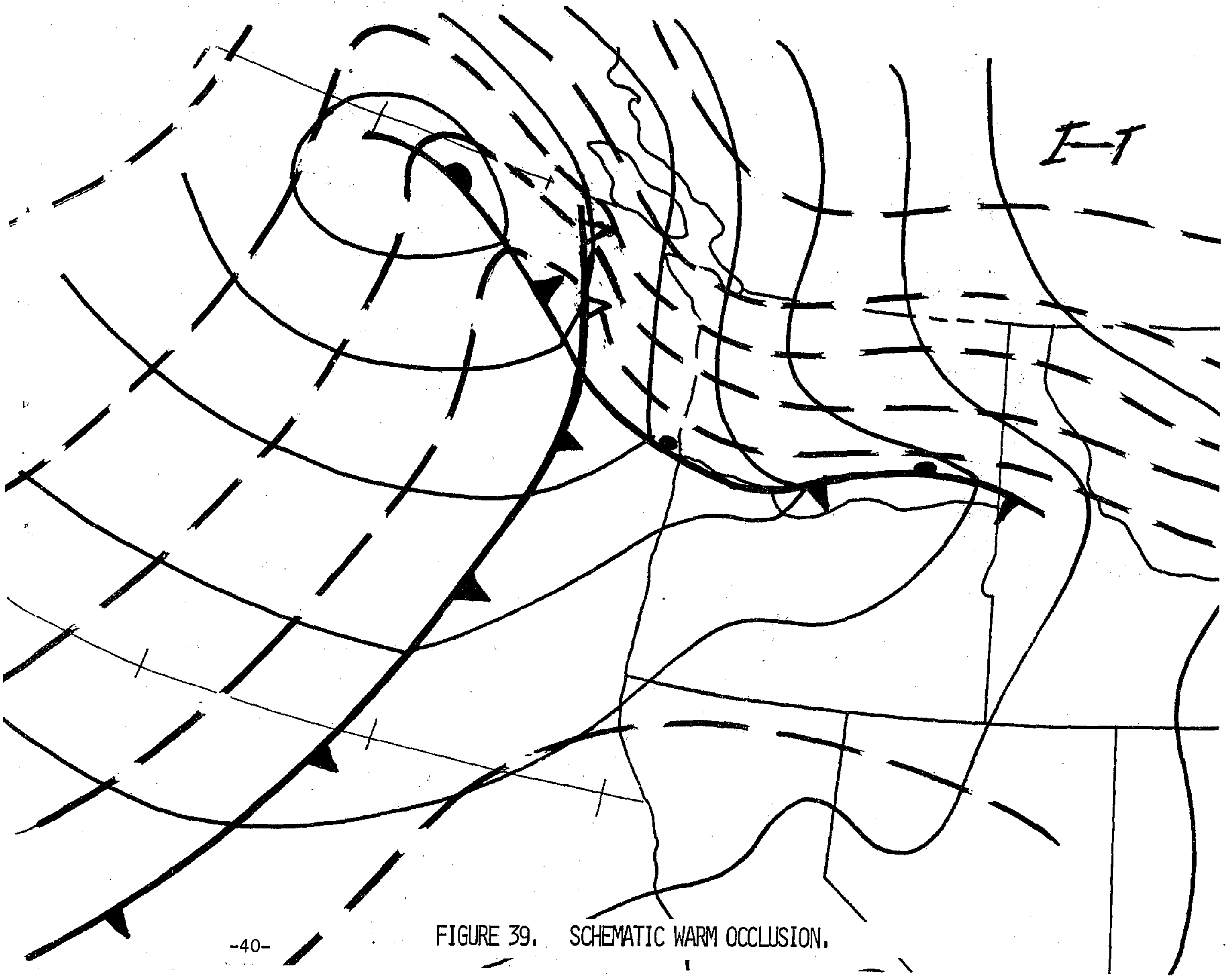


FIGURE 39. SCHEMATIC WARM OCCLUSION.

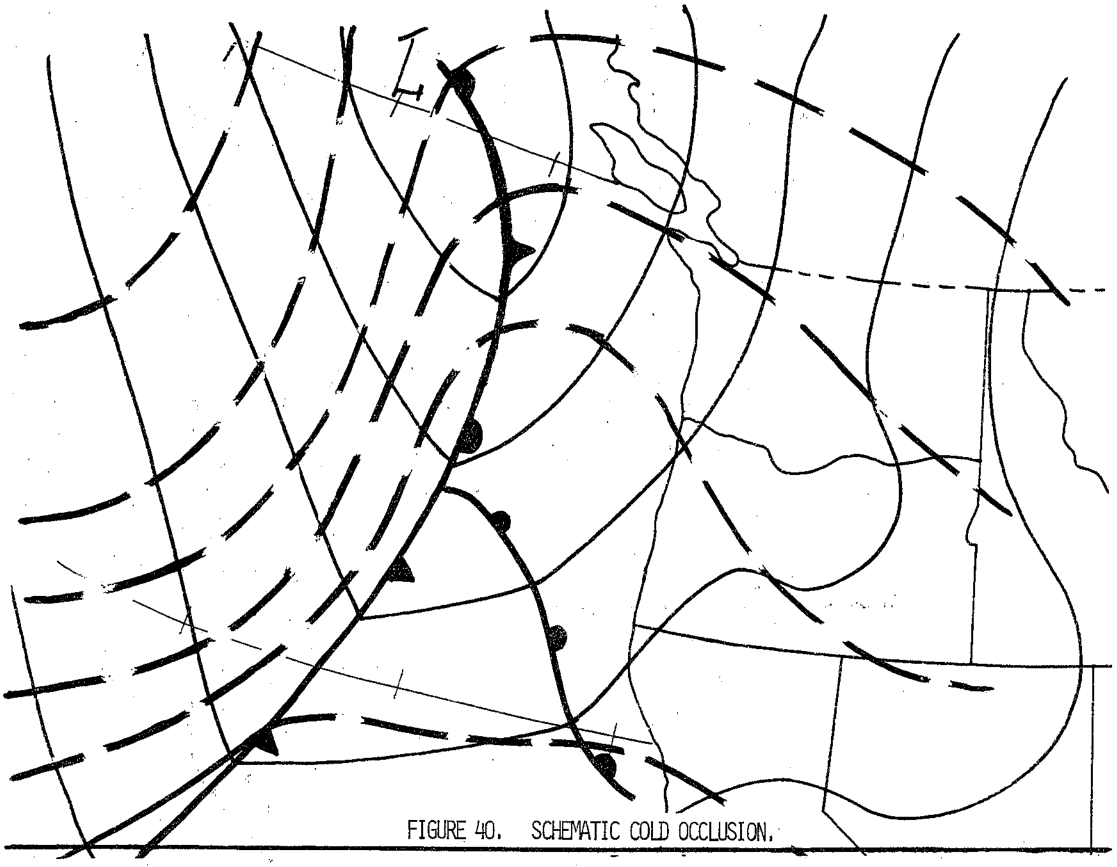


FIGURE 40. SCHEMATIC COLD OCCLUSION.

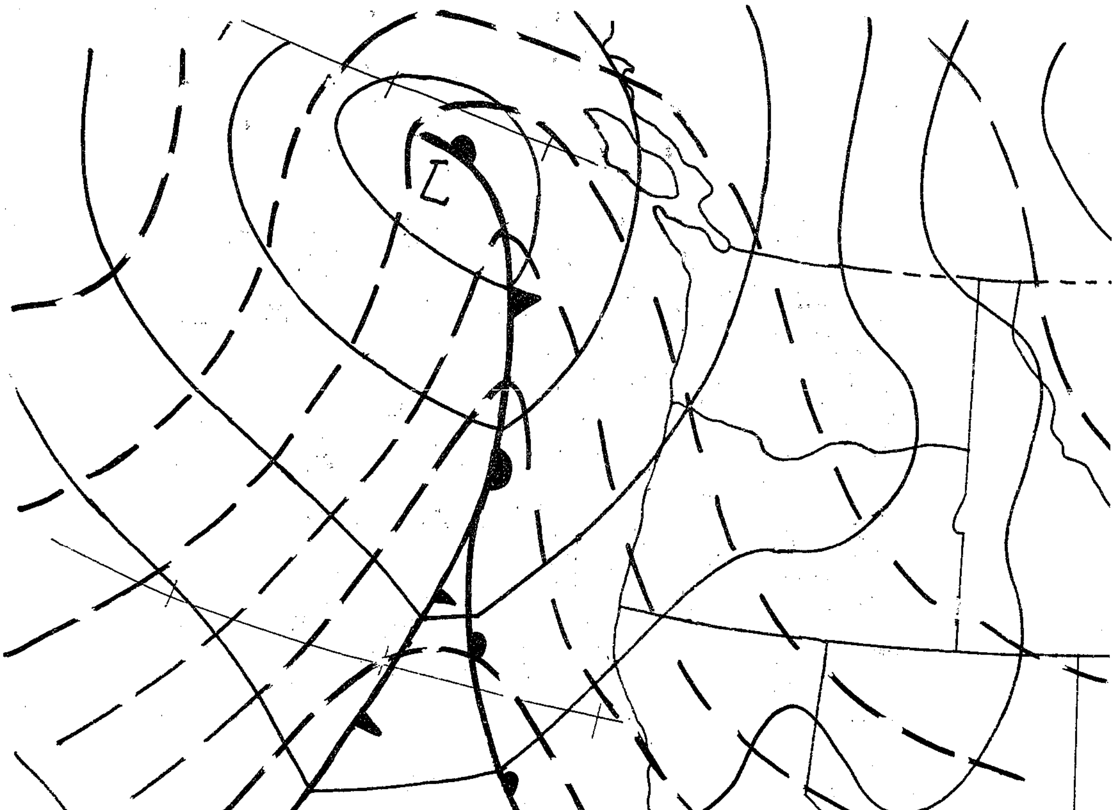


FIGURE 41. SCHEMATIC NEUTRAL OCCLUSION.

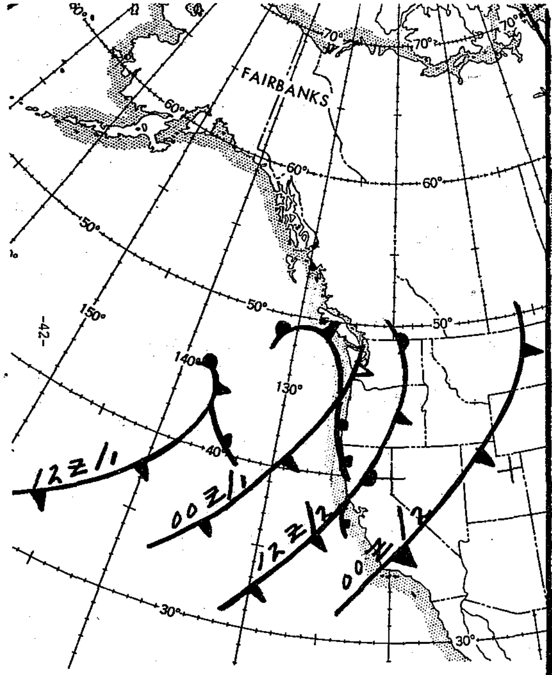


FIGURE 42. TYPICAL WINTER SYNOPTIC SEQUENCE.

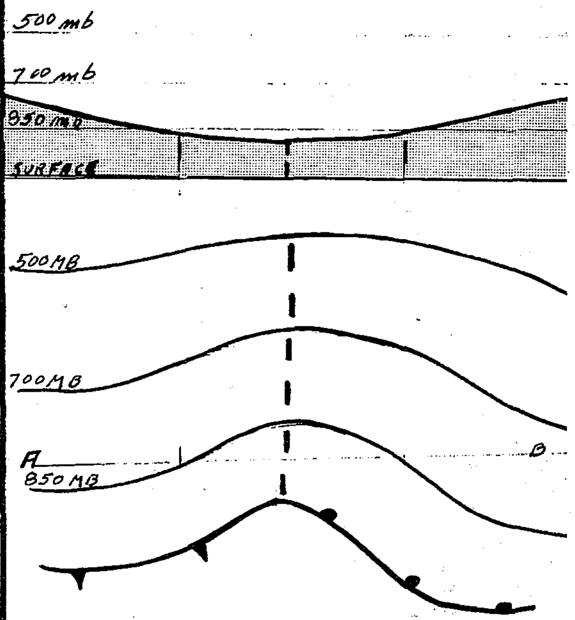


FIGURE 43. INCIPIENT TROWAL

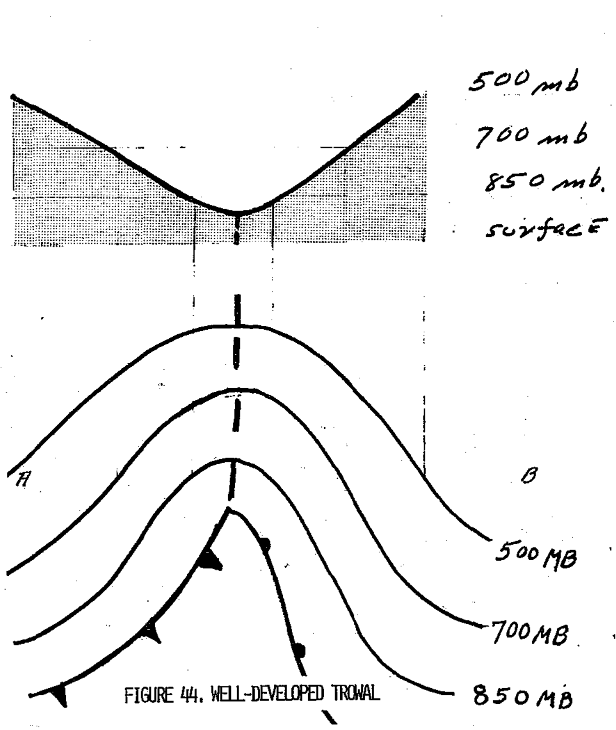


FIGURE 44. WELL-DEVELOPED TROWAL

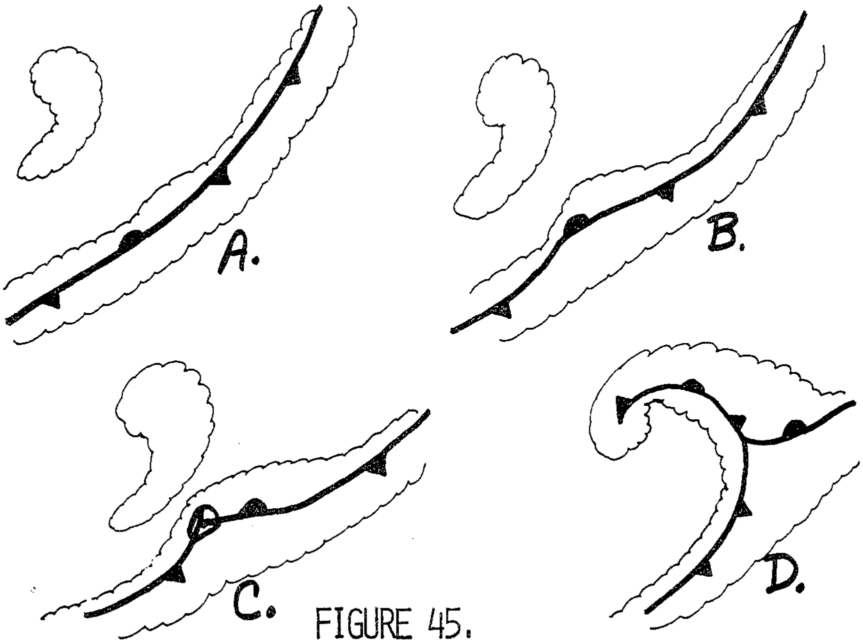


FIGURE 45.

Schematic Development of "Instant" Occlusion.

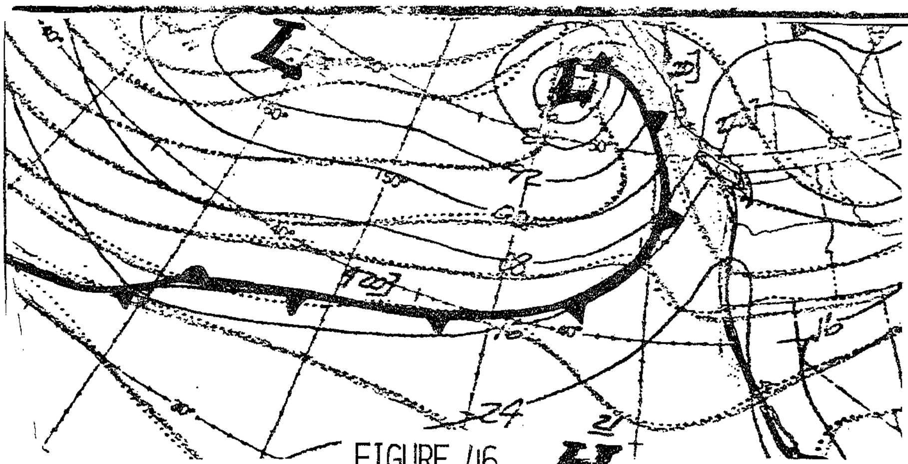


FIGURE 46.

NMC Surface Analysis 0000Z, April 8, 1970.

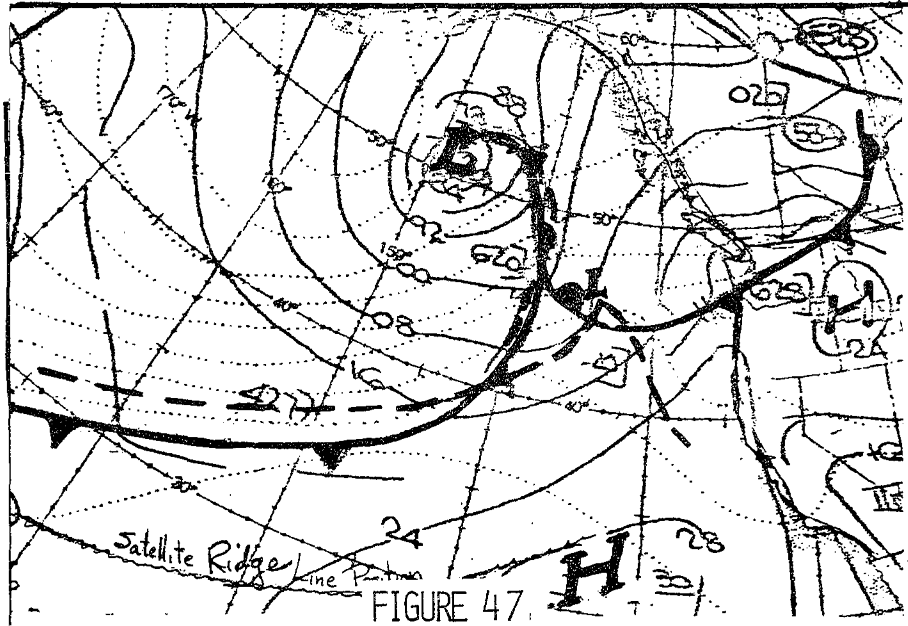


FIGURE 47.

NMC Surface Analysis 0000Z, April 9, 1970. Heavy dashed lines are analysis indicated by interpretation of satellite picture

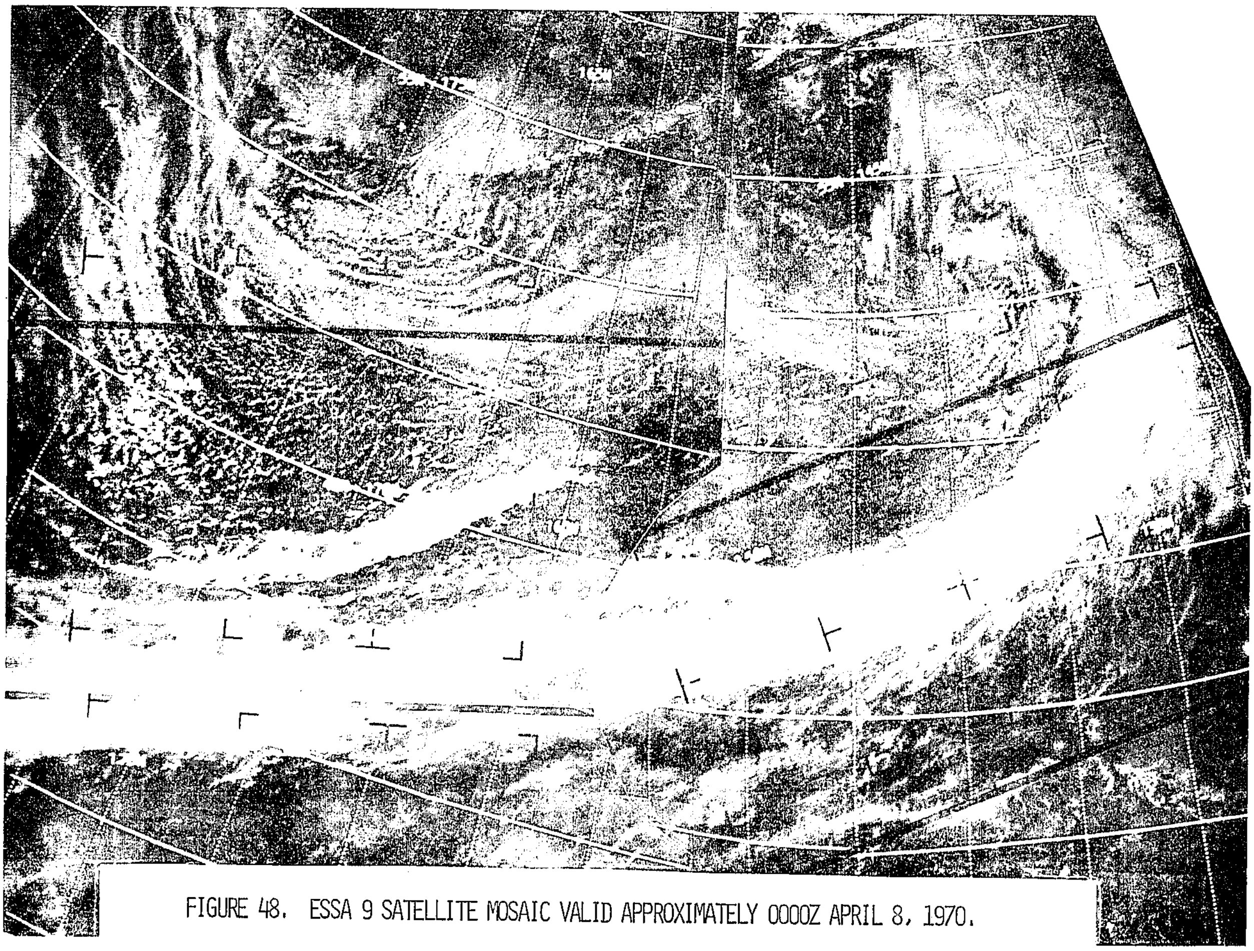


FIGURE 48. ESSA 9 SATELLITE MOSAIC VALID APPROXIMATELY 0000Z APRIL 8, 1970.

FIGURE 49. ESSA 9 SATELLITE MOSAIC VALID APPROXIMATELY 2200Z APRIL 8, 1970.

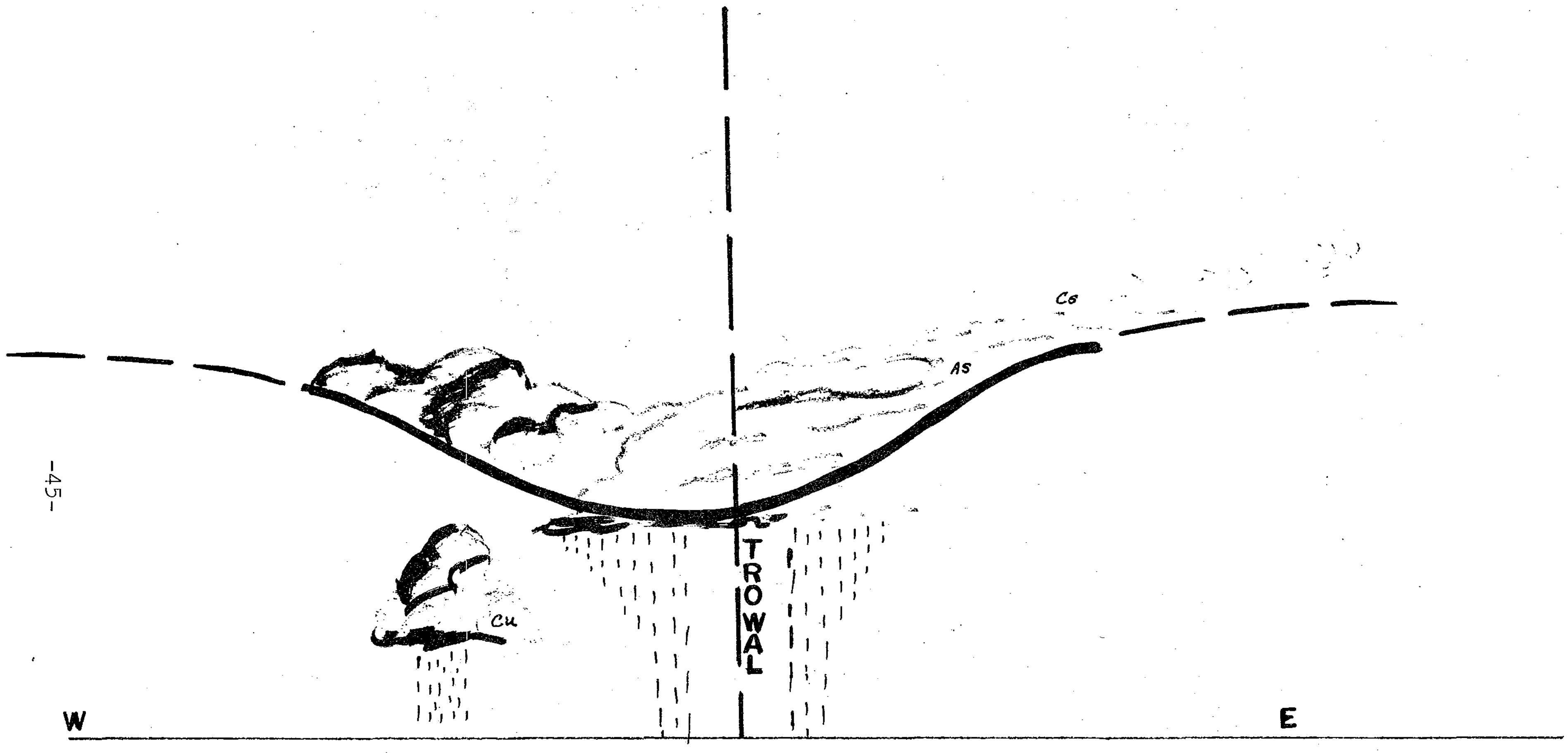


FIGURE 50. SCHEMATIC TROWAL CLOUD PATTERN.

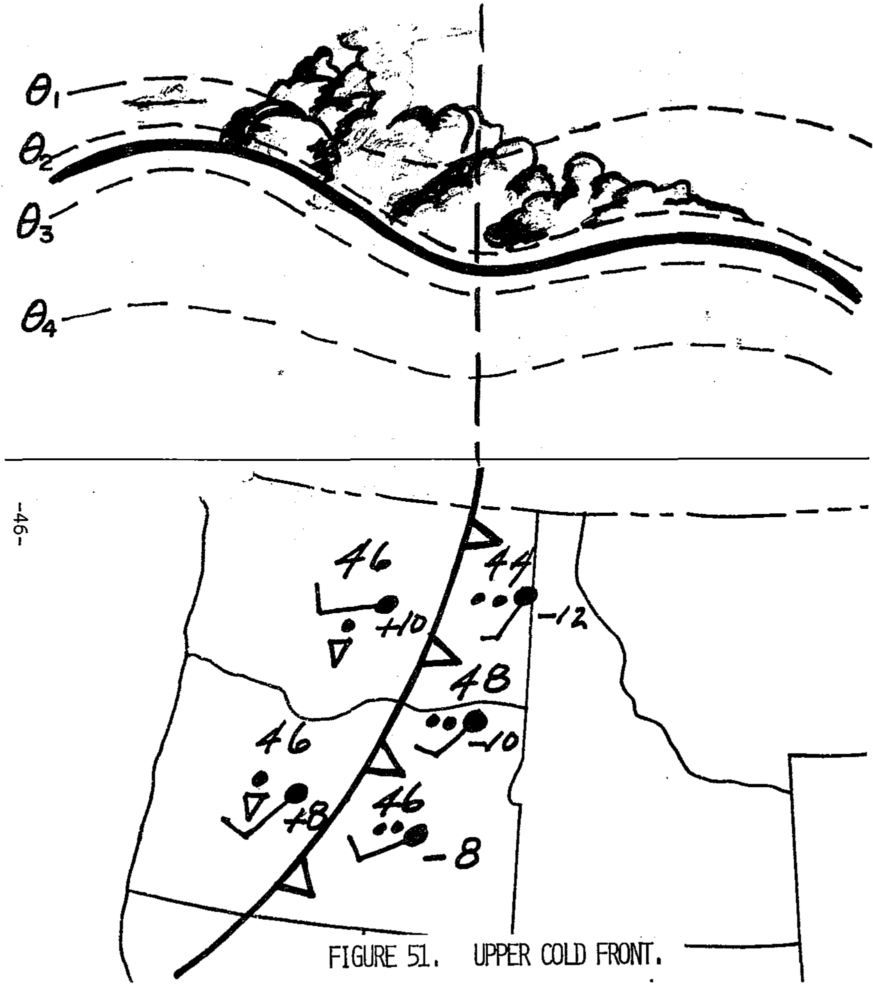


FIGURE 51. UPPER COLD FRONT.

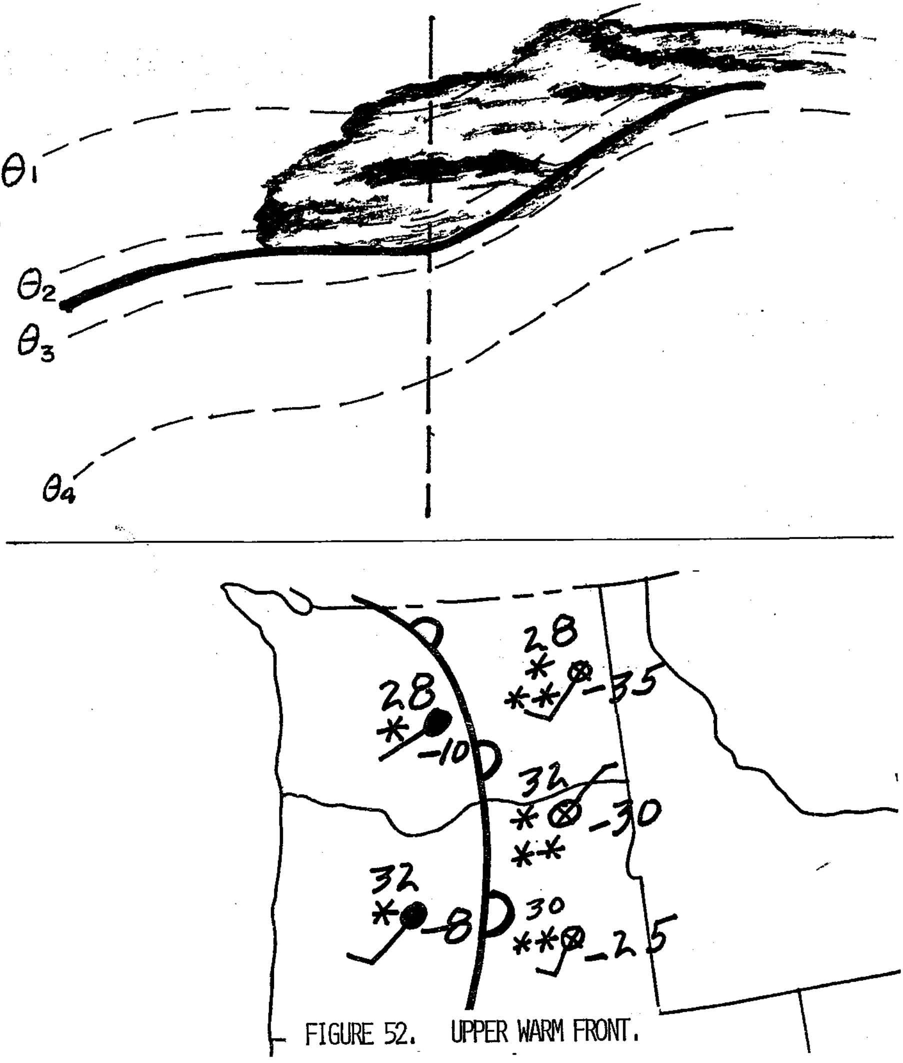


FIGURE 52. UPPER WARM FRONT.

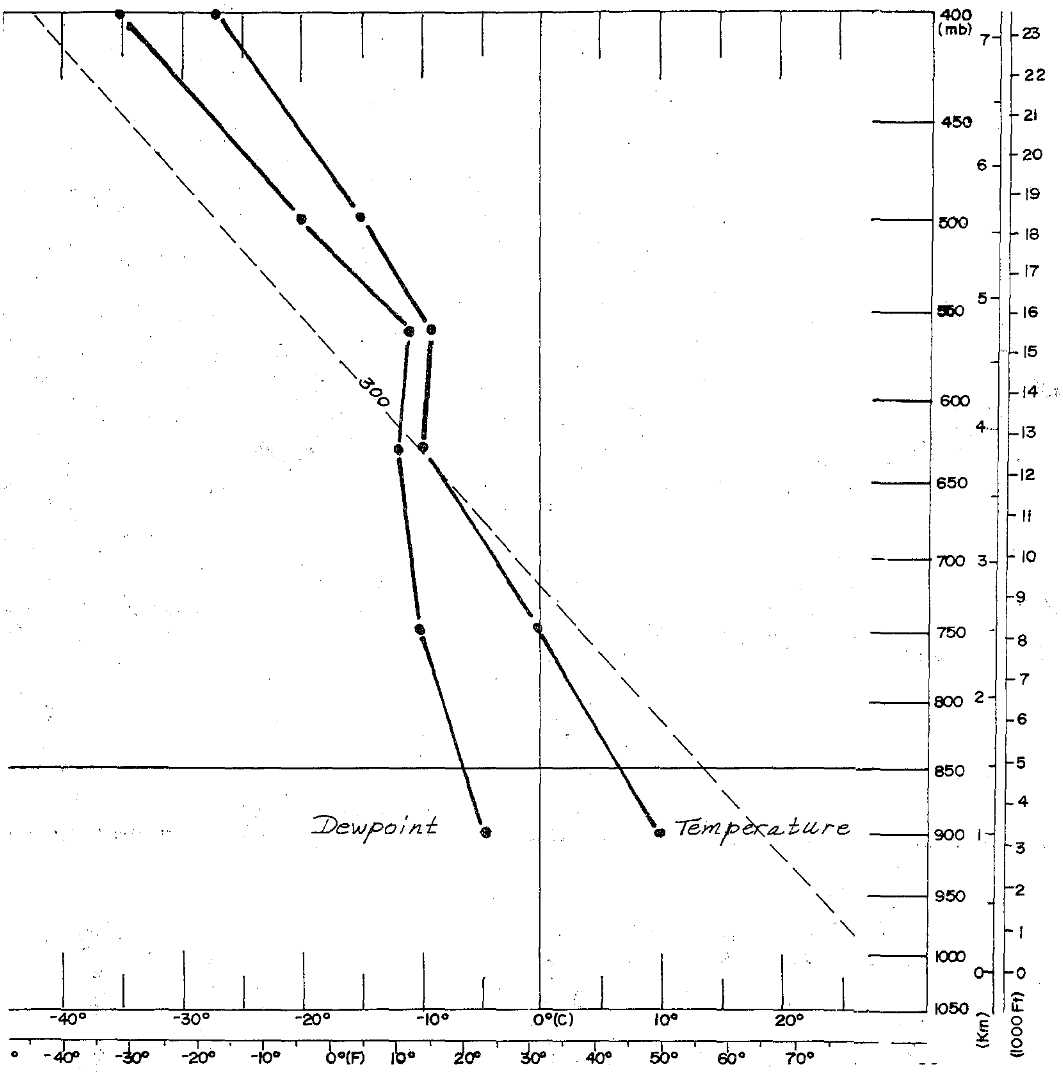


FIGURE 53. TYPICAL SOUNDING THROUGH TROWAL.

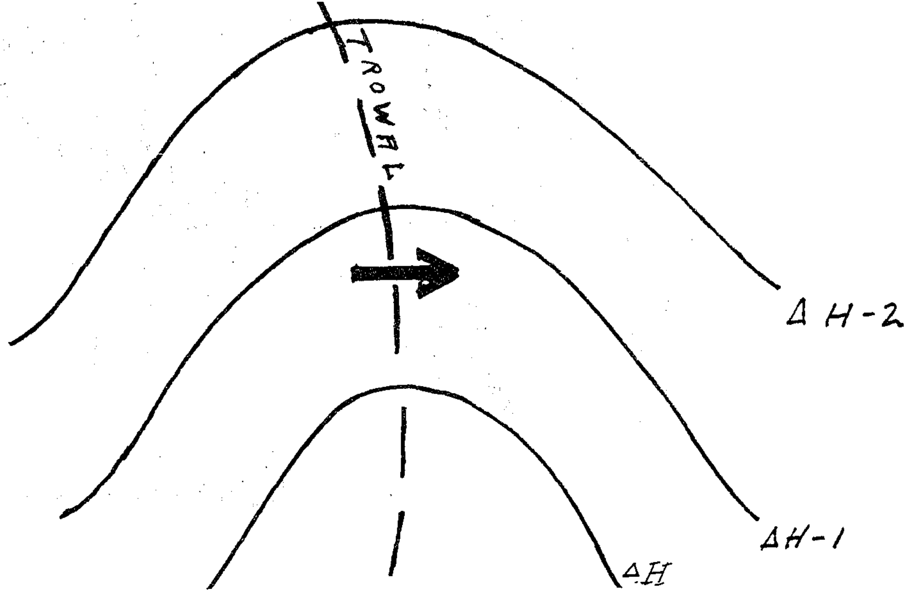


FIGURE 54. TROWAL RELATIONSHIP TO THICKNESS PATTERN.

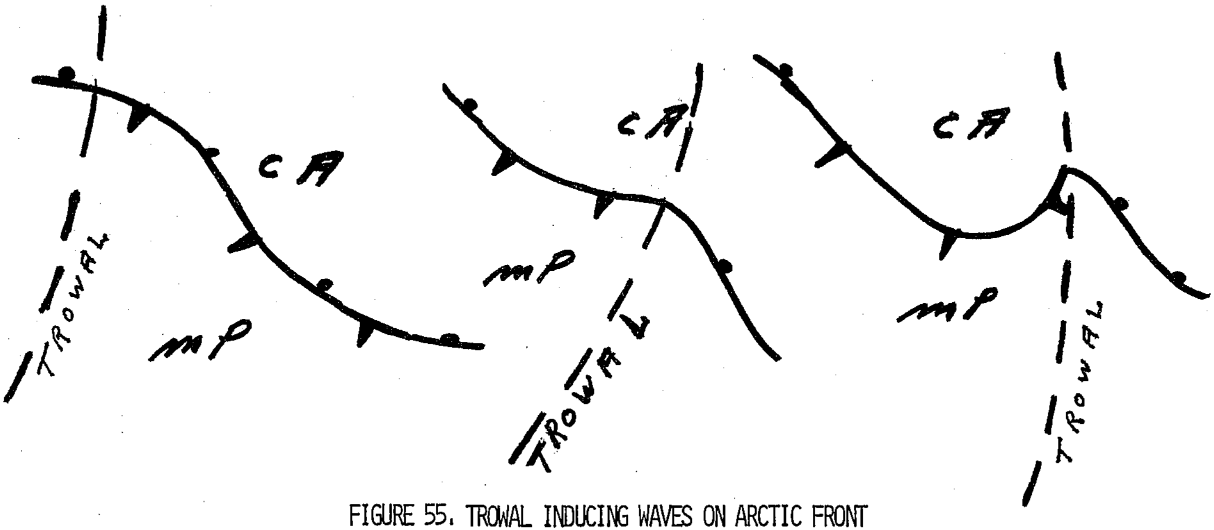


FIGURE 55. TROWAL INDUCING WAVES ON ARCTIC FRONT

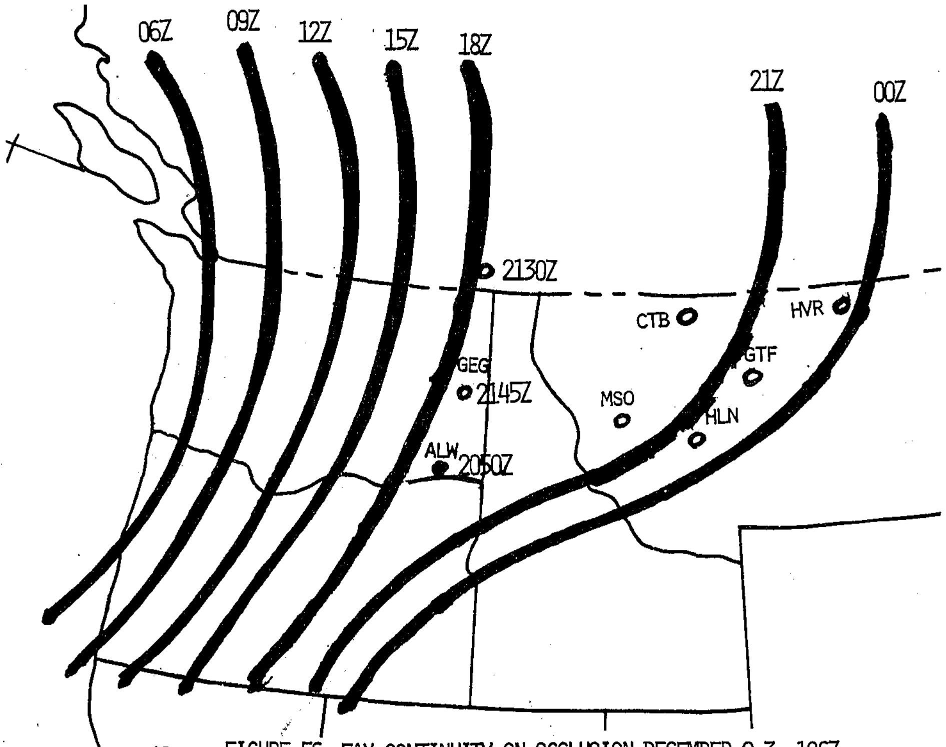


FIGURE 56. FAX CONTINUITY ON OCCLUSION DECEMBER 2-3, 1967

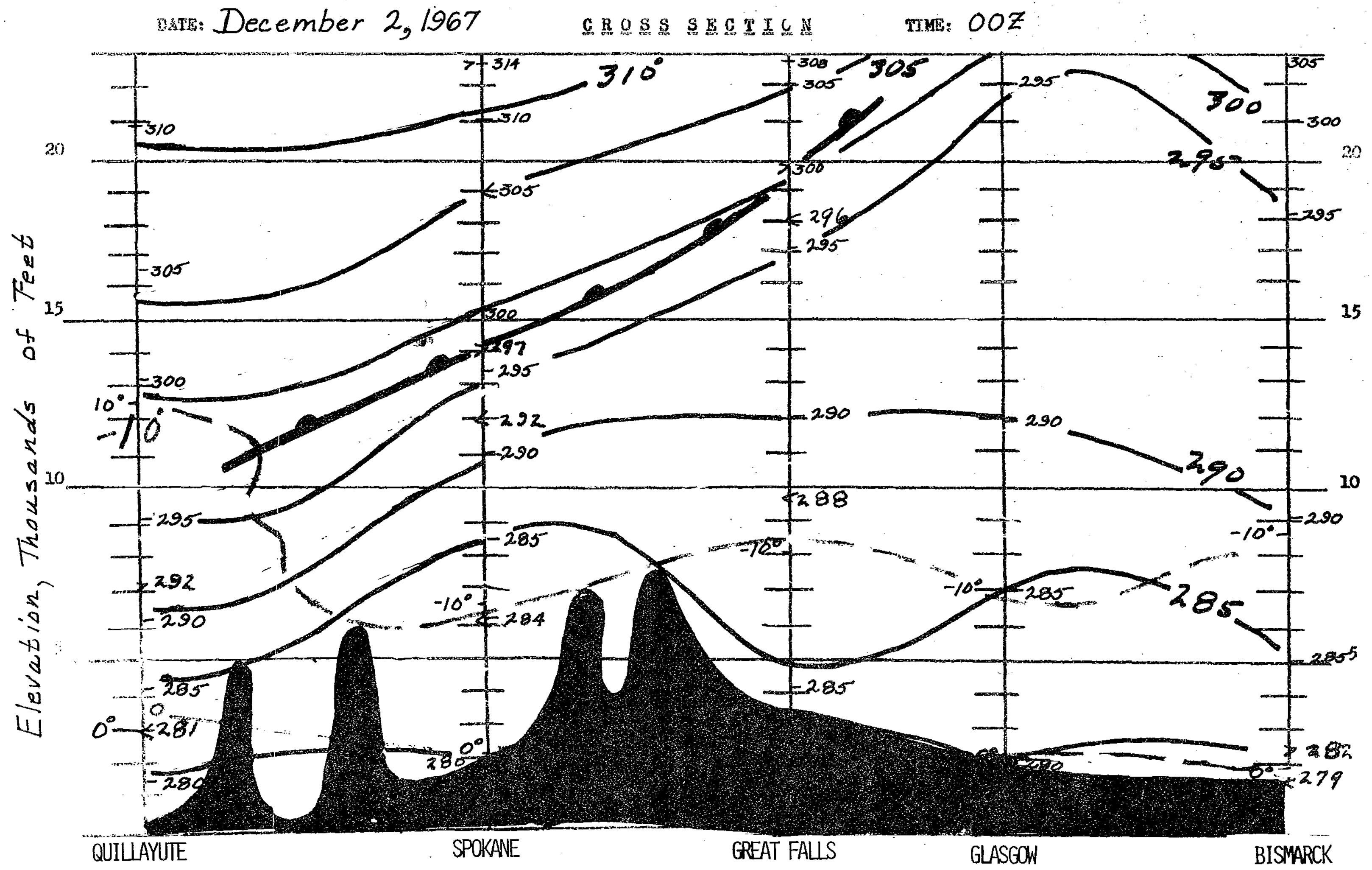


FIGURE 57. QUILLAYUTE-BISMARCK CROSS SECTION, 0000Z DECEMBER 2, 1967.

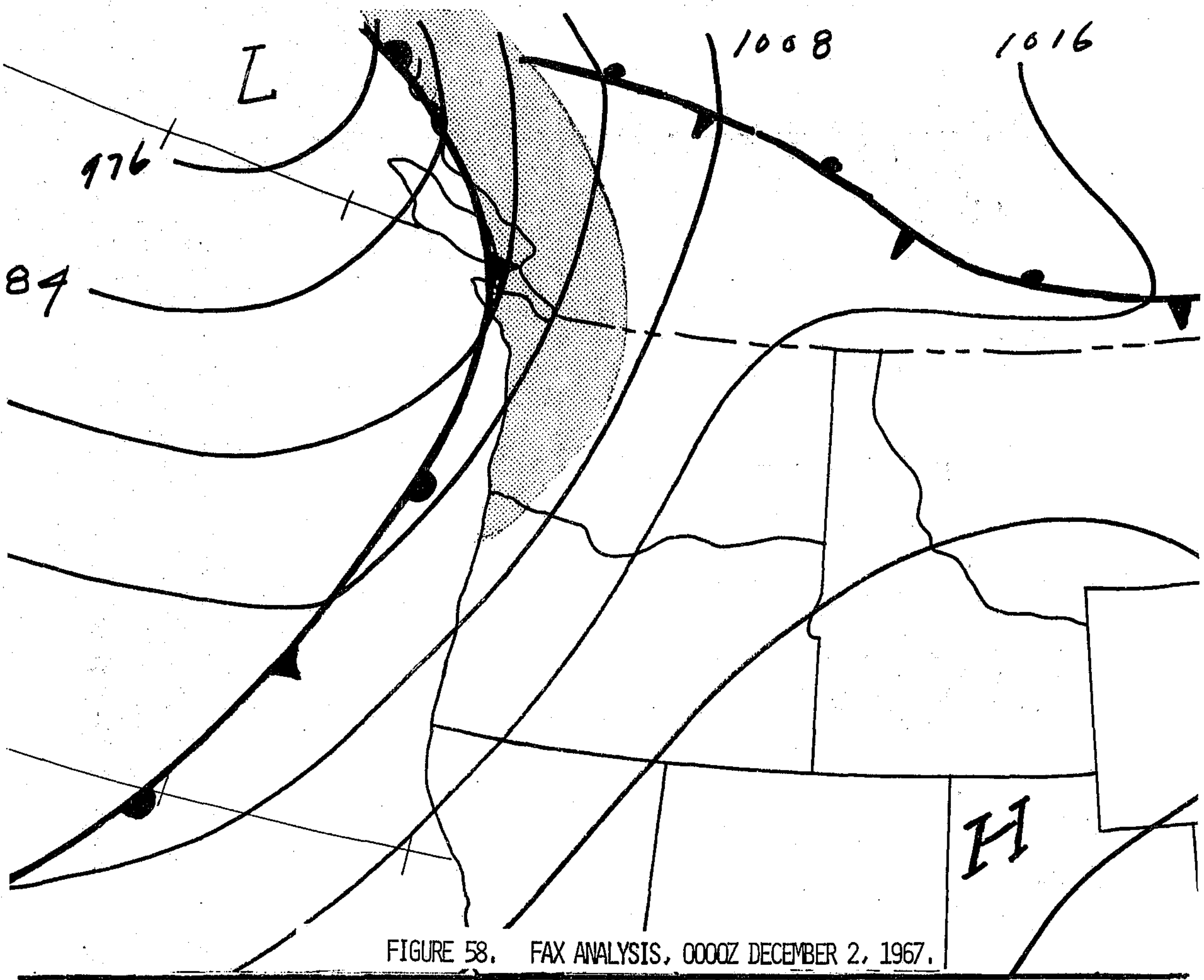


FIGURE 58. FAX ANALYSIS, 0000Z DECEMBER 2, 1967.

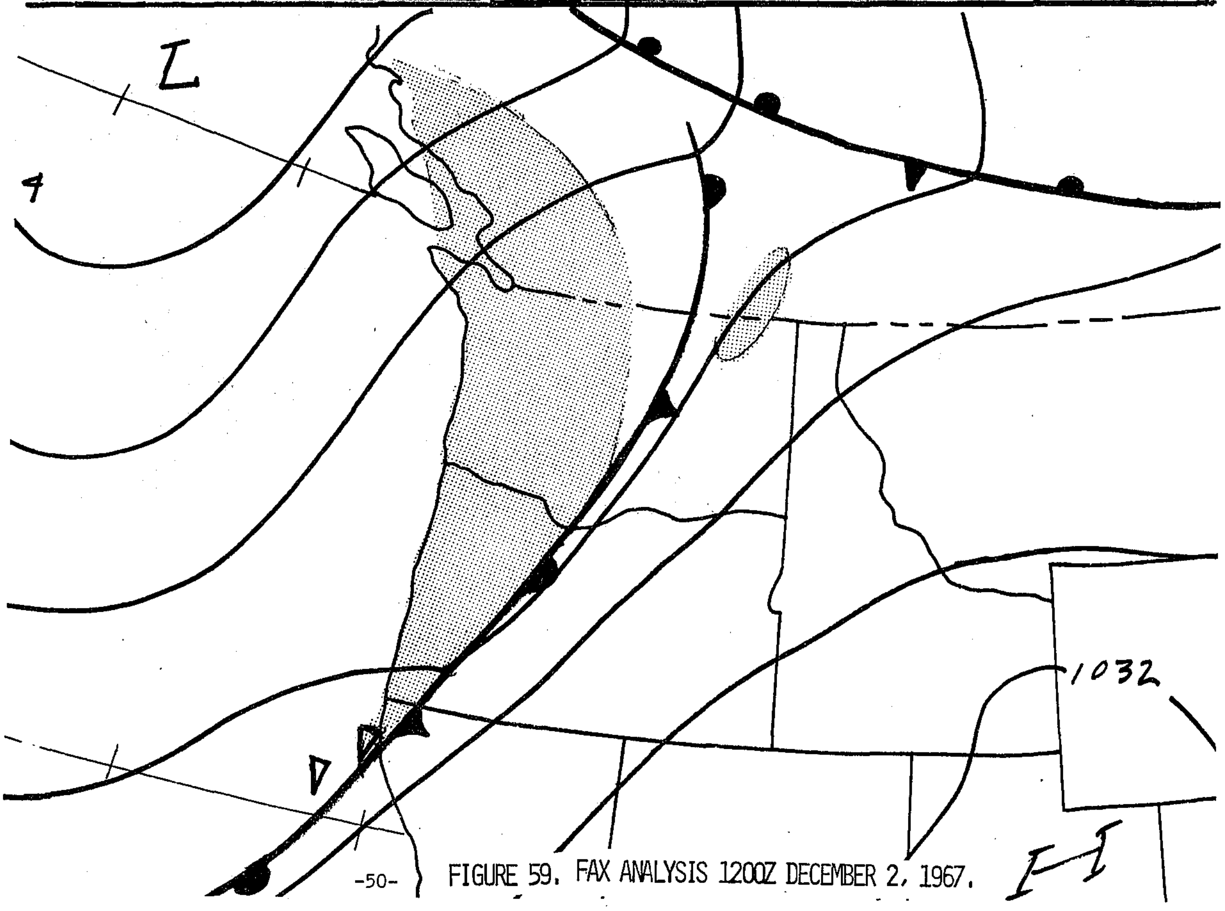


FIGURE 59. FAX ANALYSIS 1200Z DECEMBER 2, 1967.

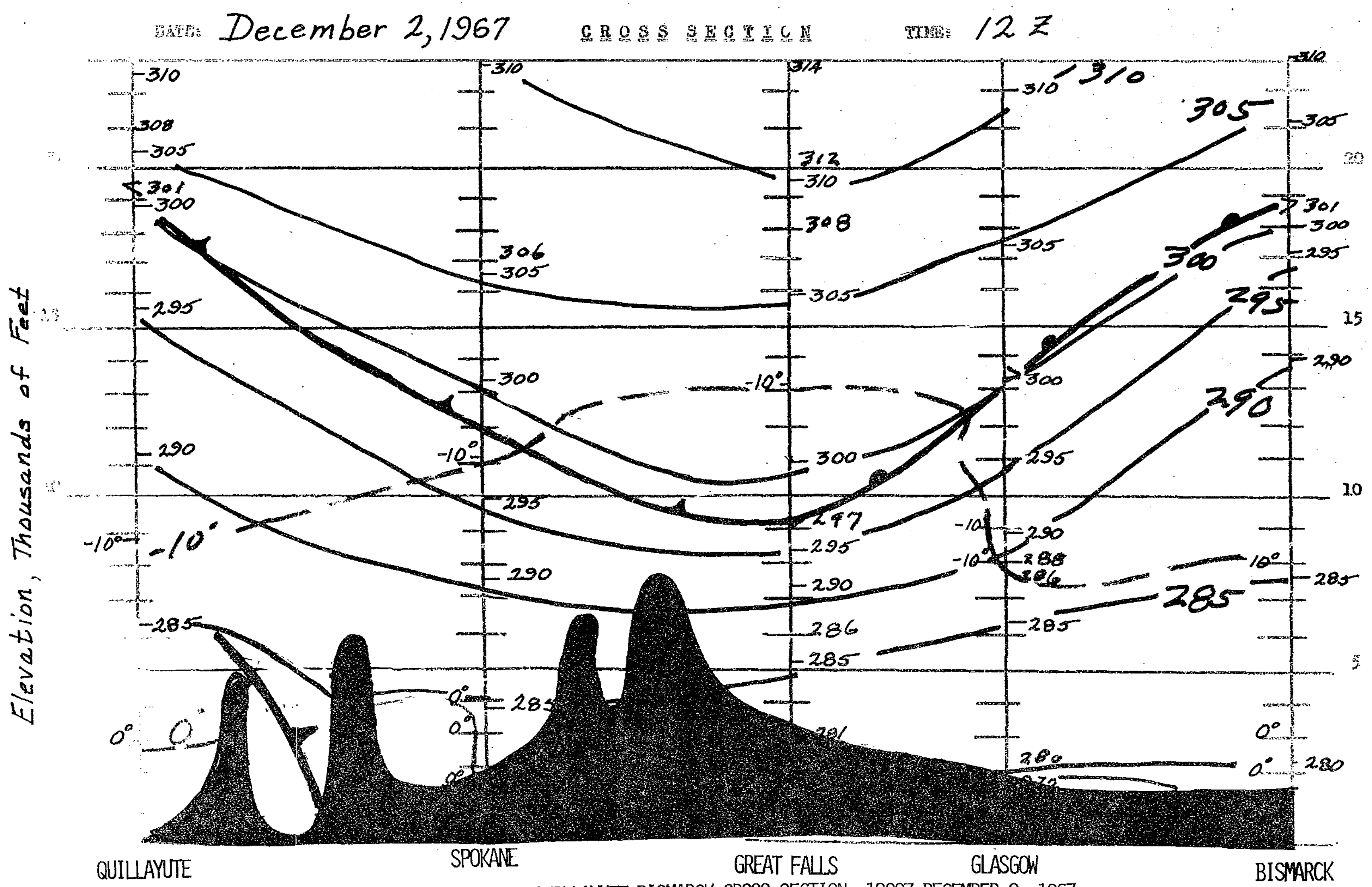


FIGURE 60. QUILLAYUTE-BISMARCK CROSS SECTION, 1200Z DECEMBER 2, 1967.

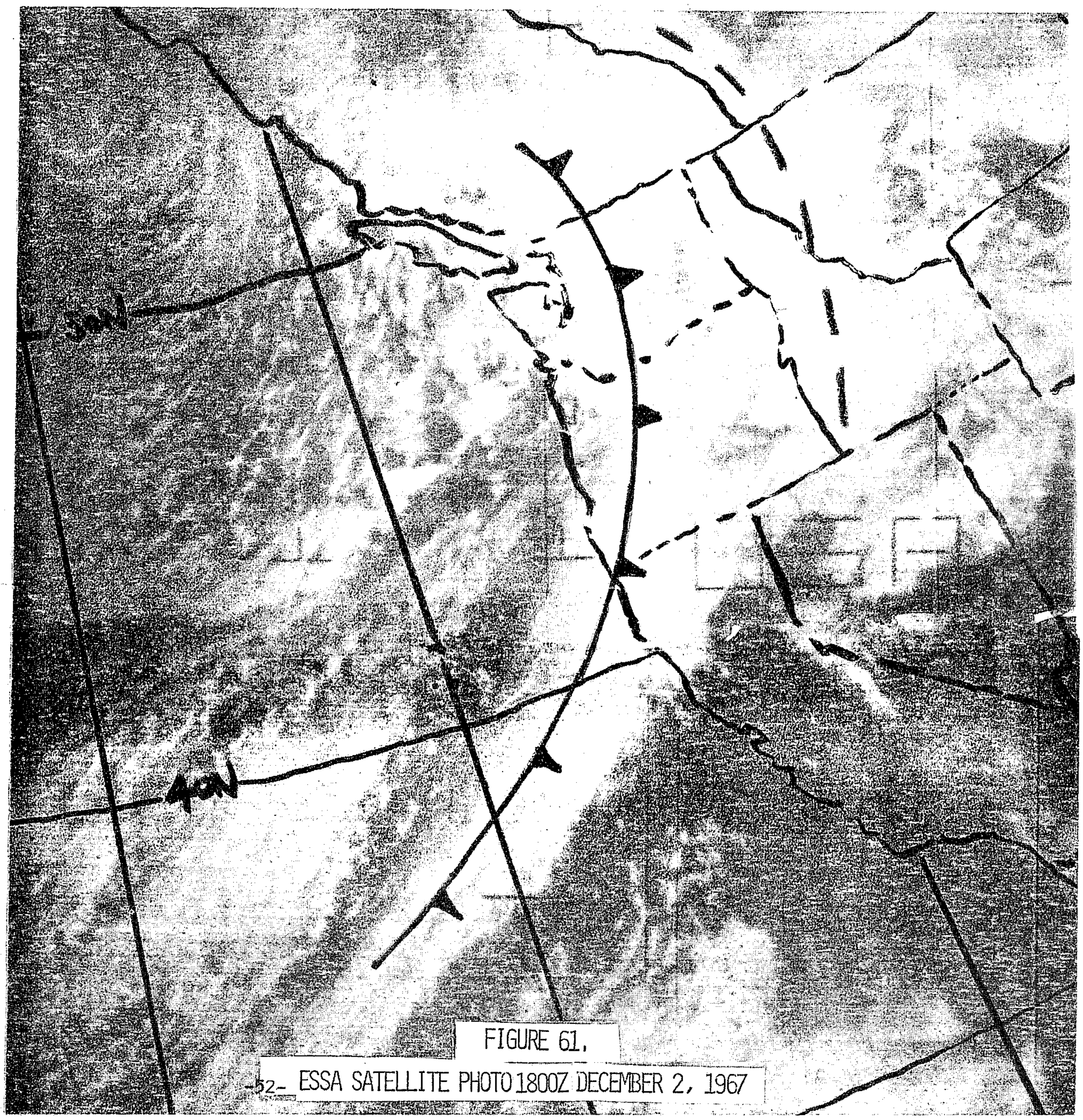


FIGURE 61.

ESSA SATELLITE PHOTO 1800Z DECEMBER 2, 1967

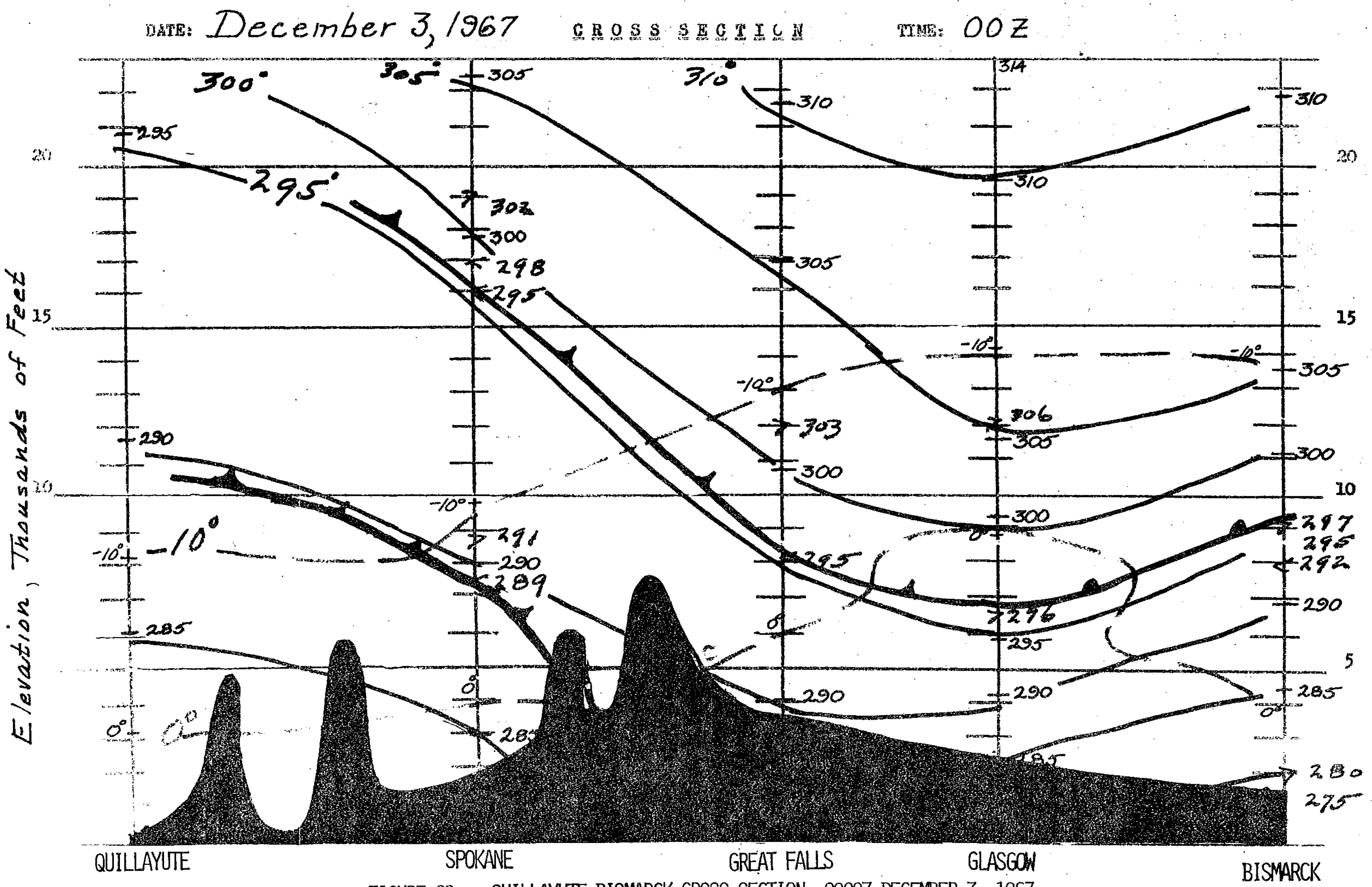


FIGURE 62. QUILLAYUTE-BISMARCK CROSS SECTION, 0000Z DECEMBER 3, 1967.

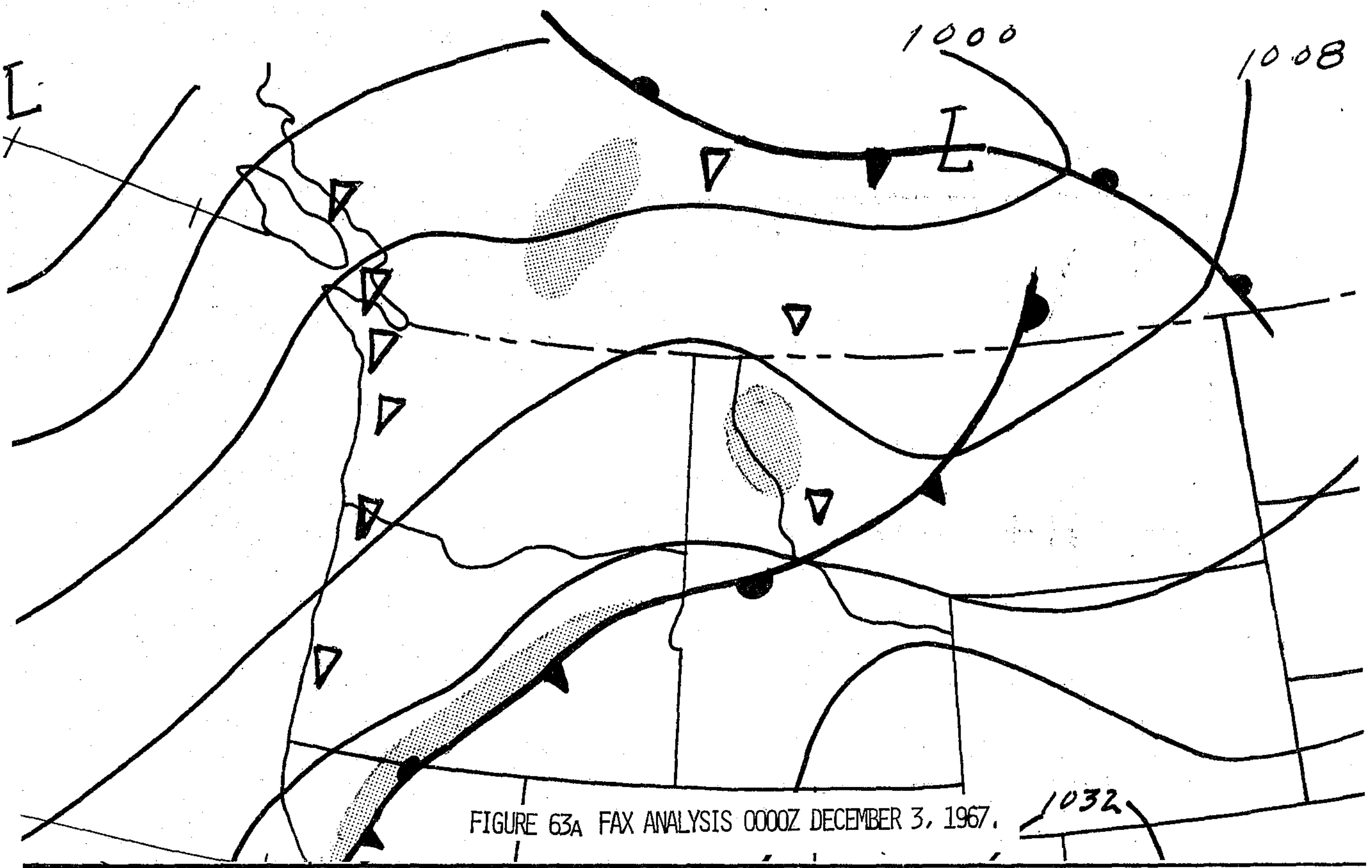


FIGURE 63A FAX ANALYSIS 0000Z DECEMBER 3, 1967.

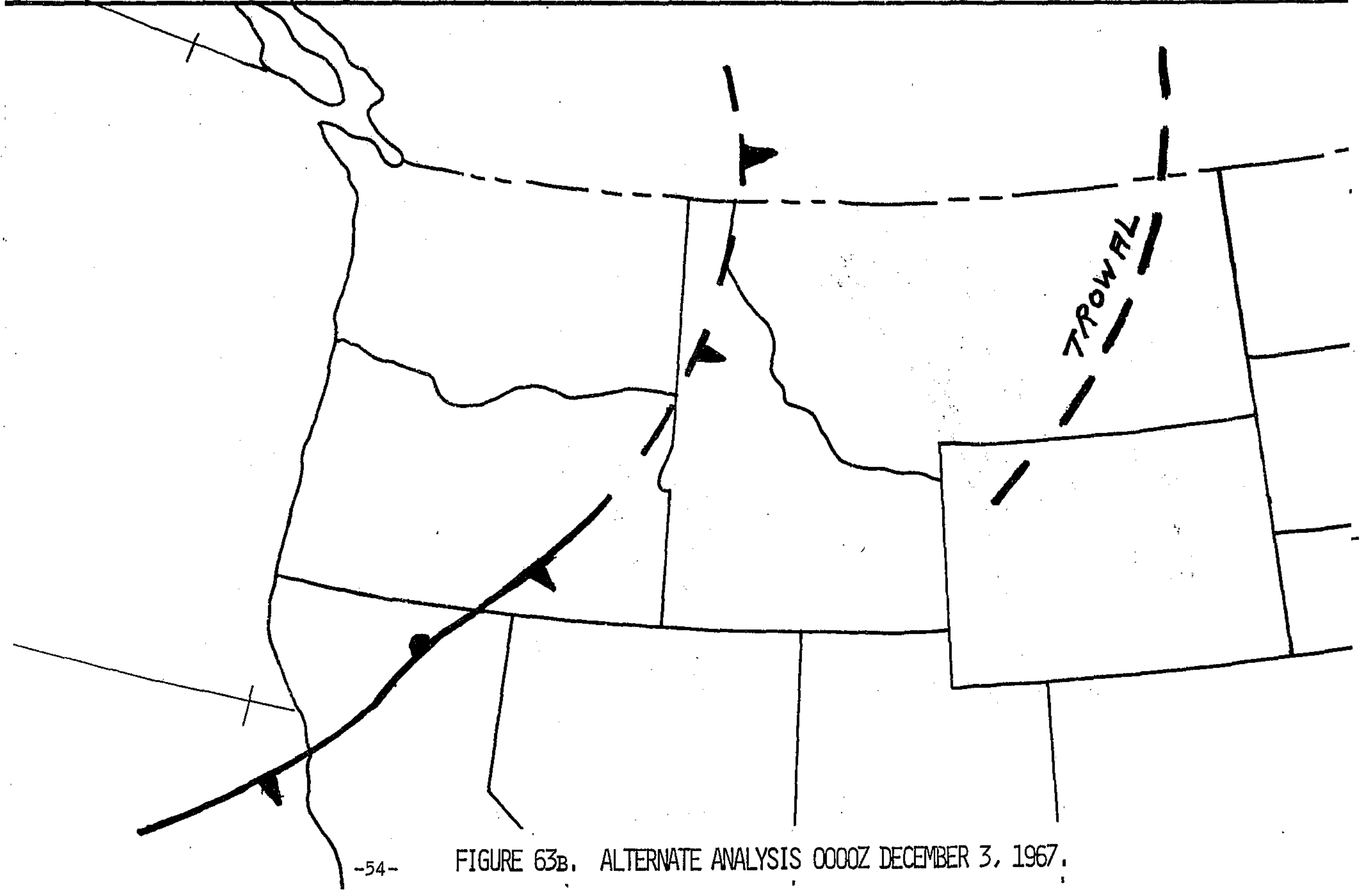


FIGURE 63B. ALTERNATE ANALYSIS 0000Z DECEMBER 3, 1967.

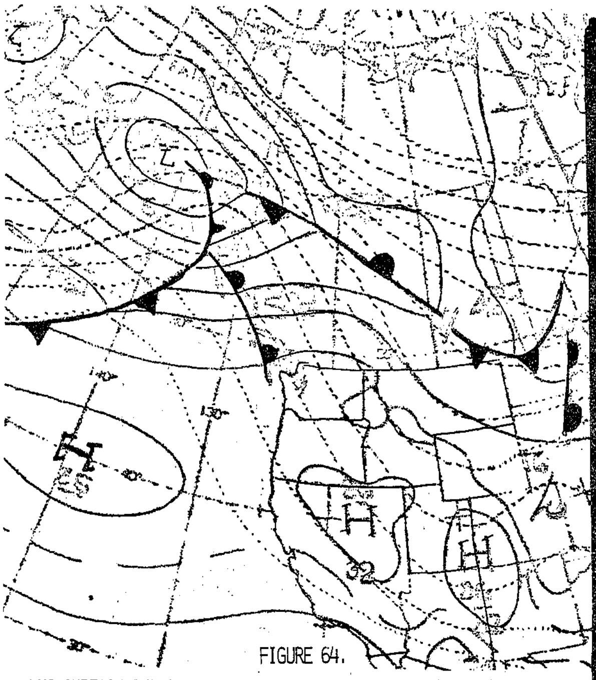


FIGURE 64.

NMC SURFACE AND 1000 - 500-MB THICKNESS, 1200Z JANUARY 5, 1972

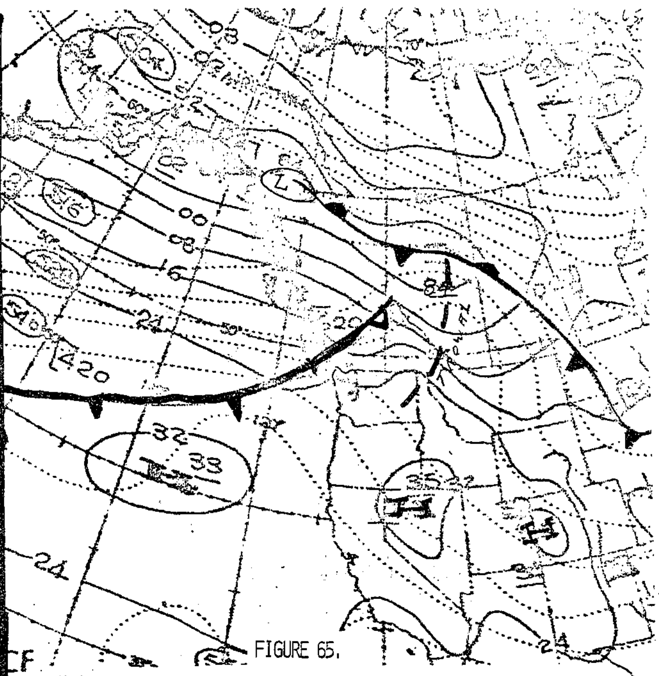


FIGURE 65.

NMC SURFACE AND 1000 - 500-MB THICKNESS, 0000Z JANUARY 6, 1972

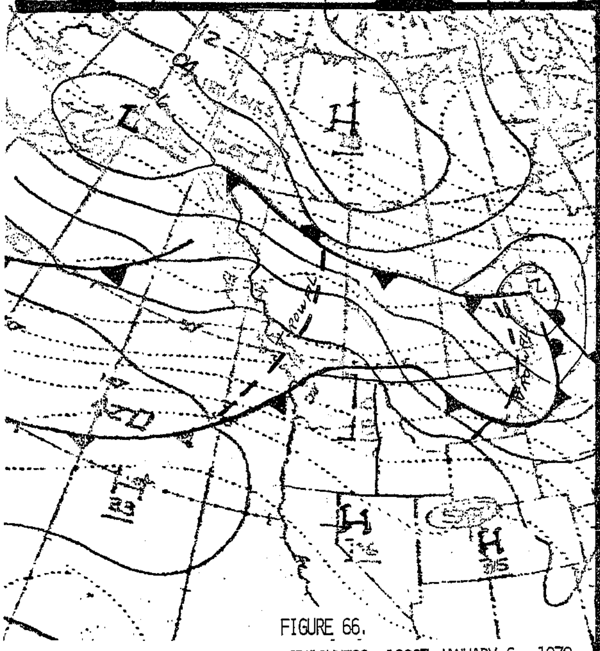


FIGURE 66.

NMC SURFACE AND 1000 - 500-MB THICKNESS, 1200Z JANUARY 6, 1972

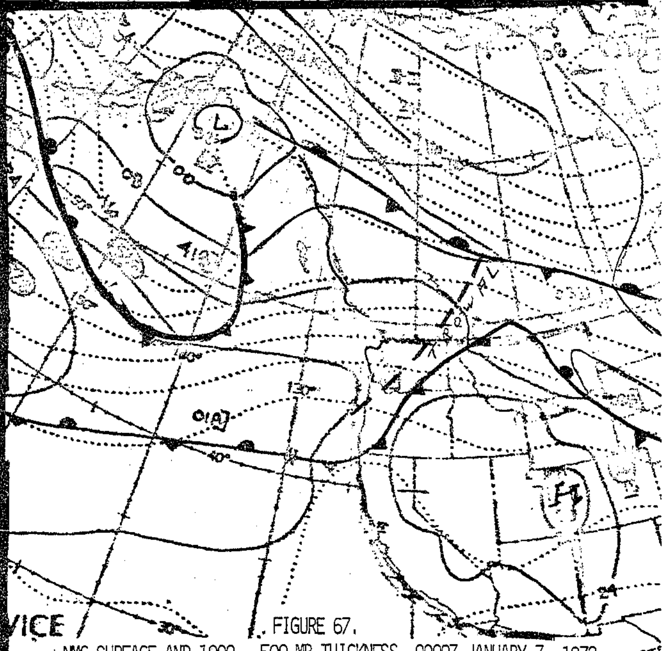


FIGURE 67.

NMC SURFACE AND 1000 - 500-MB THICKNESS, 0000Z JANUARY 7, 1972

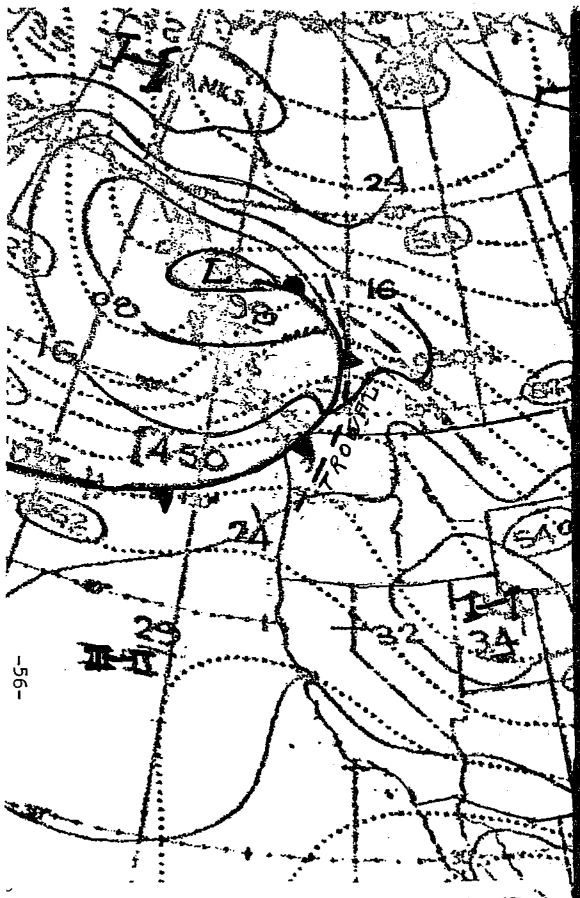


FIGURE 68. NMC SURFACE AND 1000 - 500-MB THICKNESS 1200Z NOVEMBER 3, 1971.

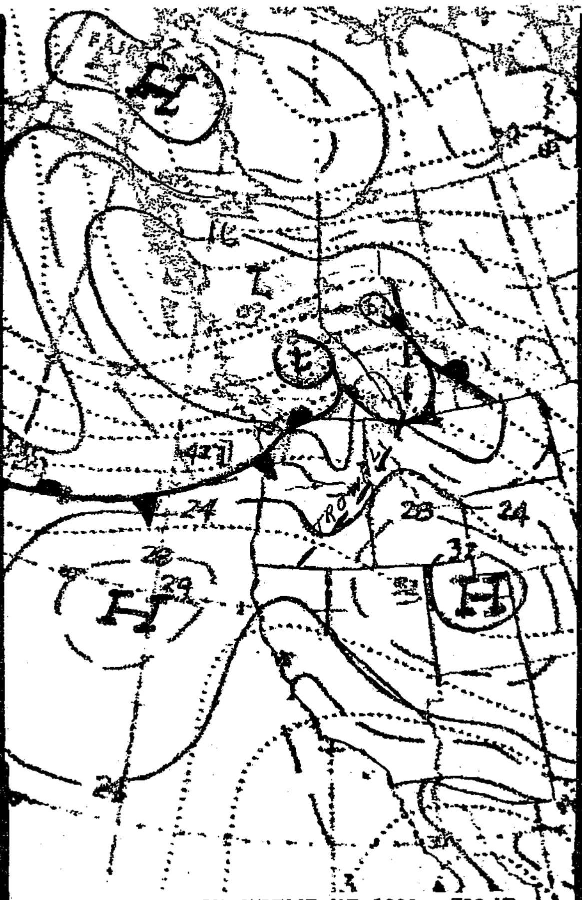


FIGURE 69. NMC SURFACE AND 1000 - 500-MB THICKNESS 0000Z NOVEMBER 4, 1971.

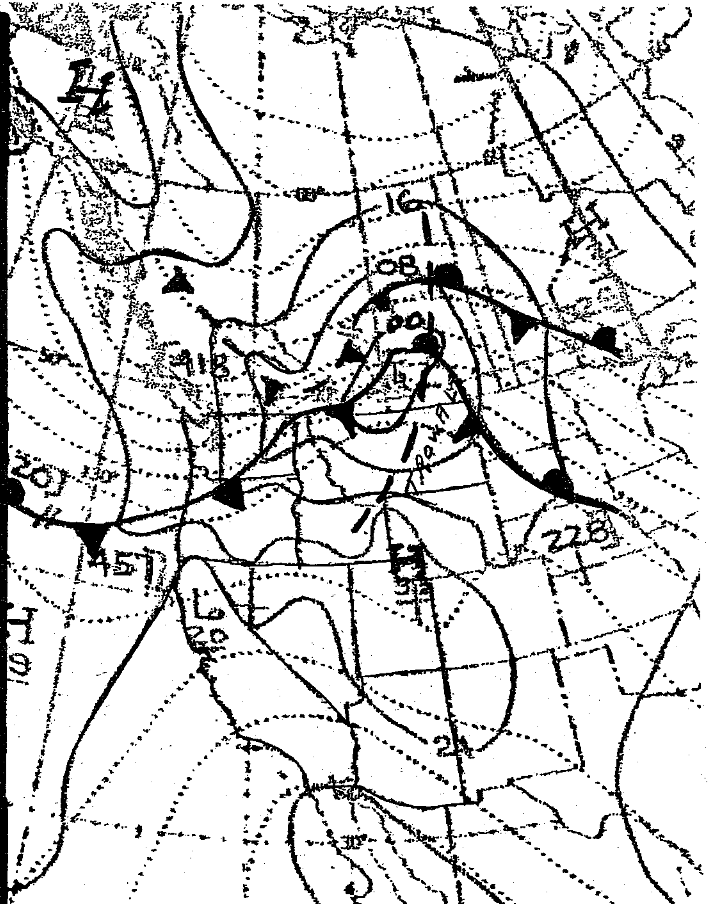


FIGURE 70. NMC SURFACE AND 1000 - 500-MB THICKNESS 1200Z NOVEMBER 4, 1971.

APPENDIX I

Technical Attachment 70-25

WESTERN REGION TECHNICAL ATTACHMENT
June 23, 1970
No. 70-25

SUMMER ANALYSIS PROBLEMS

During the summer, showery weather regimes are frequently associated with rather weak frontal systems and migratory 500-mb short-wave troughs. Because these systems are weak, they are often masked in our Region by strong climatological temperature gradients and diurnal effects. Consequently, analysts have to give special attention to details when preparing analyses for the western United States. From past experience, NMC frontal analyses during this time of year tend to drop important frontal zones too quickly or move them too slowly.

The first problem in summer frontal analysis is in trying to use the 1000-500-mb thickness and the 850- or 700-mb isotherm patterns to locate the frontal zone. The normal summertime temperature gradient from the plateau to the Washington-Oregon coastal area is quite strong (see Figure 1); therefore, a strong thermal gradient in this area is not enough to locate a migratory frontal zone. Rather, it is the changes that take place in this gradient that are important. Plotting 24-hour 850- and/or 700-mb temperature changes is very helpful. Reference to 500-mb short-wave troughs and positive-vorticity advection (PVA) areas associated with these 24-hour temperature changes should also be made to determine whether or not a frontal zone is present and where it is located. Continuity of satellite mosaic cloud patterns is also useful, even though the frontal cloudiness loses a lot of its distinctive pattern by orographic modifications once the front moves over land.

In making the 1200Z frontal analysis over the western United States on Monday, June 22, application of the above principles indicated that NMC's frontal analysis needed considerable adjustment over the northwestern states (see Figure 2). 850-mb 24-hour temperature changes (Figure 3) show cooling from Quillayute and Portland northward and little change or warming at stations to the east and south. Thus, the climatological temperature gradient was being enhanced or strengthened by a frontal zone moving through the area. The 500-mb short-wave trough and PVA pattern (not shown) support this idea. Note that the NMC analysis (Figure 2) has placed the front too far west through Canada and Washington and has dropped the western portion too soon. This front was weakening with time and was not strong enough to lower maximum temperatures significantly in western and central Washington; but it was associated with afternoon thunderstorm activity in Oregon, Idaho, and Montana (see Figure 4). This is the type of shower regime that is especially important to fire-weather forecasters when fire dangers are high.

The second problem in summer analysis is that the diurnal height changes at 500 mb are frequently of the same order of magnitude as synoptic changes related to migratory systems. Figure 5 gives the average diurnal changes from 0000Z and 1200Z data. Therefore, when using the 12-hour height changes plotted on NAFAX Charts No. 9 and 50, the significance given to changes should be determined more by their deviations from normal than their absolute values.

The 500-mb 12-hour height changes given on the analysis for 1200Z June 17 (Figure 6) illustrate this point. When considered by themselves, these changes indicate that very little change was taking place. The magnitude of changes was generally only ± 10 meters in the trough. However, since the diurnal changes for this time are minus 20 to 30 meters, the changes indicated that the large cold trough over the region was filling. The PE prognosis based on the 12-hour earlier (0000Z) data (not shown) had forecast rising heights over the region. The 1200Z 12-hour changes, although essentially zero, showed that the forecast rise was already under way during the first 12 hours of the PE forecast period.

In addition to paying special attention to relatively weak systems in surface and 500-mb analyses, the composite radar charts should be studied. Areas of organized convective weather are easily located on these NAFAX charts and can usually be related to topography and/or such frontal and trough regimes as discussed above. With the Auburn ARTC Center weather radar unit now in operation, there are very few areas of the region not under radar surveillance.

[1] REFERENCE: "Selected Level Heights, Temperatures and Dew Points for the Northern Hemisphere" -- NAVAIR 50-1C-52, January 1970.

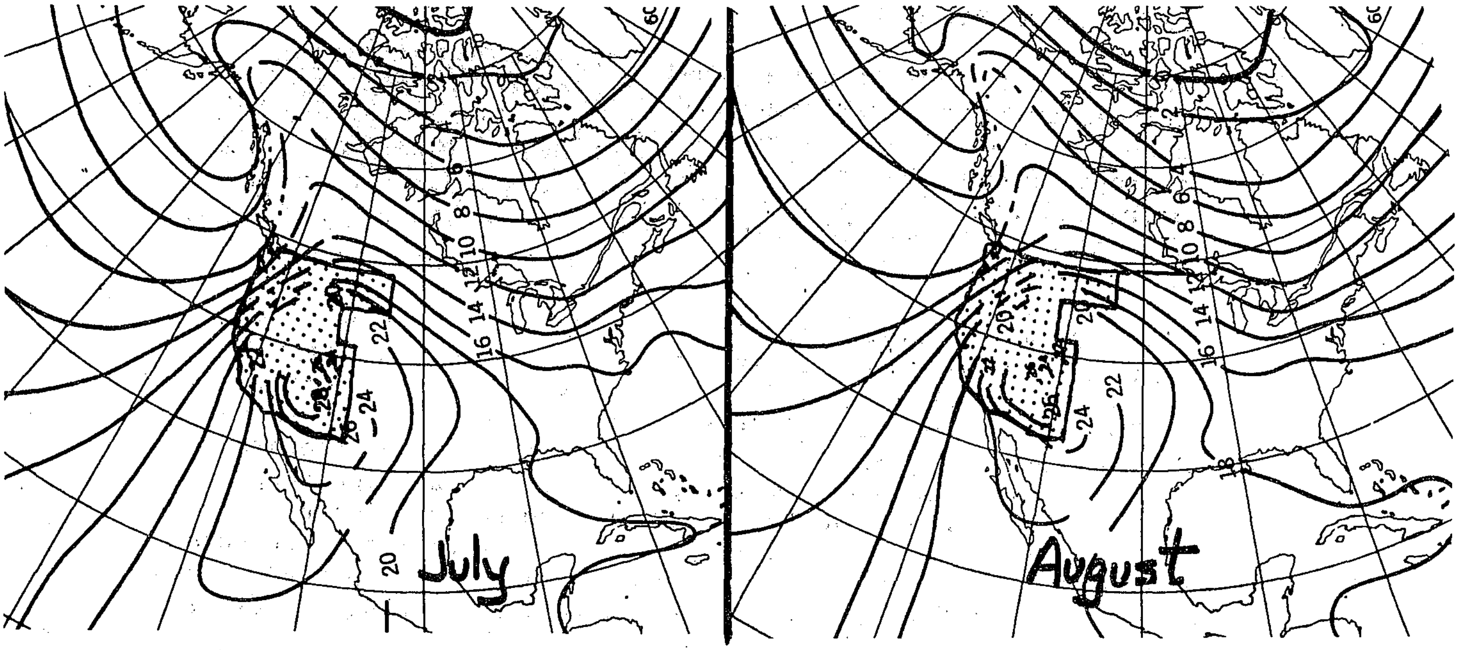


FIGURE IA. 850-MB JULY AND AUGUST NORMAL ISOTHERMS (°C). [1]

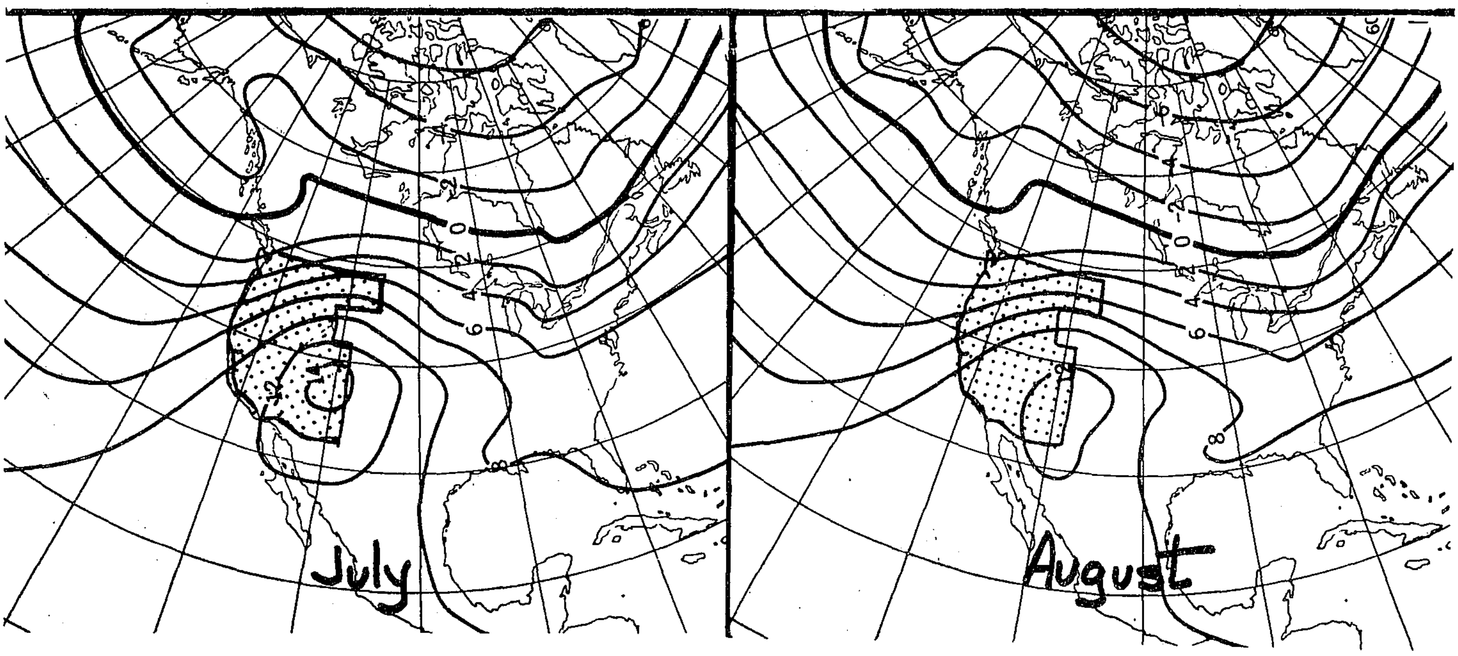


FIGURE IB. 700-MB JULY AND AUGUST NORMAL ISOTHERMS (°C). [1]

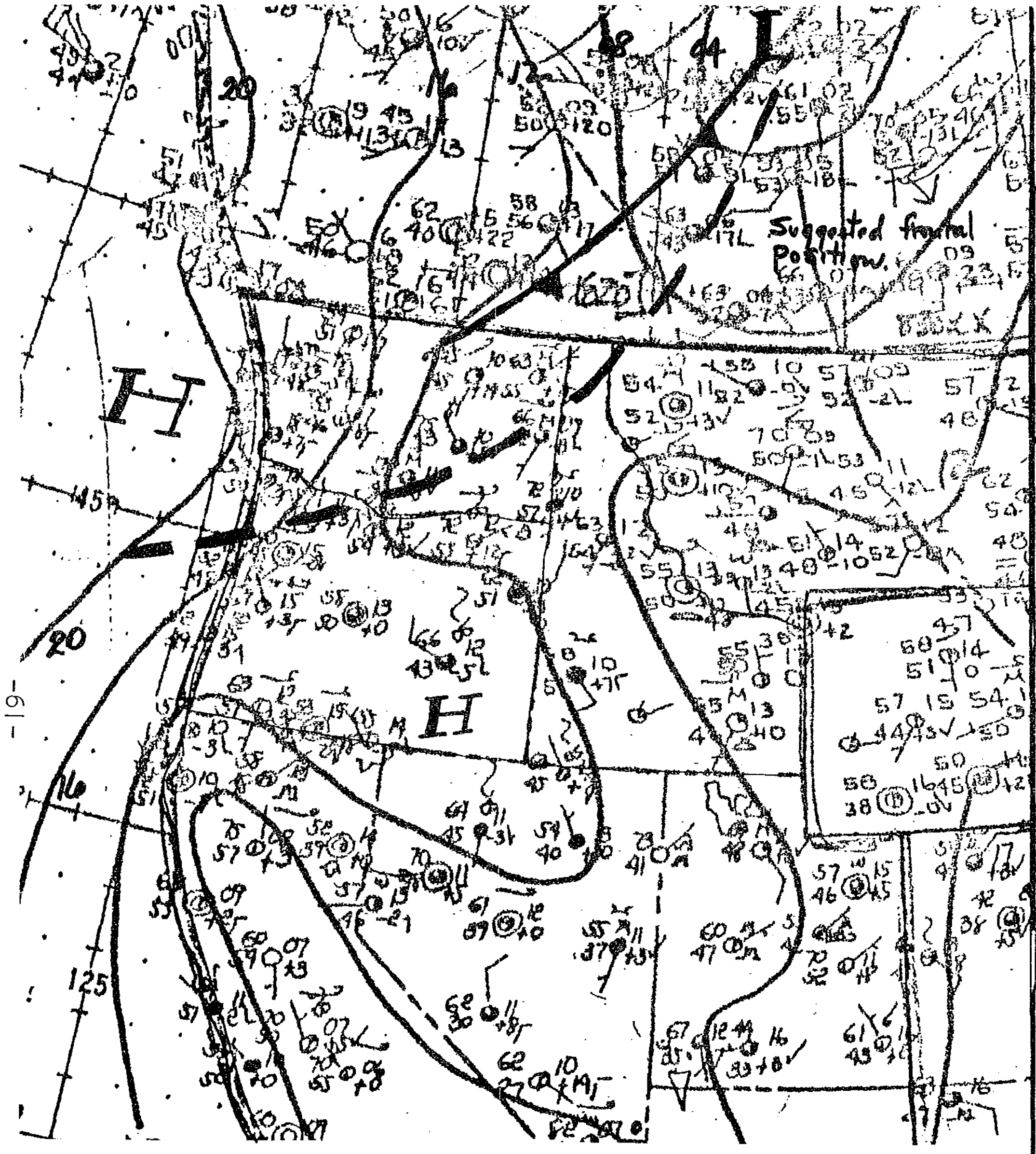


FIGURE 2. NMC SURFACE ANALYSIS 1200Z JUNE 22, 1970. HEAVY DASHED LINE IS SUGGESTED AS BETTER FRONTAL ANALYSIS. (NAFAX CHART NO. 70.)

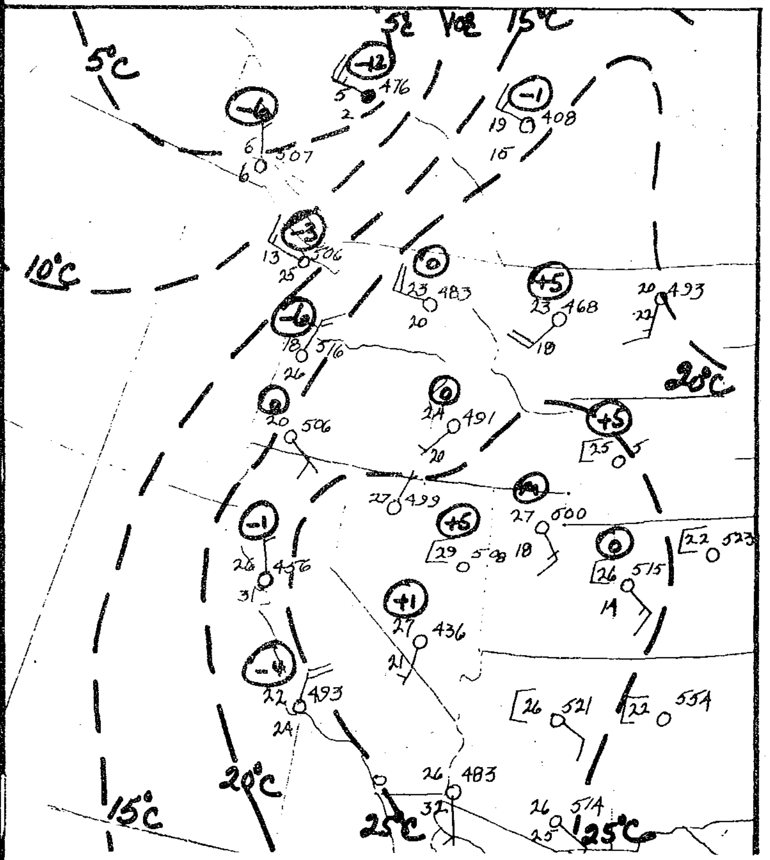


FIGURE 3. 850-MB ANALYSES FOR 1200Z JUNE 22, 1970. CIRCLED NUMBERS ARE 24-HOUR TEMPERATURE CHANGES FROM 21st TO 22nd IN DEGREES CENTIGRADE.

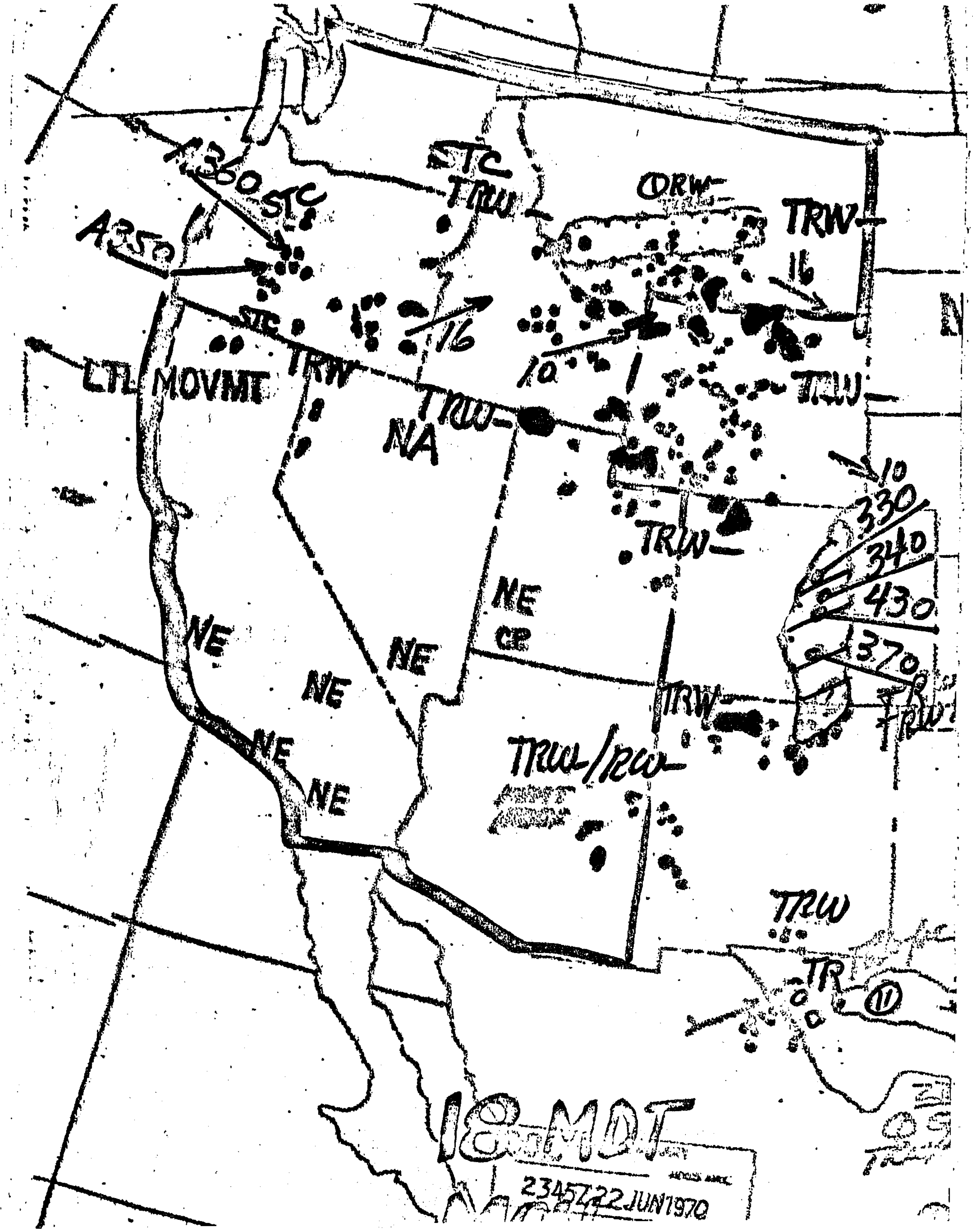


FIGURE 4. NAFAX RADAR CHART 2345Z JUNE 22, 1970. NOTE LACK OF ECHOES IN WASHINGTON, AND ORGANIZATION OF ECHOES IN OREGON, IDAHO, AND MONTANA.

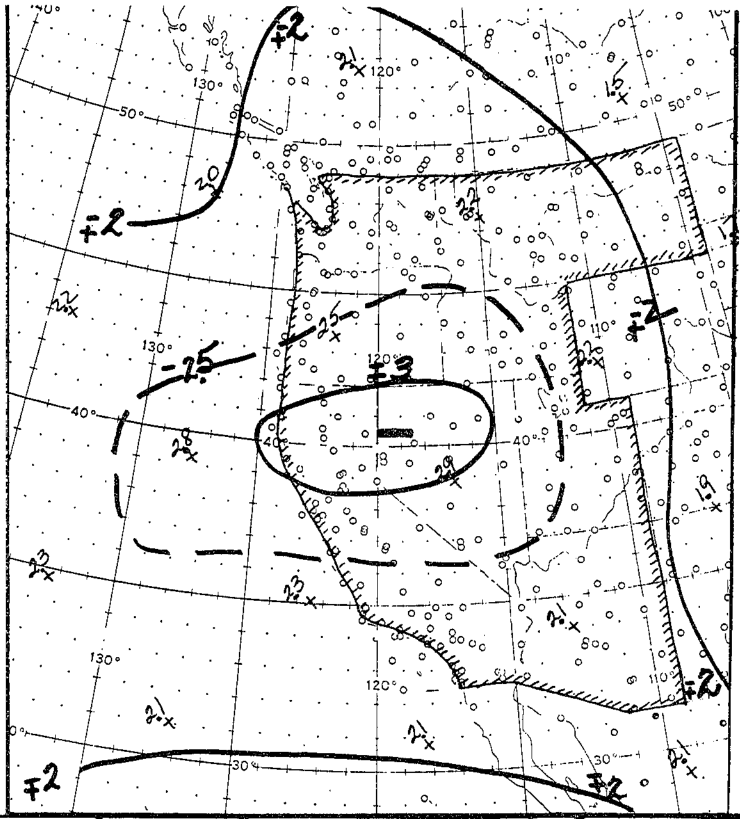
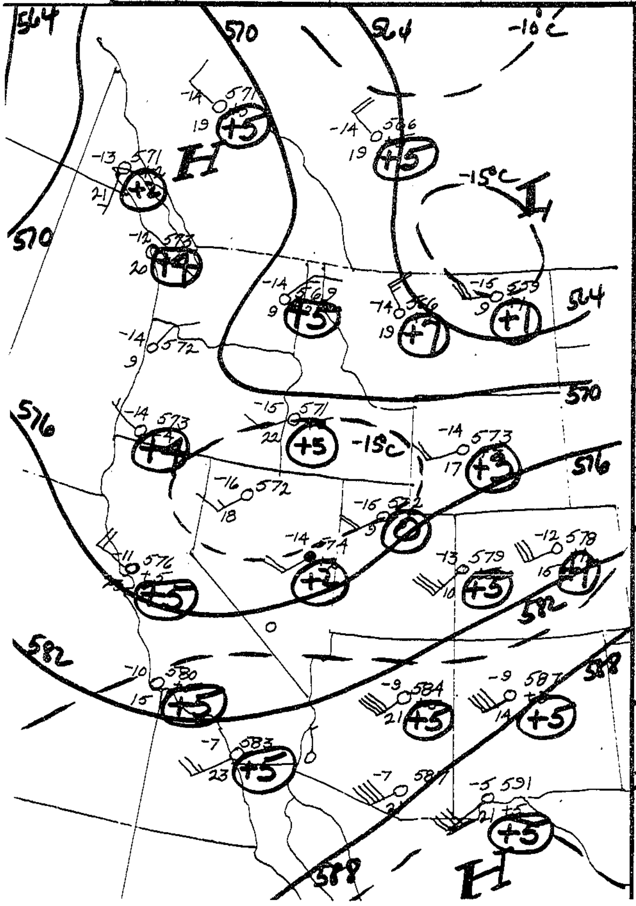


FIGURE 5. 500-MB DIURNAL HEIGHT CHANGES IN DECAMETERS FOR JULY. NEGATIVE VALUES FOR 1200Z CHART, POSITIVE VALUES FOR 0000Z. THESE DATA BASED ON 7 YEARS' DATA (1961-1968) AND MADE AVAILABLE THROUGH COURTESY OF TDL AND MR. DONALD JORGENSEN.



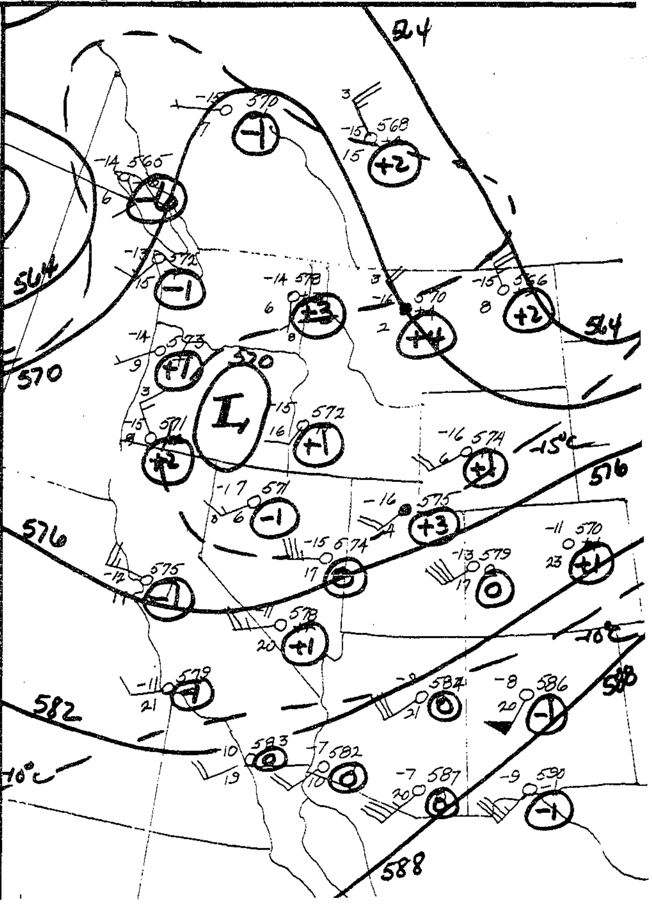


FIGURE 6A. 500-MB ANALYSES FOR 0000Z JUNE 17, 1970. 12-HOUR HEIGHT CHANGES IN DECAMETERS PLOTTED AS LARGE PLUS AND MINUS VALUES.

FIGURE 6B. 500-MB ANALYSES FOR 1200Z JUNE 17, 1970. 12-HOUR HEIGHT CHANGES IN DECAMETERS PLOTTED AS LARGE PLUS AND MINUS VALUES.

APPENDIX II

Technical Attachment 71-31

WESTERN REGION TECHNICAL ATTACHMENT
June 29, 1971
No. 71-31

REVIEW OF SOME SUMMER ANALYSIS PROBLEMS

This is the time of year when frontal analysis over the Western Region becomes difficult. This is also the season when NMC surface analyses need to be carefully massaged, since weak fronts (not always included in NMC analyses) can be of considerable importance to us. An earlier Technical Attachment [1] described in detail difficulties that arise when attempting to follow a cold front through the normally strong temperature gradient that exists between the northwestern coast and interior plateau during summer. This type of summer analysis problem is further complicated by the relatively large, normal, diurnal height changes aloft. During June 22 - 24, problems of this nature again arose in the Pacific Northwest, as the NMC analysis dropped a cold front approaching the coast, only to reinstate it some 27 hours later. Figure 1 shows the surface map for 0000Z June 23, the last map on which NMC carried the cold front. Continuity up to this time was good. We believe that the front should be a little farther ahead at this time--just inside the coastline, judging from pressure tendencies on the coast as compared to those inland. The front shows up very well on ESSA-9 satellite pictures for 2200Z June 22 (Figure 2). After 0000Z June 23, NMC dropped the cold front until 0300Z June 24, when it was reintroduced as frontogenesis in Montana, Wyoming, Utah, and Nevada. On some of the intervening maps, a trough line was indicated.

By 1200Z June 23, the cold front appeared to be located through western Montana, central Idaho to northeastern California (Figure 3), where NMC indicated a trough line. Supporting evidence for placing the front in this trough line, aside from logical continuity, is provided by isotherms and 24-hour temperature changes at 850 mbs (Figures 4a and 4b). Figure 4a for 1200Z June 22, when the cold front was still off the coast, shows the normal thermal pattern between the Central Plateau and northwestern coast (see [1]). Contrast this chart with Figure 4b for 1200 June 23, 24 hours later. Notice the sharp increase in packing of isotherms between Boise and the coast. Salem cooled 11°C, Medford 9°C, and Spokane 7°C. (Associated surface maximum temperatures are discussed later.) Winds along the coast had shifted to westerly, and Boise reported a northwest wind of 15 knots. A position for the front just past Boise agrees well with the surface position indicated in Figure 3. 1000- 500-mb thickness charts could also be used for this type of analysis but, in general, 850-mb isotherms are better for following summer cold fronts inland as the cold-air masses are sometimes rather shallow.

The barotropic vorticity chart for 1200Z June 23 (Figure 5) shows a vigorous short-wave trough along the coast with good PVA over Oregon, Washington, and Idaho. 500-mb 12-hour height changes in the Northwest were minus 70 to 80 meters--about twice the normal diurnal falls [1]. Thus, the 500-mb chart also strongly supports the concept of a cold front moving inland.

TECHNICAL ATTACHMENT

The 24-hour maximum-temperature-change chart (Figure 6) also lends support to the movement inland of a front, with cooling from coast to Cascades by the afternoon of June 22.

NMC reintroduced the front at 0300Z June 24, and by 1200Z (Figure 7) showed the front across Wyoming and central Utah, agreeing well with the position at 850 mbs (Figure 8). Note the 24-hour 850-mb temperature changes in Montana, southern Idaho, and northeastern Nevada. The front was probably just south of Salt Lake City and was associated with sharp drops in maximum temperatures (up to 20°F) across the plateau (Figure 9) from the afternoon of June 22 to June 23. Further cooling took place over eastern Montana and northern Wyoming on the 24th, but the front weakened rapidly over Utah, with little cooling noted.

Rather heavy precipitation with amounts up to 1/2 inch was reported west of the Cascades as the front passed through, but only scattered light showers fell farther inland. The main effect of the frontal passage was the breaking of an early-season heat wave over the Pacific Northwest. Maximum temperatures on June 22 were in the 90s in eastern Washington, northeastern Oregon, Idaho, portions of Montana; and in Wyoming and eastern Montana on the 23rd. Passage of the cold front brought welcome relief from this early summer heat wave.

In light of our experiences of last summer and the one just discussed, we recommend that additional attention be given to augmenting the NMC surface analyses during the next few months by giving considerable weight to:

1. 24-hour 850-mb temperature changes.
2. Radar echo <u>patterns</u>, especially looking for causes of organized patterns.
3. Satellite mosaic and IR transmissions.

REFERENCE:

[1] Western Region Technical Attachment 70-25, "Summer Analysis Problems".

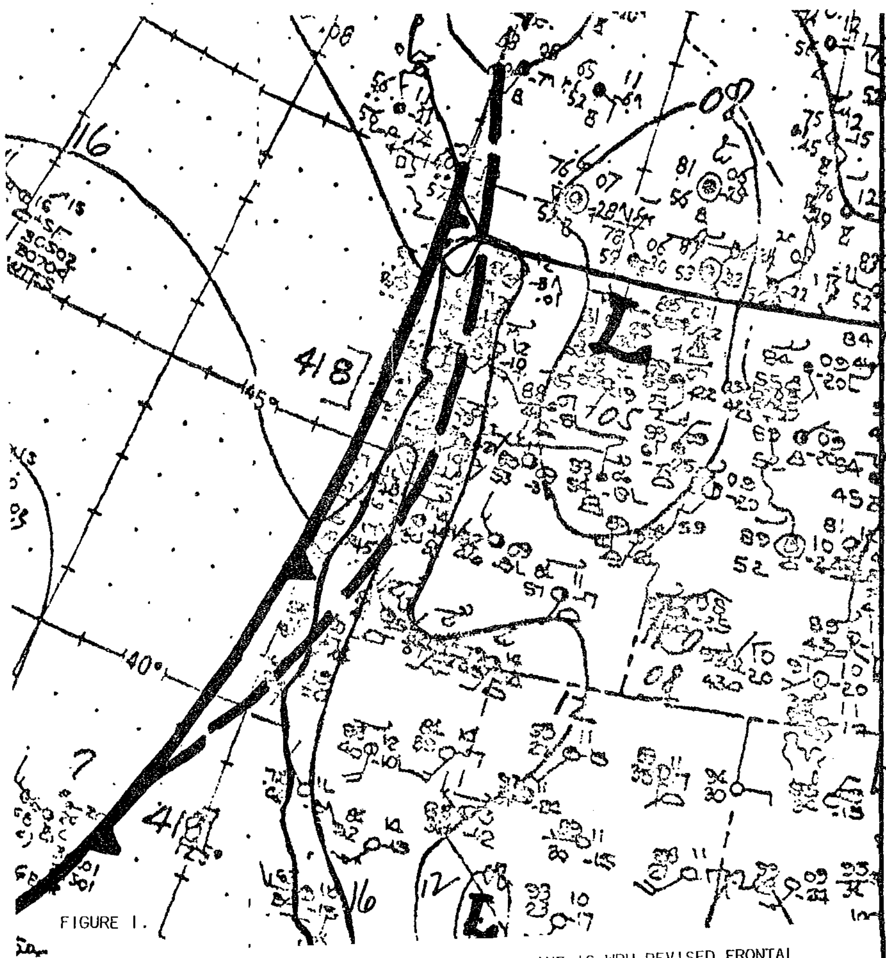


FIGURE 1.

NMC ANALYSIS 0000Z JUNE 23, 1971. HEAVY DASHED LINE IS WRH REVISED FRONTAL POSITION.

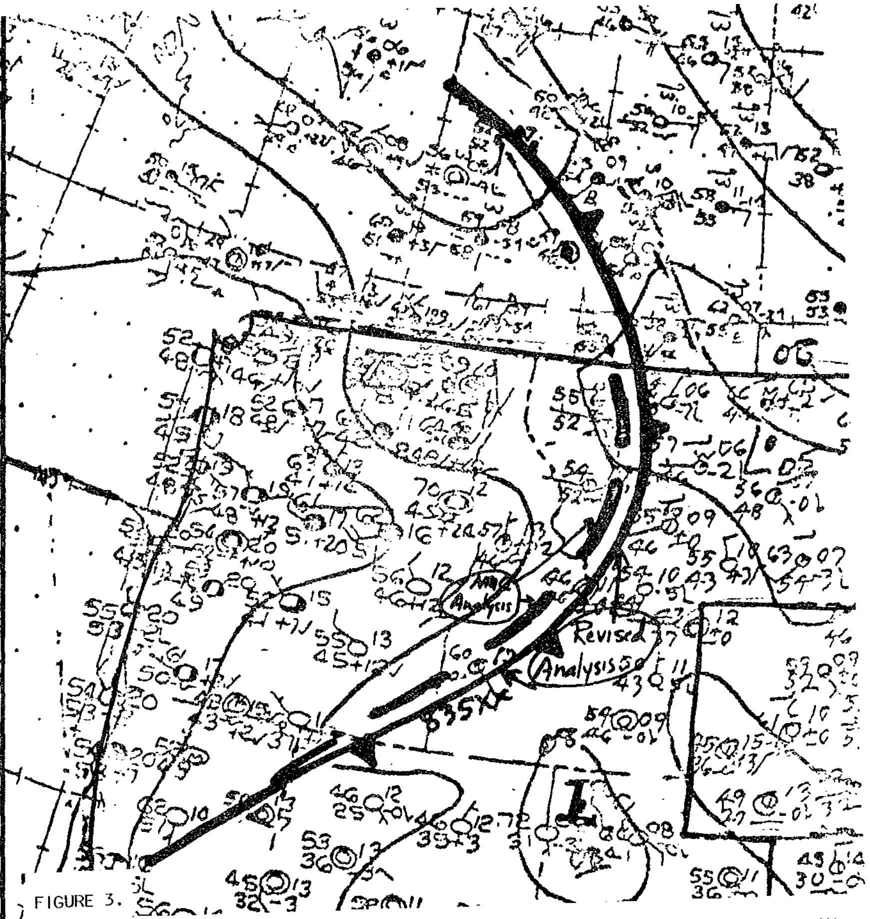


FIGURE 3.

NMC ANALYSIS 1200Z JUNE 23, 1971. DASHED LINE IS POSITION OF TROUGH INDICATED IN ORIGINAL NMC ANALYSIS. FRONTAL LINE IS WRH REVISED ANALYSIS SHOWING TROUGH AS A COLD FRONT.

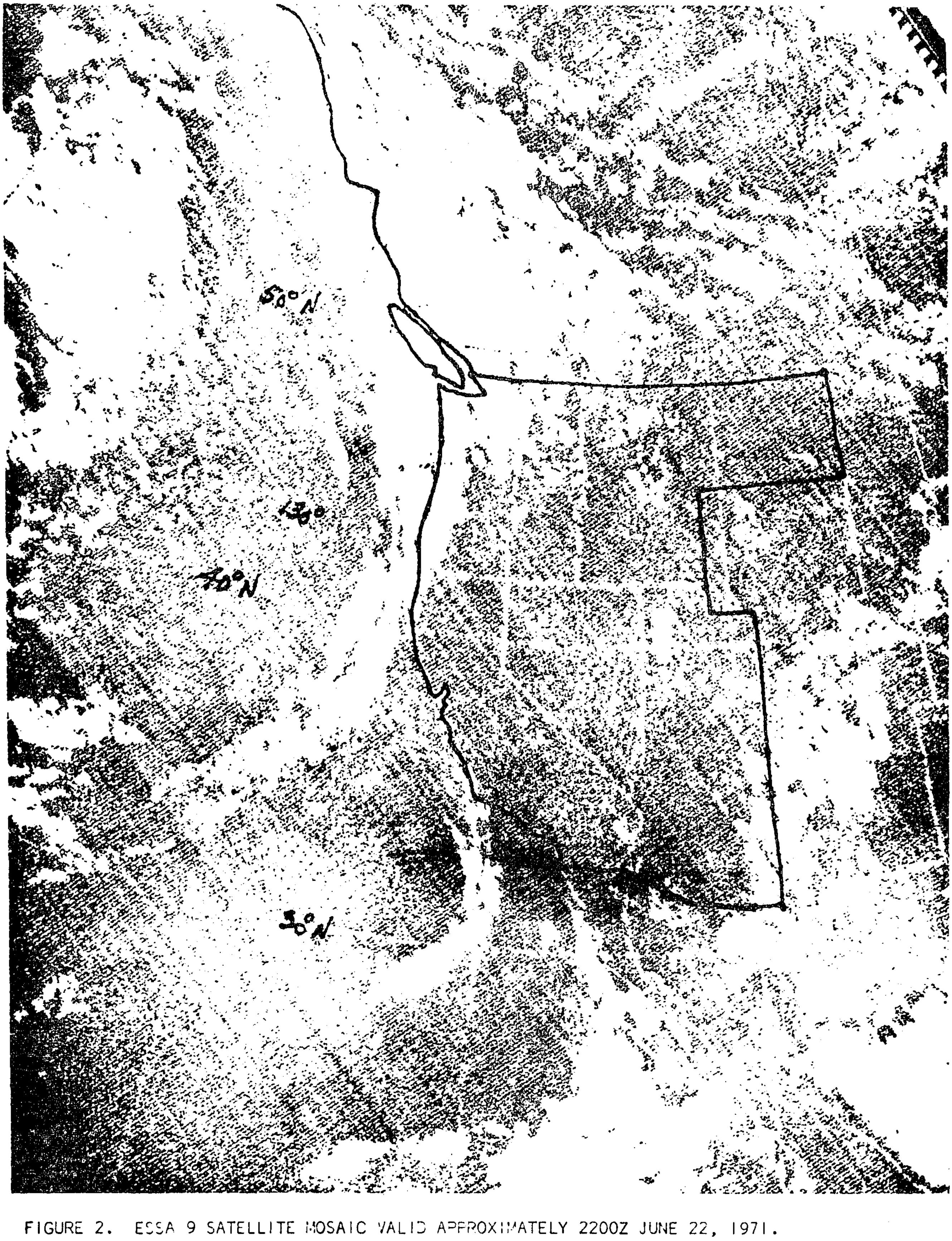


FIGURE 2. ESSA 9 SATELLITE MOSAIC VALID APPROXIMATELY 2200Z JUNE 22, 1971.

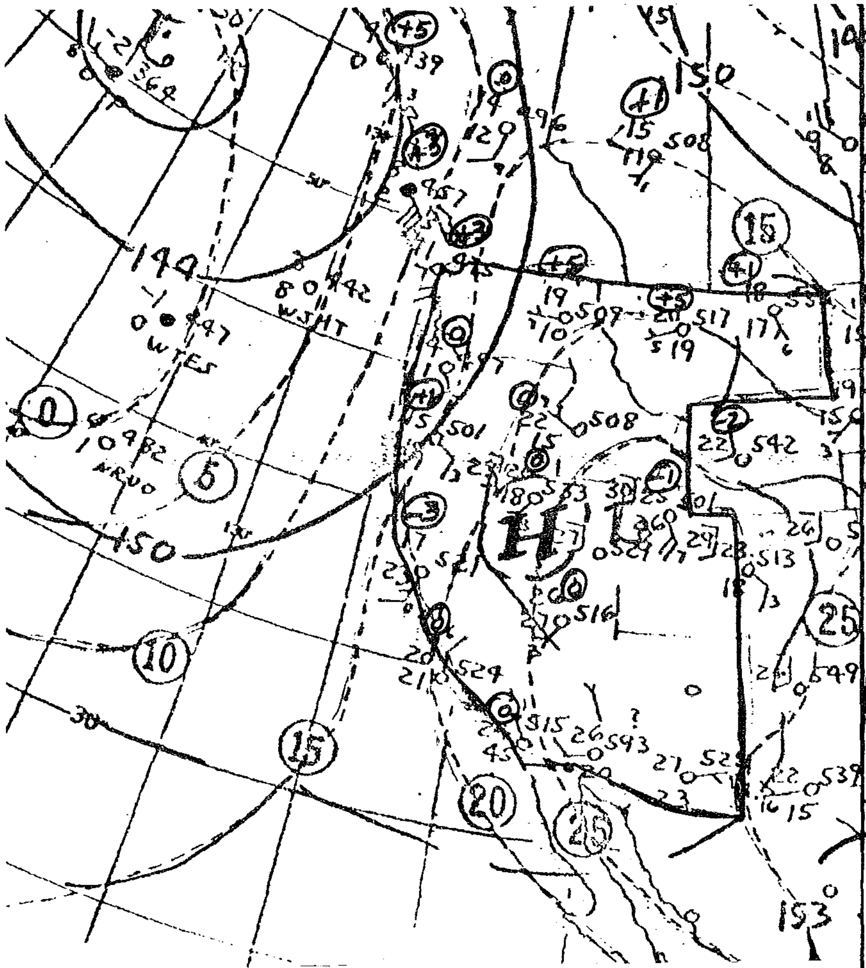


FIGURE 4A.

NMC 850-MB ANALYSIS, 1200Z JUNE 22, 1971. CIRCLED PLUS AND MINUS FIGURES ARE 24-HOUR TEMPERATURE CHANGES.

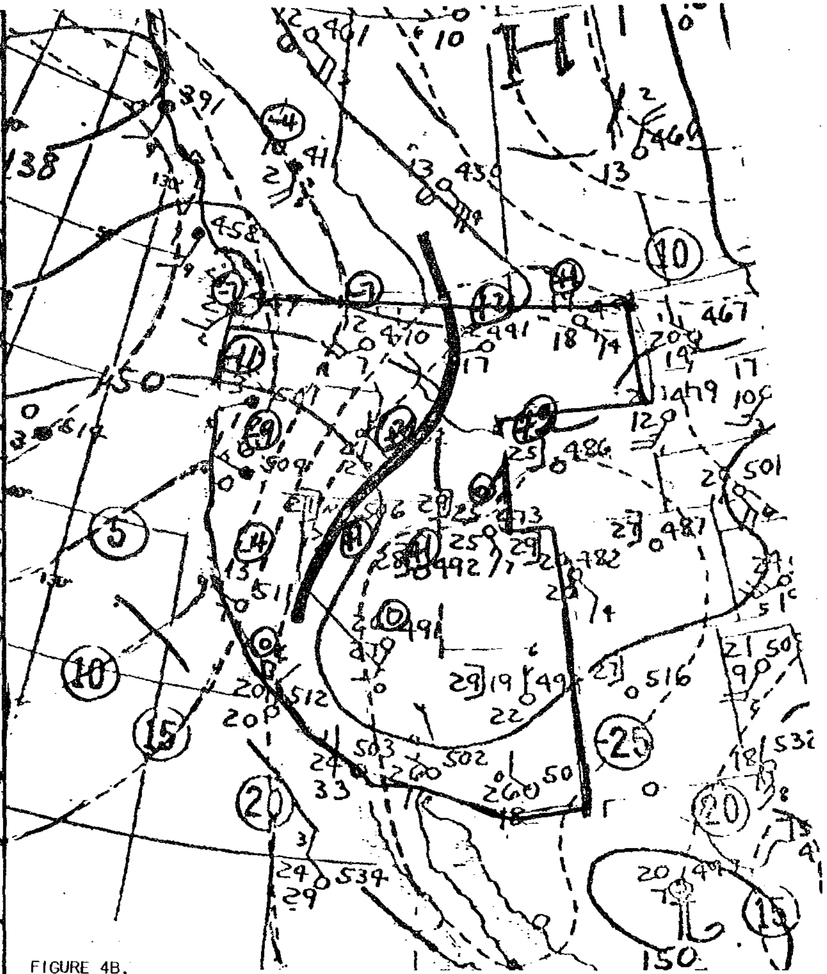


FIGURE 4B.

NMC 850-MB ANALYSIS, 1200Z JUNE 23, 1971. CIRCLED PLUS AND MINUS FIGURES ARE 24-HOUR TEMPERATURE CHANGES.

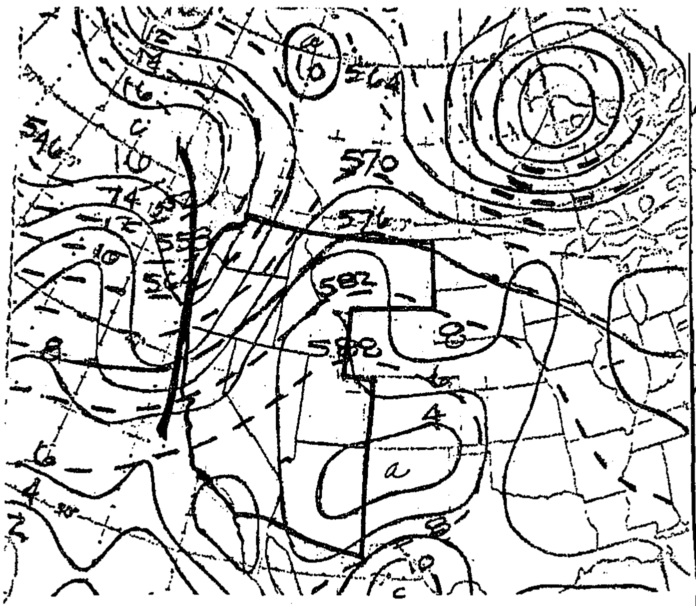


FIGURE 5. 500-MB CONTOUR AND ABSOLUTE VORTICITY ANALYSES 1200Z JUNE 23, 1971. DASHED LINES ARE 500-MB CONTOURS.

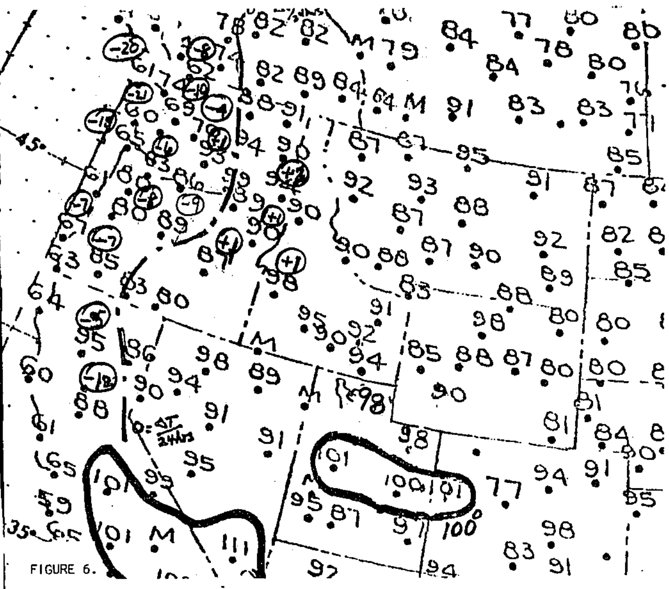


FIGURE 6.

MAXIMUM TEMPERATURE CHART FOR PERIOD ENDING 0000Z JUNE 23, 1971 (i.e., TEMPERATURES ON JUNE 22). CIRCLED PLUS AND MINUS FIGURES ARE 24-HOUR TEMPERATURE CHANGES.

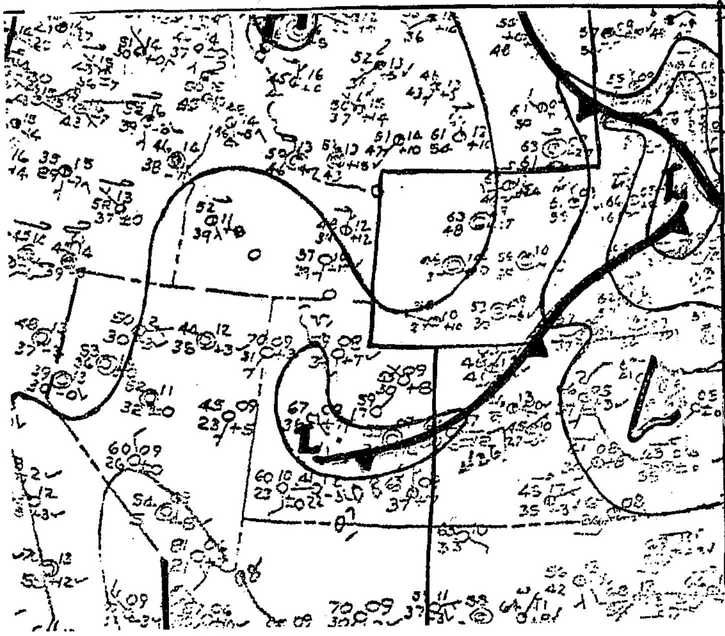


FIGURE 7. NMC ANALYSIS 1200Z JUNE 24, 1971. HEAVY FRONTAL LINES ARE NMC ORIGINAL ANALYSIS.

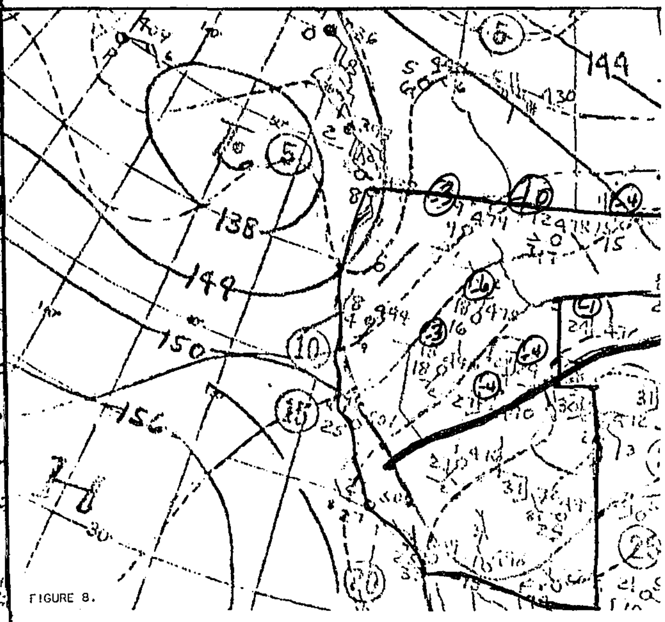


FIGURE 8.

NMC 850-MB ANALYSIS 1200Z JUNE 24, 1971. HEAVY LINE IS FRONTAL POSITION ENTERED BY WRH. CIRCLED MINUS FIGURES ARE 24-HOUR TEMPERATURE CHANGES.

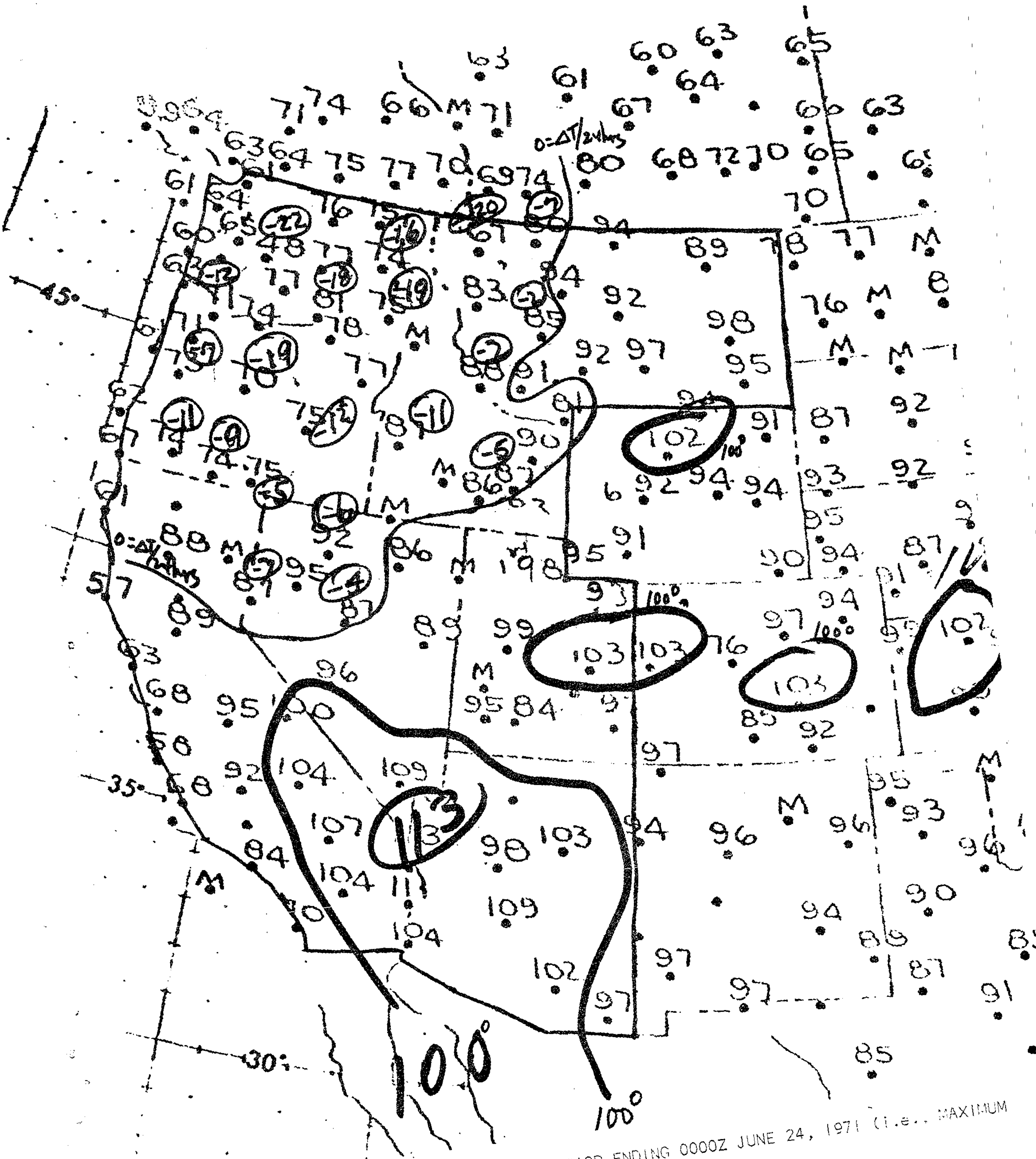


FIGURE 9. MAXIMUM TEMPERATURE CHART FOR PERIOD ENDING 0000Z JUNE 24, 1971 (i.e., MAXIMUM TEMPERATURES ON JUNE 23).

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No. 45/3 Precipitation Probabilities in the Western Region Associated with Summer 500-mb Map Types. Richard P. Augulis. January 1970. (PB-189414)

No. 45/4 Precipitation Probabilities in the Western Region Associated with Fall 500-mb Map Types. Richard P. Augulis. January 1970. (PB-189435)

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