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AN EXAMPLE OF EASTERLY WAVE ANALYSIS
IN THE WESTERN PACIFIC

8-10 July 1945

HEADQUARTERS
AIR WEATHER SERVICE
Washington 25, D. C.
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Air Weather Service Technical Report No. 105-75, "An Example of Easterly Wave Analysis in the Western Pacific, 8-10 July 1945," is published for the information and guidance of all concerned.

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PREFACE

In the tropics where the turnover of weather personnel has been rapid and published material on analytical techniques has been limited, there is a very definite danger that much valuable "know how" will be lost. During the war, when synoptic coverage in the Pacific was at its best, very little was written about the techniques in use or about the requirements for synoptic coverage.

This report, furnished by Dr. Reid A. Bryson of the Department of Meteorology of the University of Wisconsin, was initially a part of his doctoral dissertation submitted to the University of Chicago. It summarizes very well the techniques in use while Dr. Bryson was on active duty as a Major at the Weather Central on Guam in the latter part of the war. Although some of the techniques are now outdated, they may still provide ideas for developing new channels of thought and subsequently new techniques.

AN EXAMPLE OF EASTERLY WAVE ANALYSIS IN THE WESTERN PACIFIC

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ABSTRACT

Ordinary analytical techniques are generally unsatisfactory for the study of easterly waves, and must be supplemented by use of time-sections, streamlines, specialized cloud observations.

In the spring of 1945, when the deep easterlies returned to the Marianas, a long series of easterly waves began. The wave which passed Guam on the ninth of July, 1945 serves as an example to illustrate a number of characteristic features.

Analytic Technique for the Study of Easterly Waves

Despite the development of a number of auxiliary charts and devices the major tool for the tropical analyst is still the synoptic chart. The emphasis is definitely shifted, however, because of the nature of the atmospheric processes of greatest importance in low latitudes. Temperature and dew-point, so useful in frontal analysis, might as well be omitted, for the synoptic variation of those elements is much less than the diurnal and is caused by local conditions such as cloud or a shower more than by some general change in the tropical air mass. Temperature and dew-point data are useful in fog forecasting, but fog is so rare in the oceanic portions of the tropics that few forecasters even consider the possibility.

The pressure as such has no great significance unless very low, and the combined observational error, large diurnal variation, and scarcity of surface observations makes the drawing of isobars an interesting, but very nearly useless pastime. Three-hour pressure tendencies, unless extremely large, are of little value. Twenty-four hour pressure changes are much better where the stations are fairly closely spaced, as in the Caribbean, but at isolated stations synoptic variations due to secondary circulations may be indistinguishable from those due to minor changes in the intensity or location of the centers of action.

Wind, cloud, and weather data constitute the main bases for analysis of the synoptic chart. Though surface stations are scarce in oceanic regions, during the war, at least, the great number of aircraft reports (mostly wind, cloud, and weather) made analysis possible. Streamlines may be drawn to the wind data in place of the usual isobars. Several techniques may be used. That employed by the author has been described by Allen and Bryson, (Reference 1), and served very well in the western Pacific. Since the average <u>weak</u> easterly wave in the Pacific area is associated with a wind shift of less than 10 degrees it is clear that wind analysis can not serve as the sole analytical tool, except in the case of strong waves.

Clouds and weather are so closely related in the tropics that for purposes of comparison they may be grouped together. The form of the clouds may be used as a sensitive indicator of stability conditions which seem to have rather typical distributions about the major secondary circulations in the tropics. Carrying these ideas over to the synoptic chart, the distribution of cloud form (Reference 2) may be used to supplement the streamline chart. Unfortunately, the cloud form must be deduced from the cloud amounts, sizes, and associations reported rather than from the International Code for state of the sky, for the latter is often not applicable in the tropics. We have here the anomalous situation of data reported by untrained observers in aircraft being more complete and reliable than that furnished by trained observers on the ground.

The ideal streamline pattern associated with an easterly wave is usually indicated on the chart where easterly waves are suspected unless evidence to the contrary is present.

In addition to the streamline chart, the time-section of winds has found rather wide favor in the study of easterly waves, for pibals and rawins are more accurate than aircraft winds and offer a more continuous set of observations both in time and elevation. Another time-section found especially useful by the author is that of cloud form stability index, but, like all observations taken at the point for which the forecasts are issued, it is more valuable for diagnostic than for prognostic purposes.

One of the most promising tools where numerous inflight reports are available is the route-time diagram, (Figure 1), but it has not been sufficiently tested in practice for a detailed description of its use to be given here.

Probably the most useful criterion in the study of easterly waves is continuity, despite the fact that continuity is frequently uncertain and sometimes definitely missing. Changes in intensity are so pronounced and rapid, and the data often so sparse that the safest guess for the analyst is to continue the presence and rate of motion of the wave until again verified by the data or definitely shown to have disappeared. Easterly waves have been traced through distances of several thousand miles, continuously and demonstrably, and while others have been seen to disappear or apparently be generated in situ, such is an exception that needs further study before discarding the best-tested and time-honored approach in synoptic analysis--continuity.

Synoptic Description of an Easterly Wave Situation in the Western North Pacific

During the early winter of 1944-45, the weather of the western Pacific was dominated by a series of migratory subtropical anticyclones sweeping eastward. This was also a period of westerly steering over Japan. Between these anticyclones a series of polar troughs or, as referred to by Hines, (Reference 3), inter-cell troughs, also moved from west to east. Along the southern boundaries of the highs, the trade current was little disturbed by the polar troughs and a series of easterly waves, some associated with storms, moved westward. Westerlies appeared aloft over the Marianas only with the stronger of the polar troughs. On these occasions the base of the westerlies at Saipan was near 25,000 feet, but some of the data showed that easterlies reappeared above 50,000 feet. During the periods of deep easterlies this was the case, easterly waves usually were present.

As the interior of Asia became colder, the highs drifted farther southward and consequently westerlies were more frequently present aloft. From mid-January through early February the base of the westerlies gradually but irregularly lowered until 8,000 feet was an everyday figure.

Few easterly waves were observed during this period.

This period was one of marked northwest flow over the region of Japan which then turned to northeast across the Marianas. Under these conditions a major semipermanent trough was located considerably to the east of Saipan and the subtropical anticyclones were intermittently replaced by new masses of modified polar air. This is the closest approach to a northeast monsoon observed in the Marianas.

Early in March the steering pattern off the coast of Asia changed to southwest, and the Pacific anticyclones became quasi-stationary south of a polar front along which wave cyclones moved from the Formosa region towards the Aleutians. With this reestablishment of normal trade current conditions, easterly waves once more became prominent features of the weather, if any feature of trade weather may be called prominent. During March the easterlies deepened and easterly waves were common.

April marked a return to the conditions of November, westerlies at the surface or in the middle troposphere alternating with deep easterlies. Several of the easterly waves of April deepened to storm intensity. Again the easterlies were found to be present above westerlies at heights of 45,000 to 50,000 feet.

With the advent of May, the easterlies rapidly deepened as the Pacific became dominated by the expansion of the eastern Pacific anticyclone from which a broad, deep easterly current emanated. As a result, there followed in May, June, July, and August an almost unbroken succession of easterly waves. Only when the equatorial front was far north and the trade current not present was this series interrupted.

Example of 8-10 July 1945

The series of six-hourly synoptic charts for 9 July 1945 illustrate the general situation during a trade-wind period over the Marianas in the early part of the wet season.* (Figures 2a - 2e)

Several days before the period illustrated, there had been a separate anticyclone in that portion of the North Pacific between the Marianas and the Ryukyu Retto which caused the main trade current from the large high in the central North Pacific to turn sharply northward over the Marianas. By 8 July 1945, these highs had nearly fused into one, but traces of the separation still remained on 9 July 1950. Coincident with the fusion, the intertropical convergence, often called the equatorial front, began a northward surge from its position across the Palau group to the Philippines and Hainan. About the same time a new equatorial front developed from the northern Indies to Indo-China. The polar front had not yet retreated north of the Japanese home islands.

An easterly current at least 2,000 miles broad flowed across the Gilbert, Marshall, Caroline, and southern Marianas Islands on 9 July 1945. Over most of this area, the winds in the lower troposphere were from the east or east-southeast but varied in velocity from a few knots on the poleward edge near latitude 25°N to a core of maximum velocity (20-25 knots) near 10°N. The axis of the central North Pacific high tilted strongly southwestward so that the easterlies over the Marshalls turned to southwest at 30,000 feet, though over Guam and Saipan light easterlies continued

* The data on the charts in Figure 2 were copied from the charts of the Tropical Section of AAF Weather Station 7-43. The polar front analysis is modified somewhat from that of the original analyst. The analysis of the tropical portions including the streamlines is that of the author.

to at least 55,000 feet. The axial plane of the surface easterly jet also tilted somewhat southward as indicated by the 50-60 knot easterlies at 50,000 feet over Palau, near 5°N, and weaker northeasterlies at Guam and Saipan. On the equatorward side this broad belt of northern hemisphere easterlies merged with those of the southern hemisphere at about 5°N but with no equatorial front (or only a vestigial one) between the airstreams of different origin east of about 155°E.

Imbedded in this easterly current, a series of wave-like disturbances moved steadily westward, sometimes with more pronounced windshifts, sometimes with larger associated clouds, but deviating little from their mean speed of about six degrees of longitude per day. This rather uniform speed is indicated by the six hourly positions of the waves on the charts as well as by the uniform slant of the bands of high and low cloud tops in the route-time diagram (Figure 1). This wave speed is about equal to the mean wind in the lower troposphere in the region where it is measured, but is somewhat less than the winds in the core of the jet. Under these circumstances it is difficult to draw conclusions as to the relation of wave and speed of the basic current.

Not all the waves shown on the charts can be readily justified on the basis of the synoptic data alone, especially on the night-time charts (1200Z and 1800Z), but nearly always some of the waves in a series will be evident. Since there is a degree of regularity in the passage of waves at a station, a suggestion of uniformity in the spacing of cloud bands on the route-time diagram, and in exceptional cases good evidence of uniform

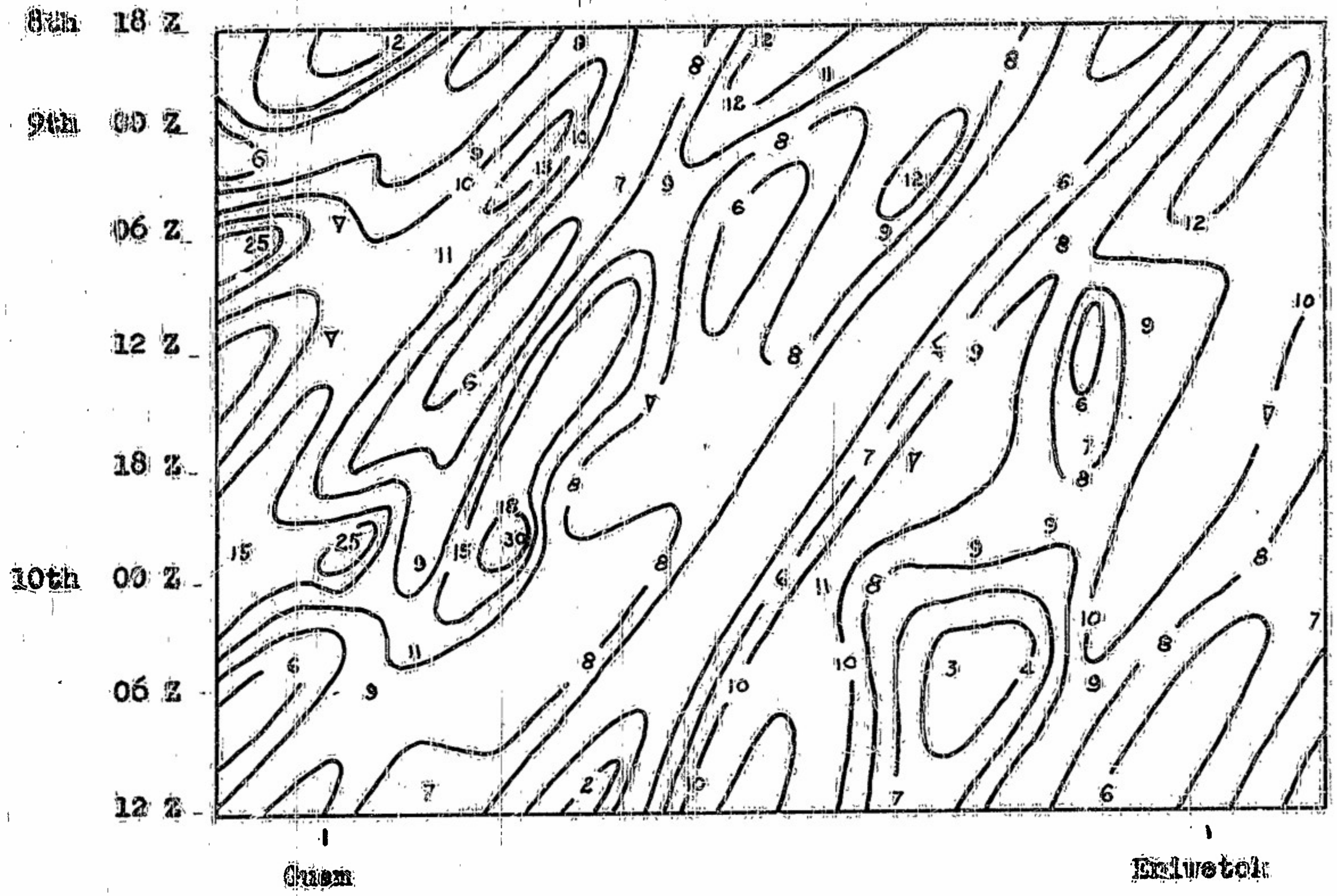

Fig. 1.-- Time variation of height of low cloud tops along the route from Guam towards Kwajalein. July, 1945. Taken from Guam Weather Central charts.

spacing on the charts, a most useful "rule of thumb" is to space waves uniformly on the chart. Some of each series will then be located by data; some will be entered tentatively on the basis of uniformity of spacing and continuity. With the sort of data available, no other course is open.

It will be noted that two main types of data are used besides continuity--the wind field and the distribution of low cloud. On the first chart of the series the most prominent easterly wave is that just east of the Marianas. The evidence for this particular wave is good in that not only is the wave apparent in the wind-field, but it appears as a well-marked band of cloud on the route-time diagram. On the preceding day's charts this particular wave was not outstanding, though every chart bore some evidence of its existence.

The next wave eastward is not so clear, nor is that which is at about 165°E. This latter wave, however, becomes more pronounced by 0000Z on 10 July 1945. It is not uncommon for strong or moderate easterly waves or disturbances to alternate with weak disturbances. The weakest waves which may be found on the charts have been drawn in. These alternate waves seem weak, yet examination of the route-time diagram shows that between the cloud bands which may be identified on the chart there are still other cloud bands moving along parallel to them, but which cannot be seen in the wind field. On the other hand the strong waves such as those described by Riehl are still less frequent than the stronger of those drawn on this particular set of charts. Referring to the route-time diagram in Figure 1, it may be seen that the distance between cloud bands is about half that between waves on the chart. Of these, every other wave seems to be weak.* The stronger of those on the streamline chart appear to alternate on the Saipan wind time-section, (Figure 3), between pronounced waves below about 10 km and those pronounced above that level. The wave which passed the Marianas on 9 July 1945 appeared as a pronounced wind shift below 10 km at Saipan and Guam. The interval between waves of this sort is about that between the waves described by Riehl; in fact, only these could have been detected with the techniques he employed. This nature of the disturbances must be accounted for in any satisfactory explanation of the easterly wave.

The wave east of Saipan on the 0000Z chart of 9 July 1945 is drawn for the winds at about 3,000 feet and passed that station shortly after 1200Z at that level as shown both by the synoptic chart and the wind time-section. At 20,000 feet, however, the wind shift did not take place until about 12 hours later. With a save speed of 15 knots, a slope of about 1:60 is indicated. This is a rather usual value though portions or all of the wave may be vertical. Slope to the west is rare. Since the slope may range up to 1:100 or more, considerable care must be exercised to maintain consistency of level for which the streamlines and analysis are drawn. What may be a weather area ahead of the wind shift at 8,000 feet may be behind it at 2,000. Riehl's examples from the Caribbean show similar slopes, (Reference 4).

From the synoptic chart it appears that early on 9 July 1945, the

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* Not invariably so, for all sorts of intensity changes have been observed.

easterly wave which passed Guam on that day was characterized by the worst weather preceding the wind shift at 3,000 feet, whereas late in the day this condition was reversed. This seems to be corroborated by the stability index record, (Figure 4), but may be a function of the chance location of the aircraft reports and individual cloud groups. Probably all that can be said is that the areas of worst weather are associated with the line of wind shift in the lower layers. Much investigation needs to be done along this line, but with waves moving at 15 knots and cloud bands one to four hours wide, six-hourly wind observations are too gross for conclusive results. This easterly wave passed Saipan at 30,000 feet about the same time that the next following wave passed at the surface.

The wind shift itself is well-defined in about one-half of the disturbances drawn on the charts. On the time sections of wind practically all orders of disturbance produce some fluctuation of direction or speed but about one in four displays the slowly increasing north component followed by a rapid change to south component and decreased speed that betrays the trochoidal shape of the wave that is apparent on the synoptic chart. Examination of the wind time-section reveals that superimposed upon this turning to northeast then change to southeast with passage of the wave there are a number of minor fluctuations. All the features described above suggest that rather than a number of isolated waves or a single series of similar wavelength, those drawn on the chart or seen in the time section are part of a broad spectrum of disturbances in the trade current.

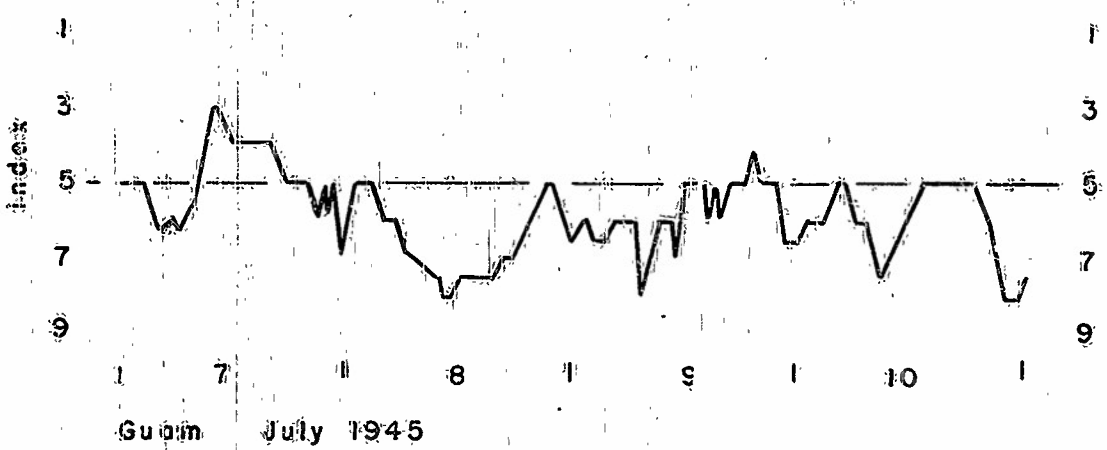

Fig. 4. - Record of stability index at Guam. July 1945.

In summary, as the synoptic situation developed during the period 8-10 July 1945, the upper winds at Guam and Saipan gradually but irregularly turned to northeast. The weather which had been characterized by rather large cumulus congestus improved temporarily on the morning of 9 July 1945 (local time). At 0700Z on the ninth (1700 local) a band of heavy cumulus congestus and showers passed Guam. The next rawin showed that the wind had shifted in the lower layers at both Saipan and Guam, while above 10 km the wind had become still more northerly. By 1800Z the middle clouds, which had thickened in the hours preceding the wind shift, decreased as the band of cumulus in which they had originated moved on by and the stability in the lower troposphere increased. The wind shift by this time had been felt to about 15,000 feet and clouds of the "trade cumulus" type with an occasional congestus area dominated the rest of the day.

Since for purposes of reproduction at a reduced scale, it is not possible to include all data which is normally placed on the synoptic chart, Figure 5 is included to indicate the scope of the data used in the analysis for 0000Z on 10 July 1945.

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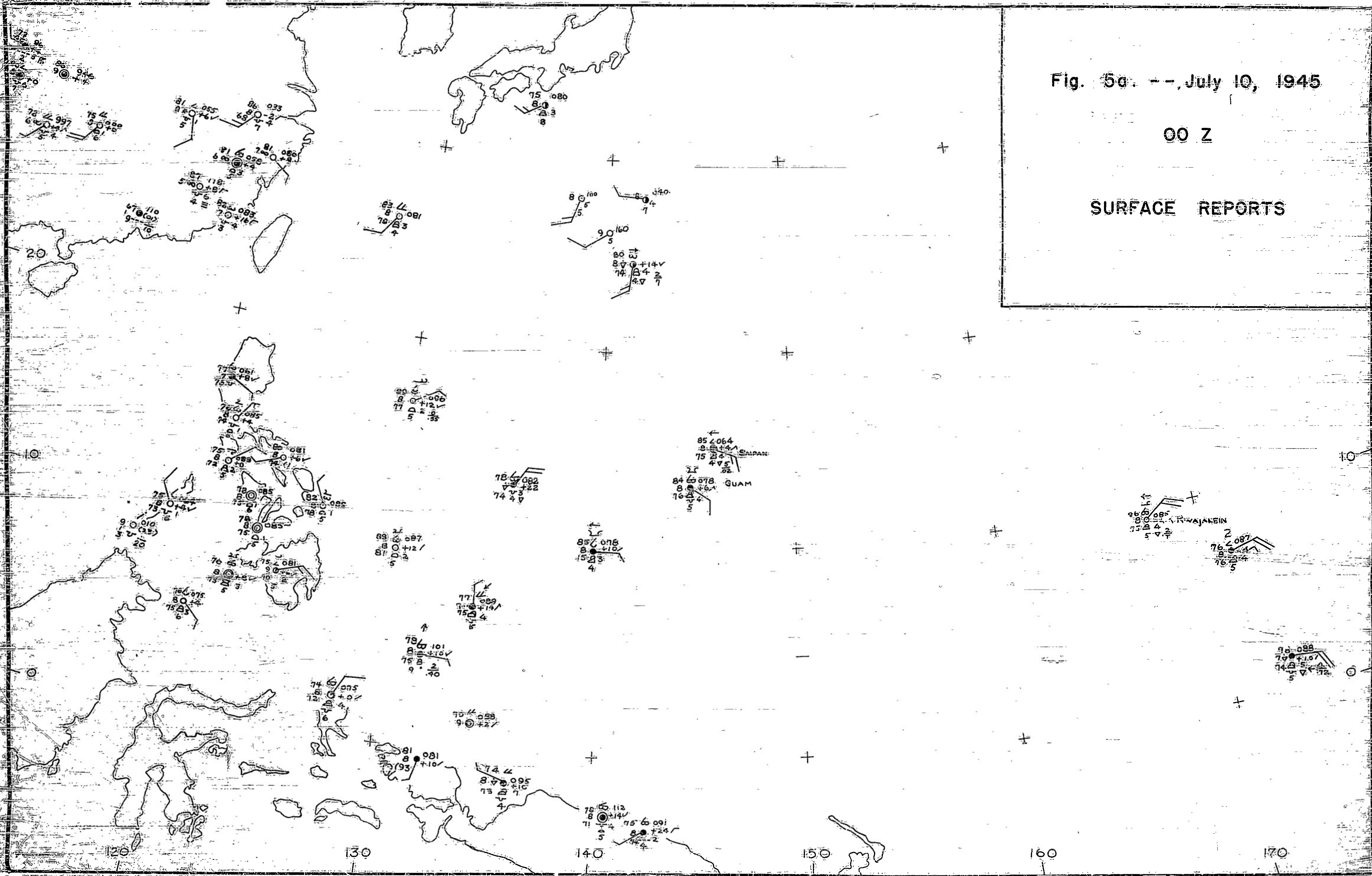

Fig. 5a. --, July 10, 1945

00 Z

SURFACE REPORTS

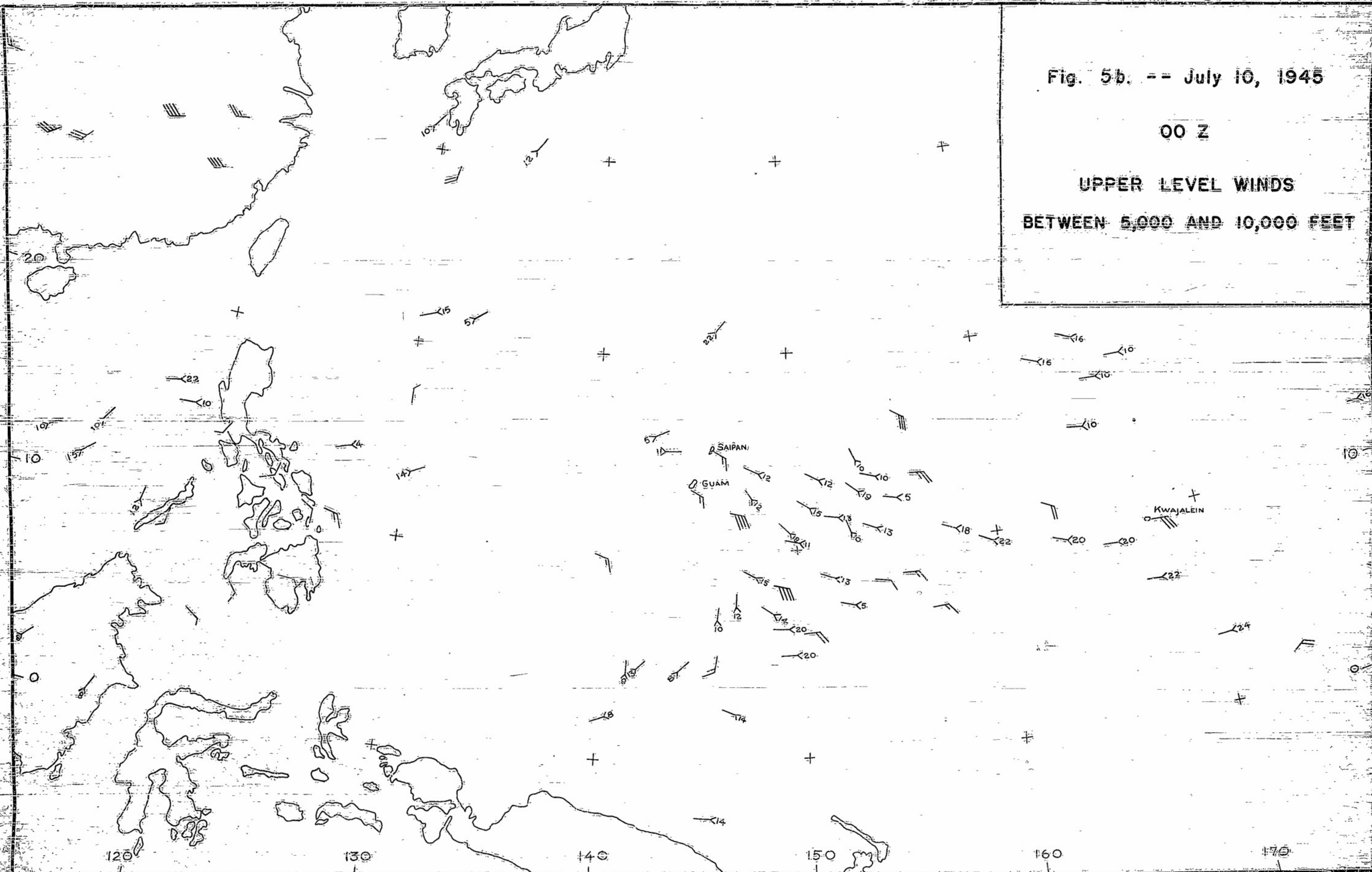

Fig. 5b. -- July 10, 1945

00 Z

UPPER LEVEL WINDS

BETWEEN 5,000 AND 10,000 FEET

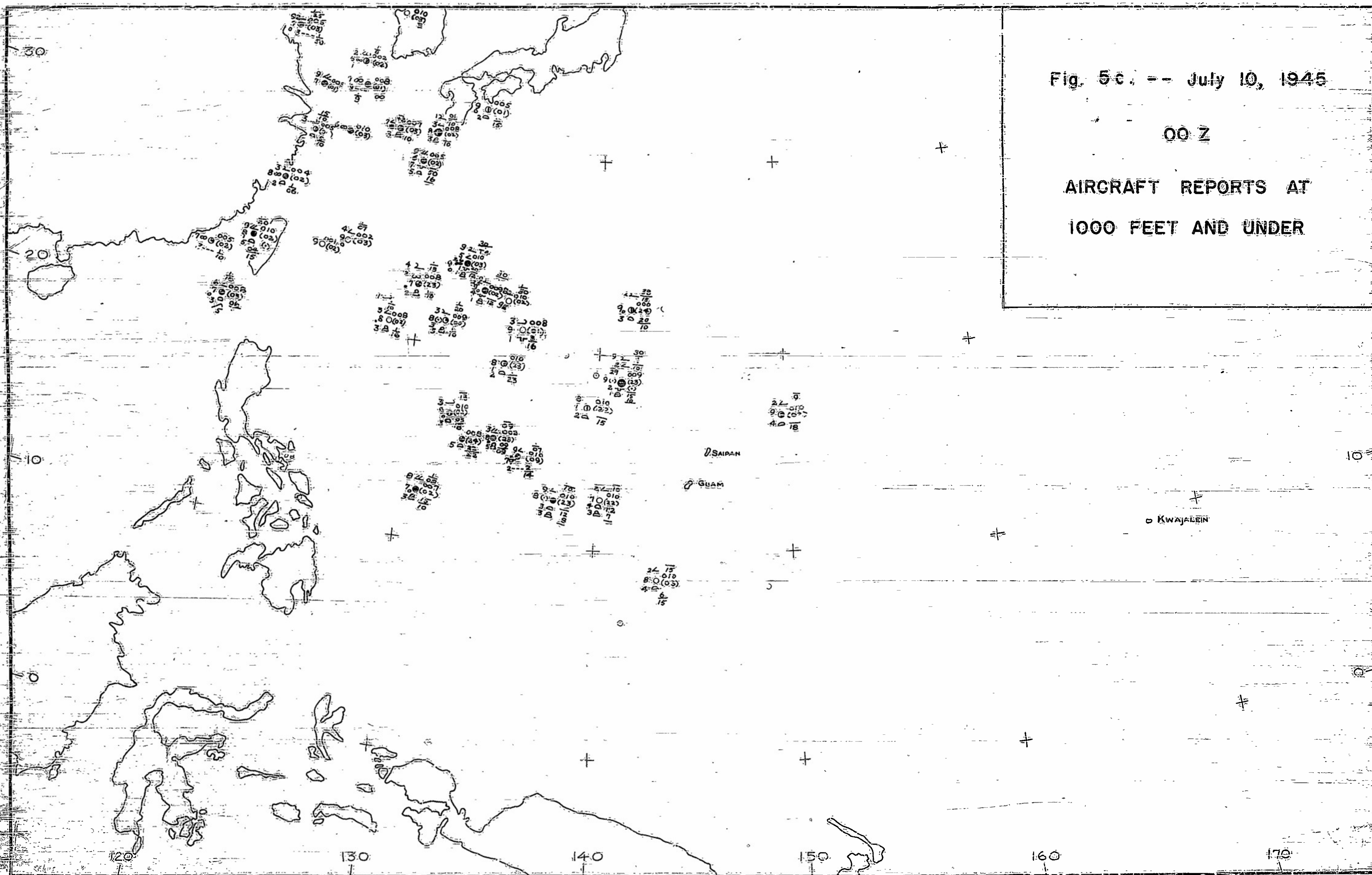
Fig. 5c. -- July 10, 1945
00 Z
AIRCRAFT REPORTS AT
1000 FEET AND UNDER
SAIPAN
GUAM
KWAJALEIN
30
20
10
0
120
130
140
150
160
170

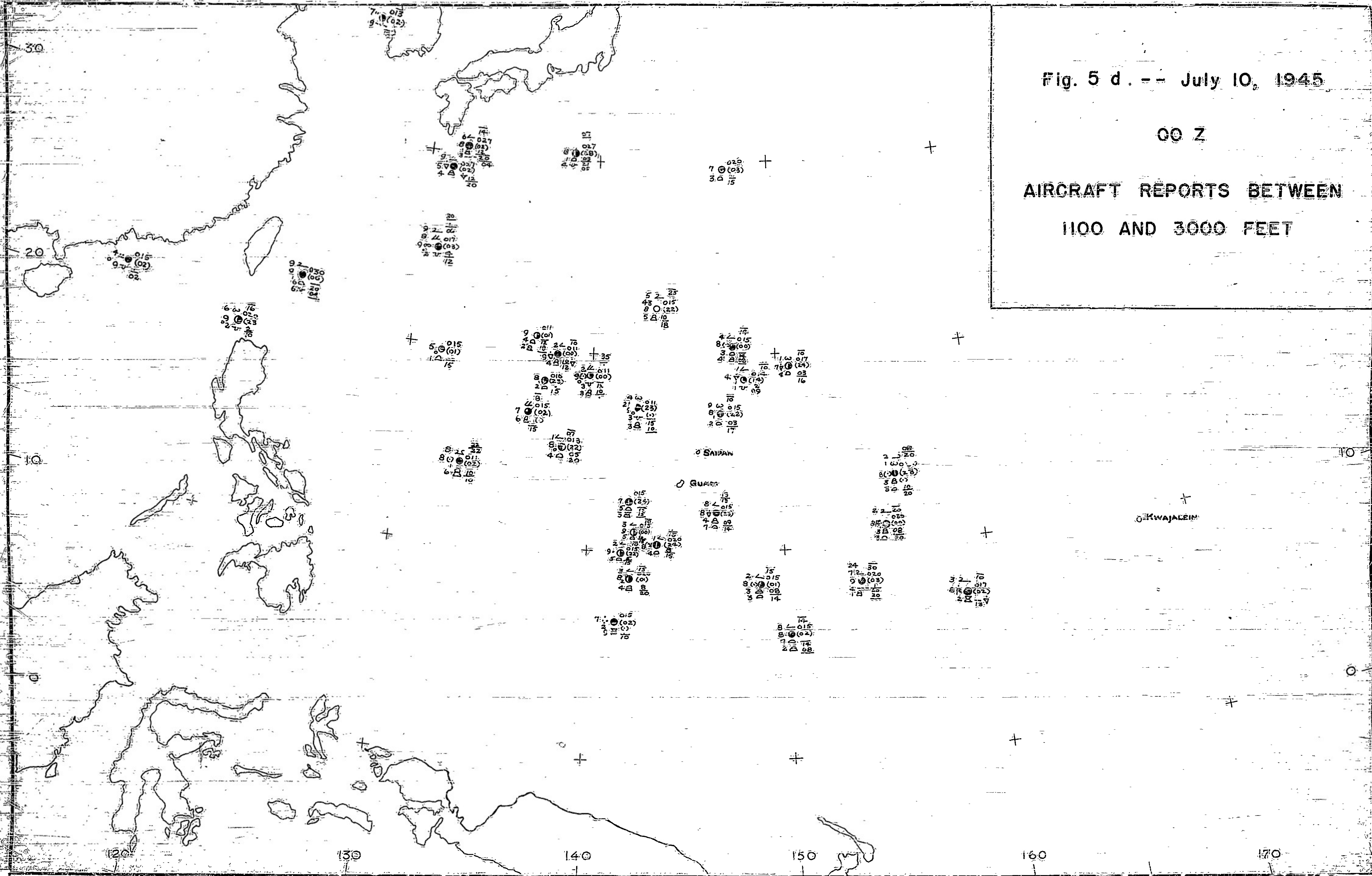
Fig. 5 d. -- July 10, 1945
00 Z
AIRCRAFT REPORTS BETWEEN
1100 AND 3000 FEET
SAIPAN
GUAM
KWAJALEIN
30
20
10
0
120
130
140
150
160
170

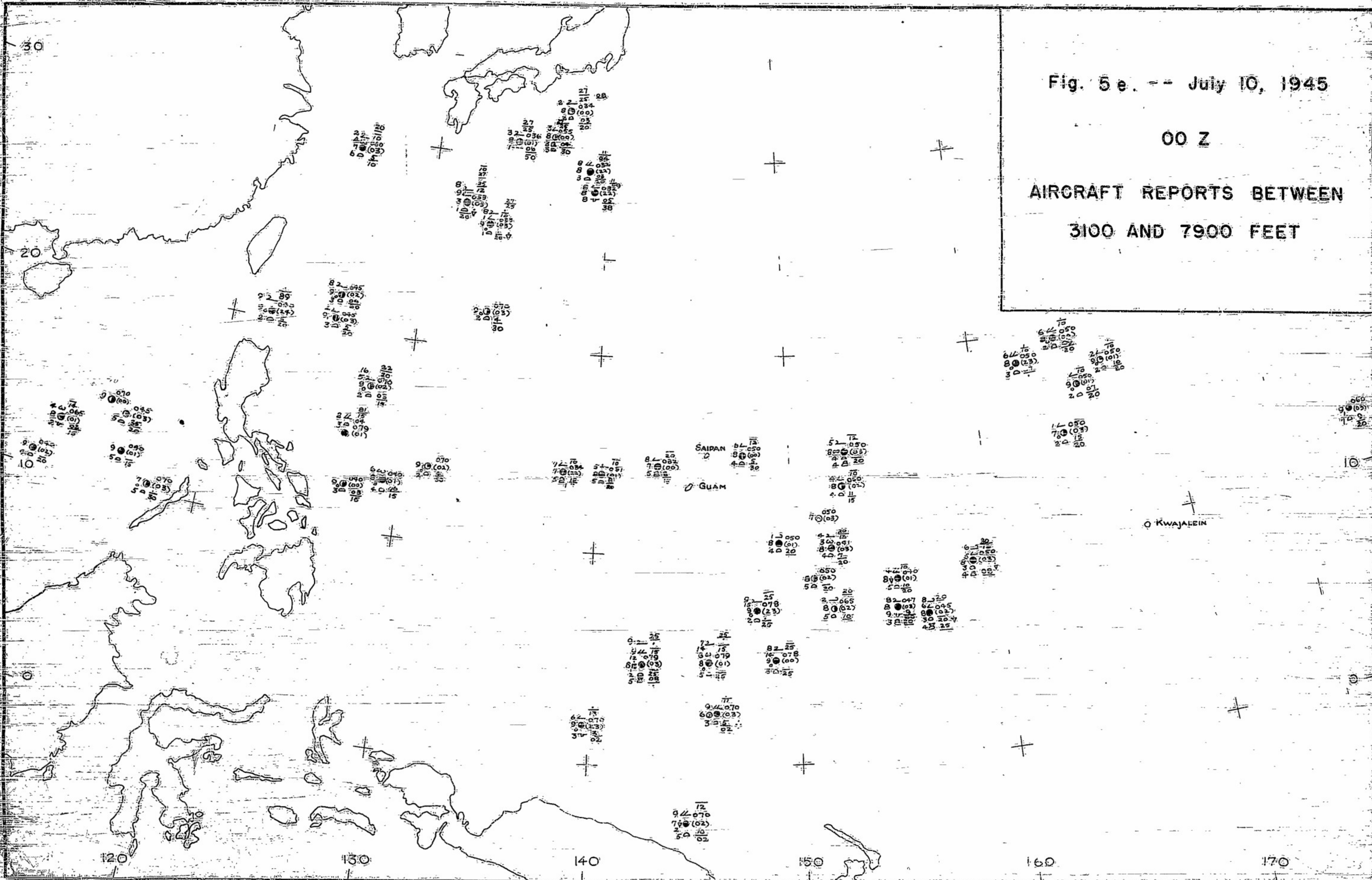

Fig. 5 e. -- July 10, 1945

00 Z

AIRCRAFT REPORTS BETWEEN 3100 AND 7900 FEET

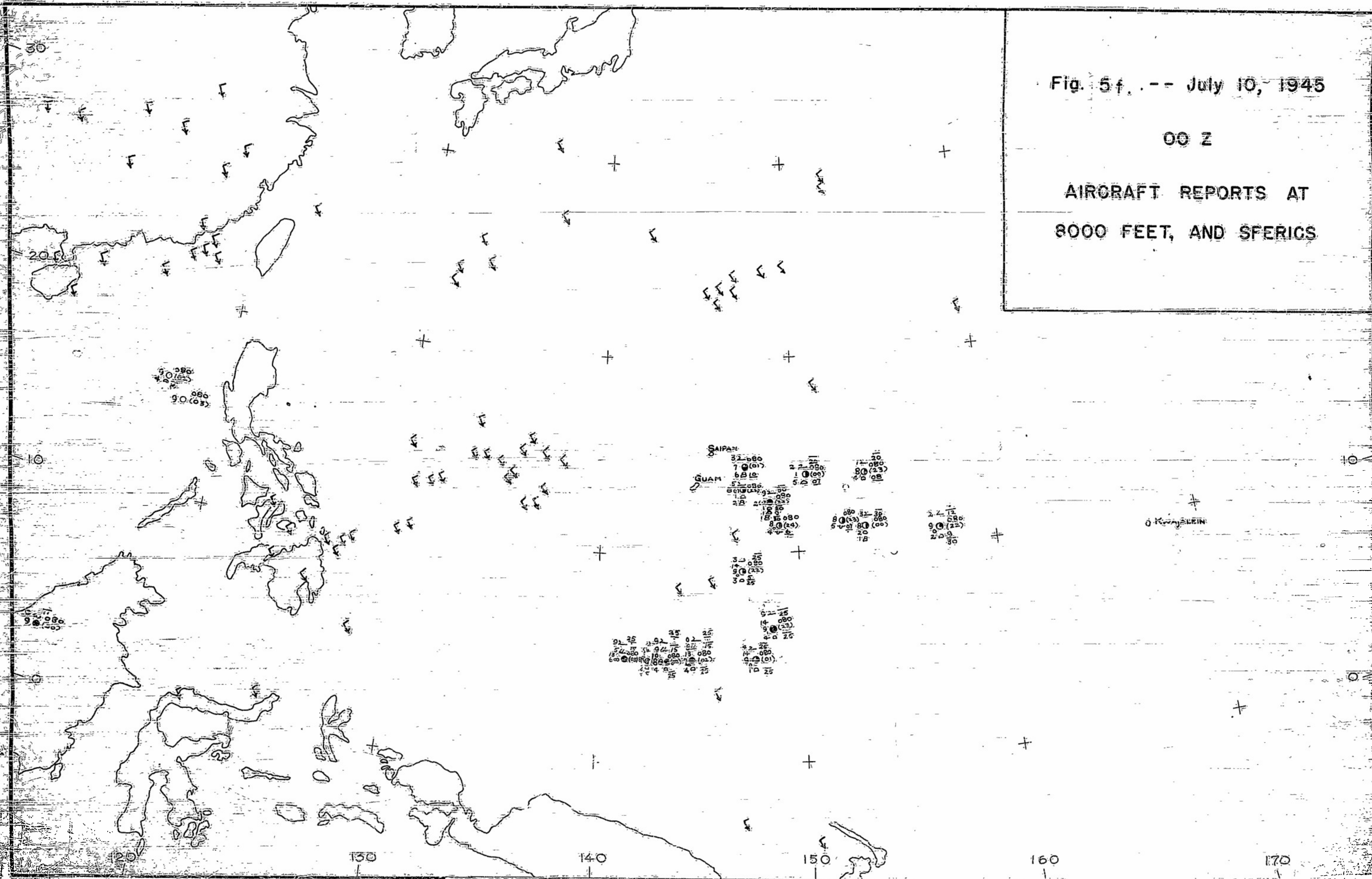
Fig. 5f. -- July 10, 1945
00 Z
AIRCRAFT REPORTS AT
8000 FEET, AND SFERICS
SAIPAN
GUAM
KWAJALEIN
30
20
10
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120
130
140
150
160
170

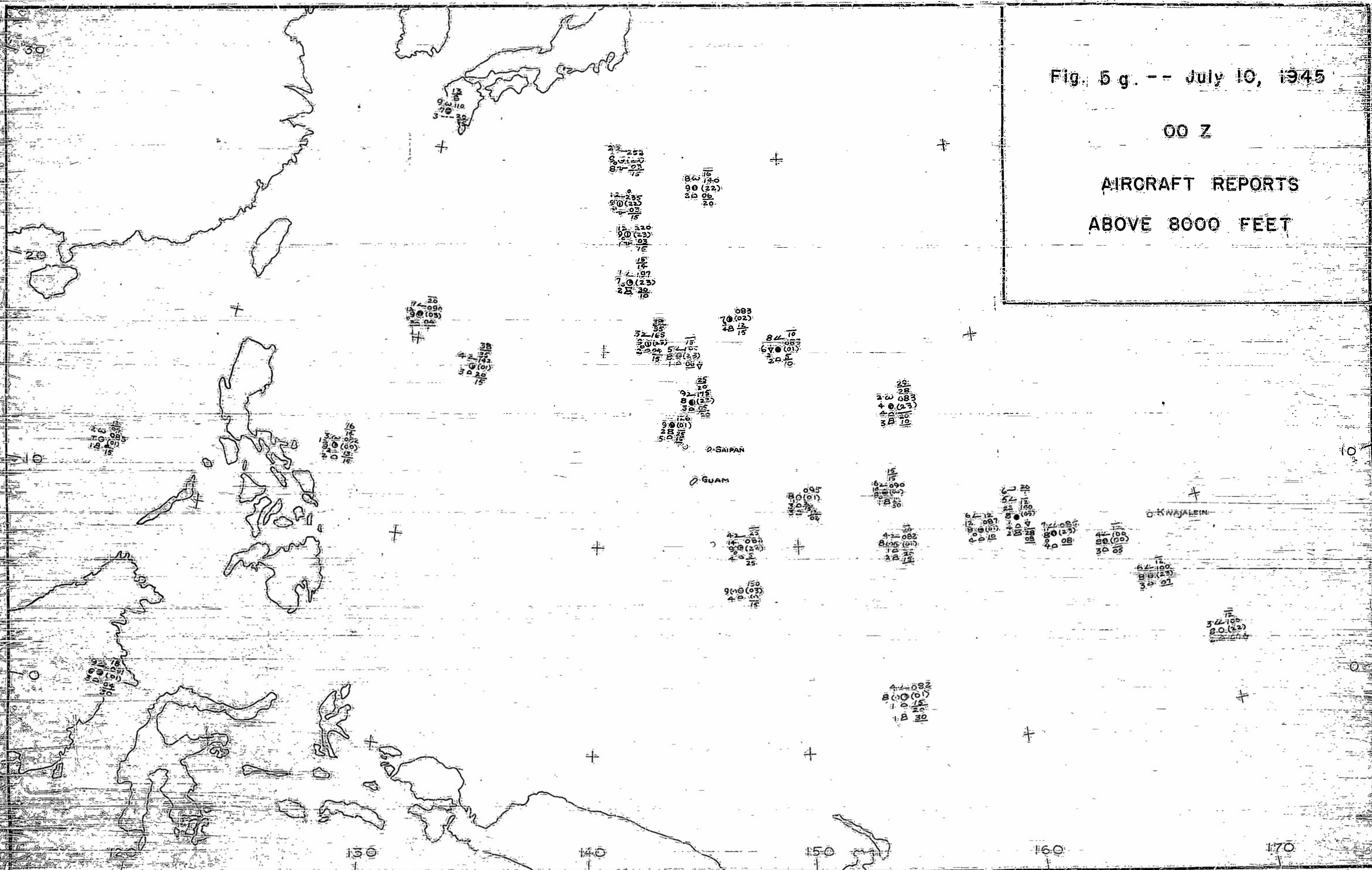
Fig. 5 g. -- July 10, 1945
00 Z
AIRCRAFT REPORTS
ABOVE 8000 FEET
SAIPAN
GUAM
KWAJALEIN
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20
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130
140
150
160
170

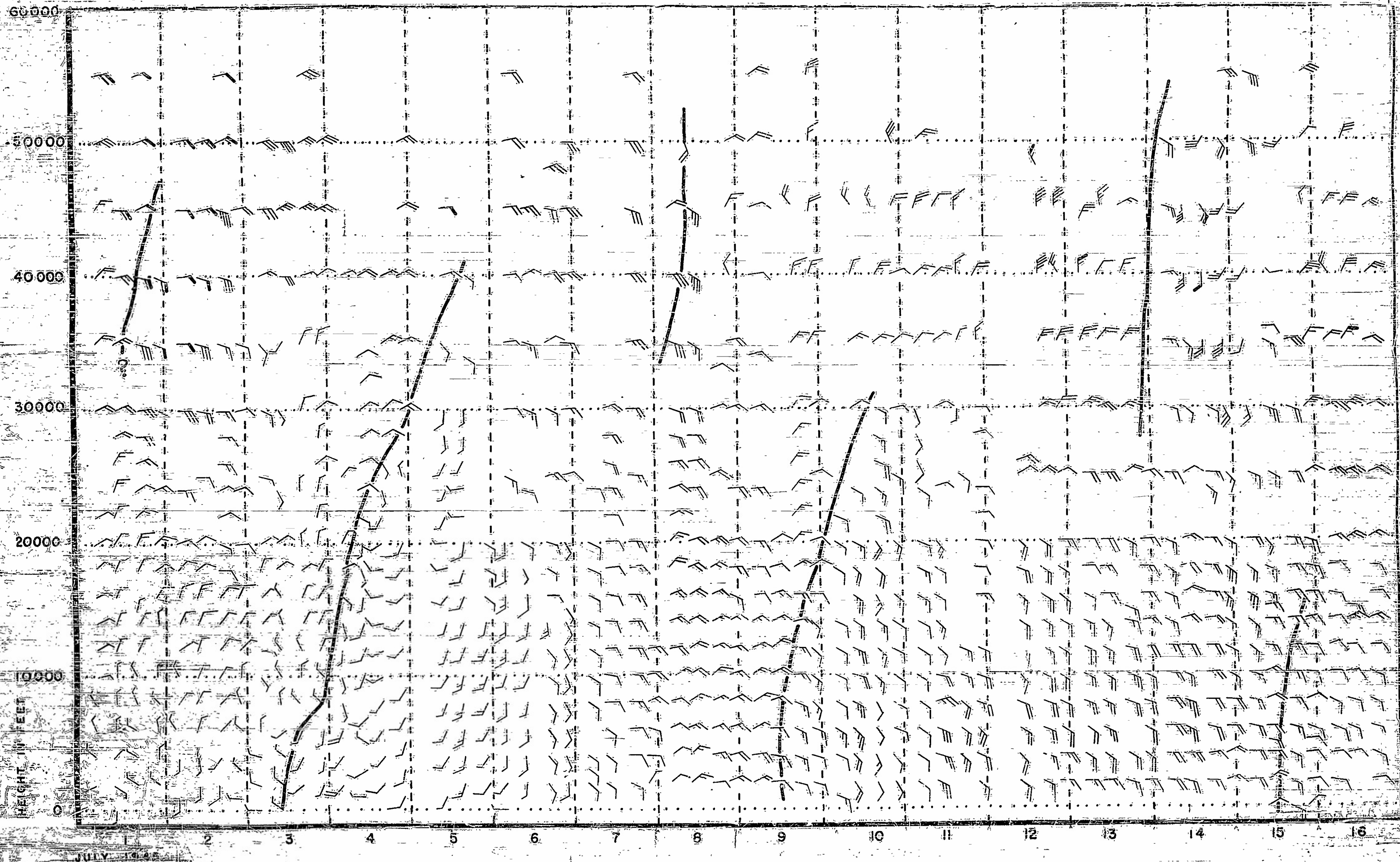

Fig. 3.—— Time-section of winds aloft over Saipan.

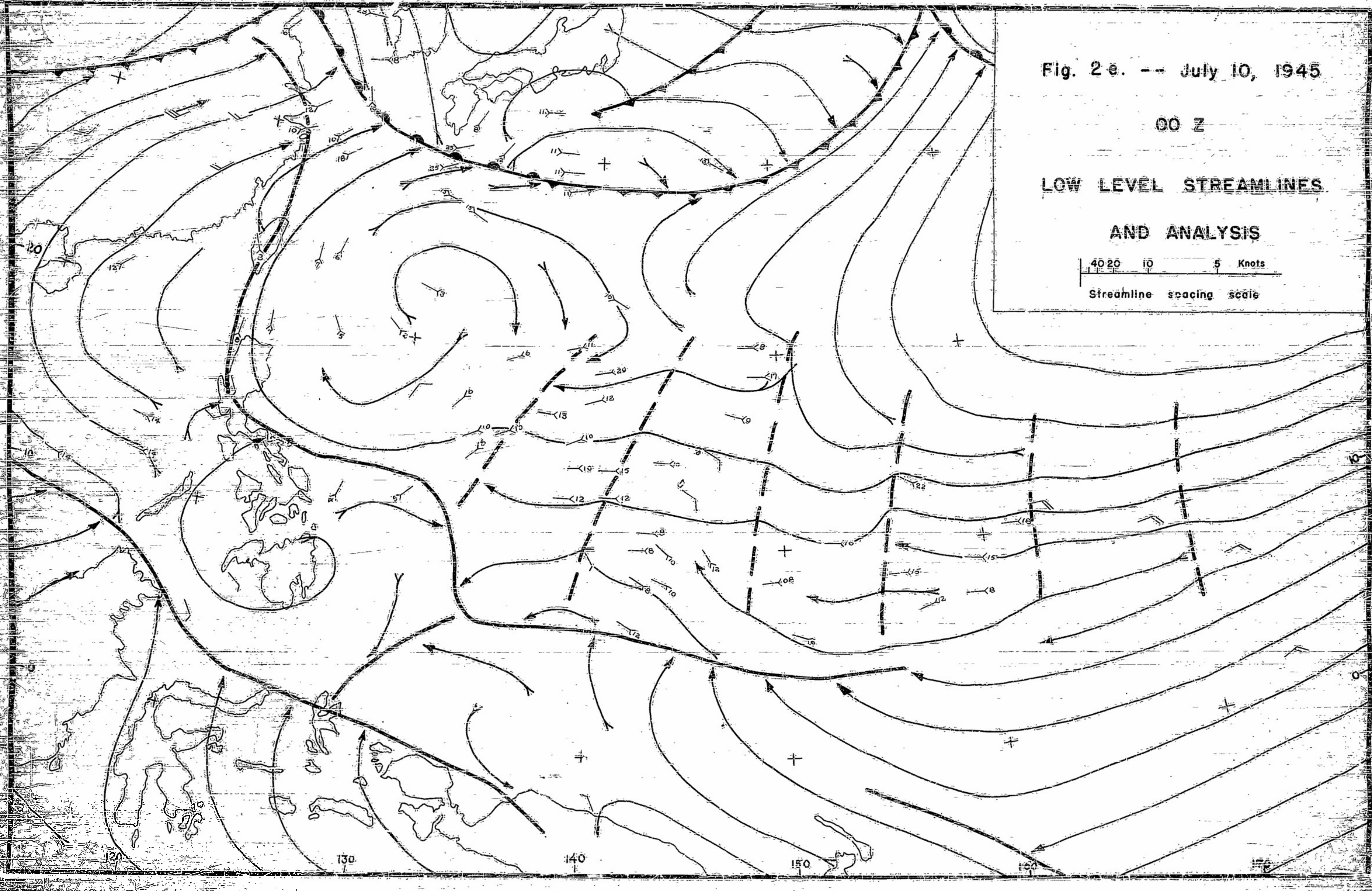

Fig. 2e. -- July 10, 1945

00 Z

LOW LEVEL STREAMLINES AND ANALYSIS

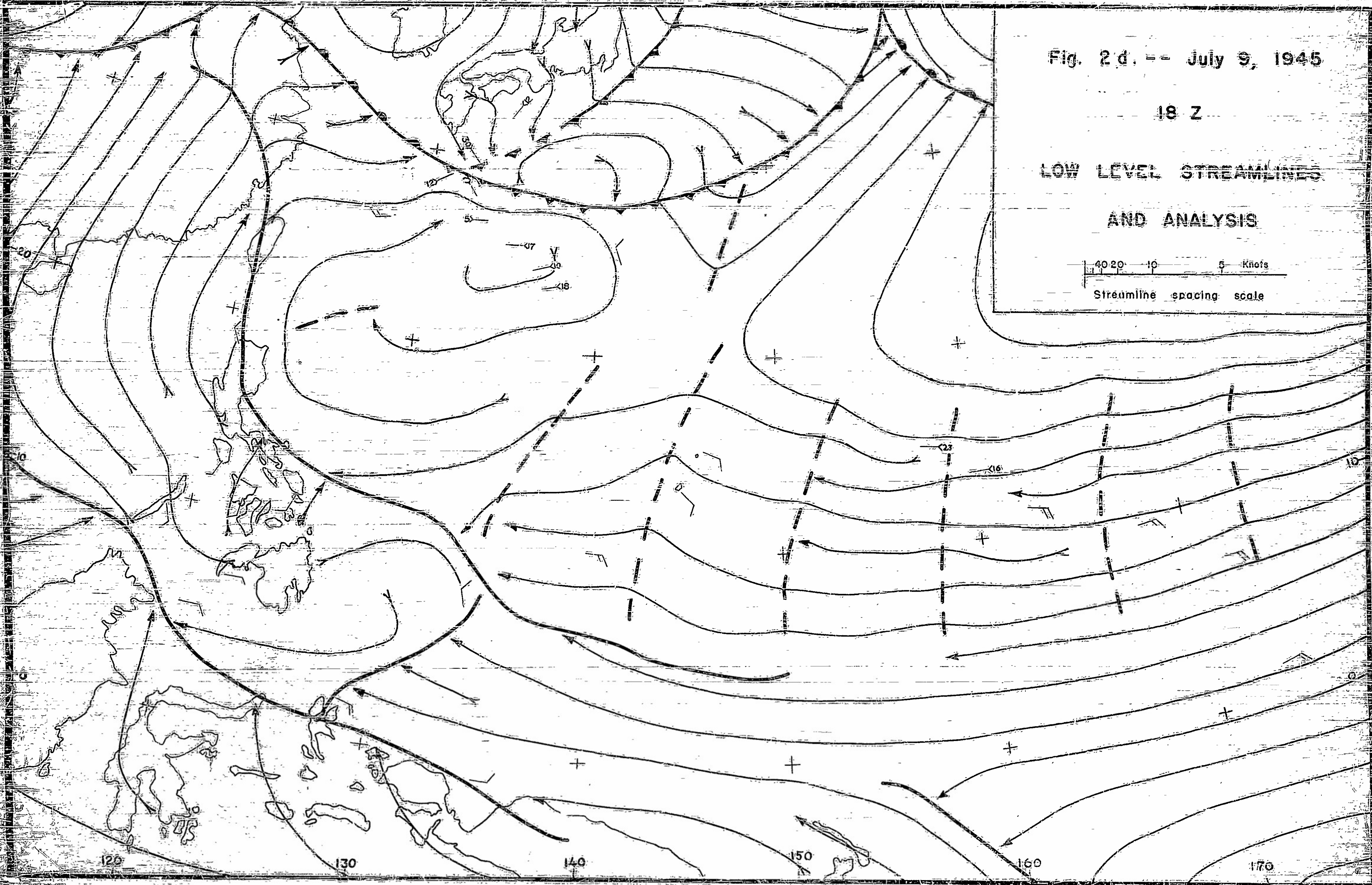

Fig. 2d. -- July 9, 1945

18 Z

LOW LEVEL STREAMLINES AND ANALYSIS

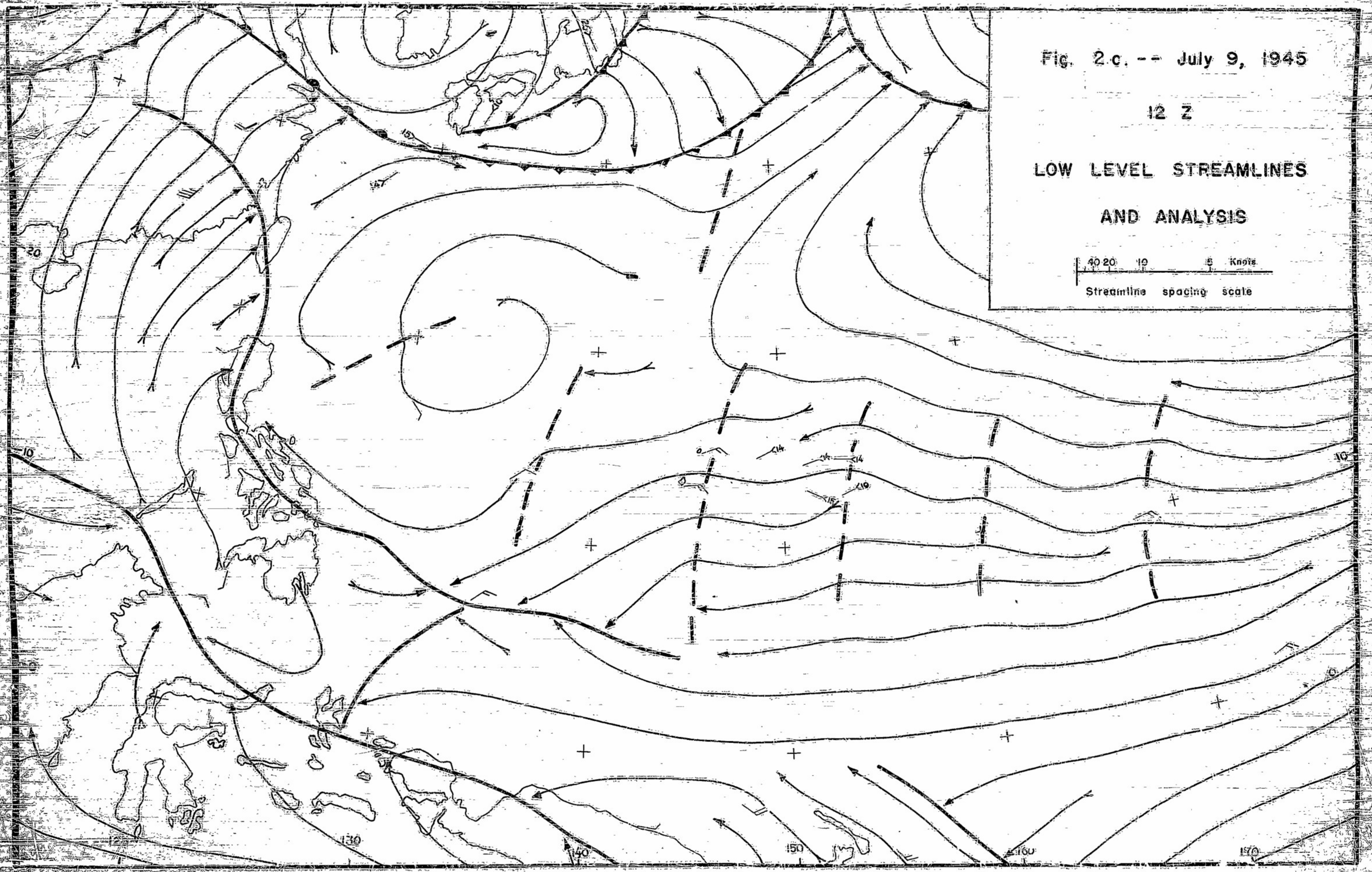

Fig. 2c. -- July 9, 1945

12 Z

LOW LEVEL STREAMLINES

AND ANALYSIS

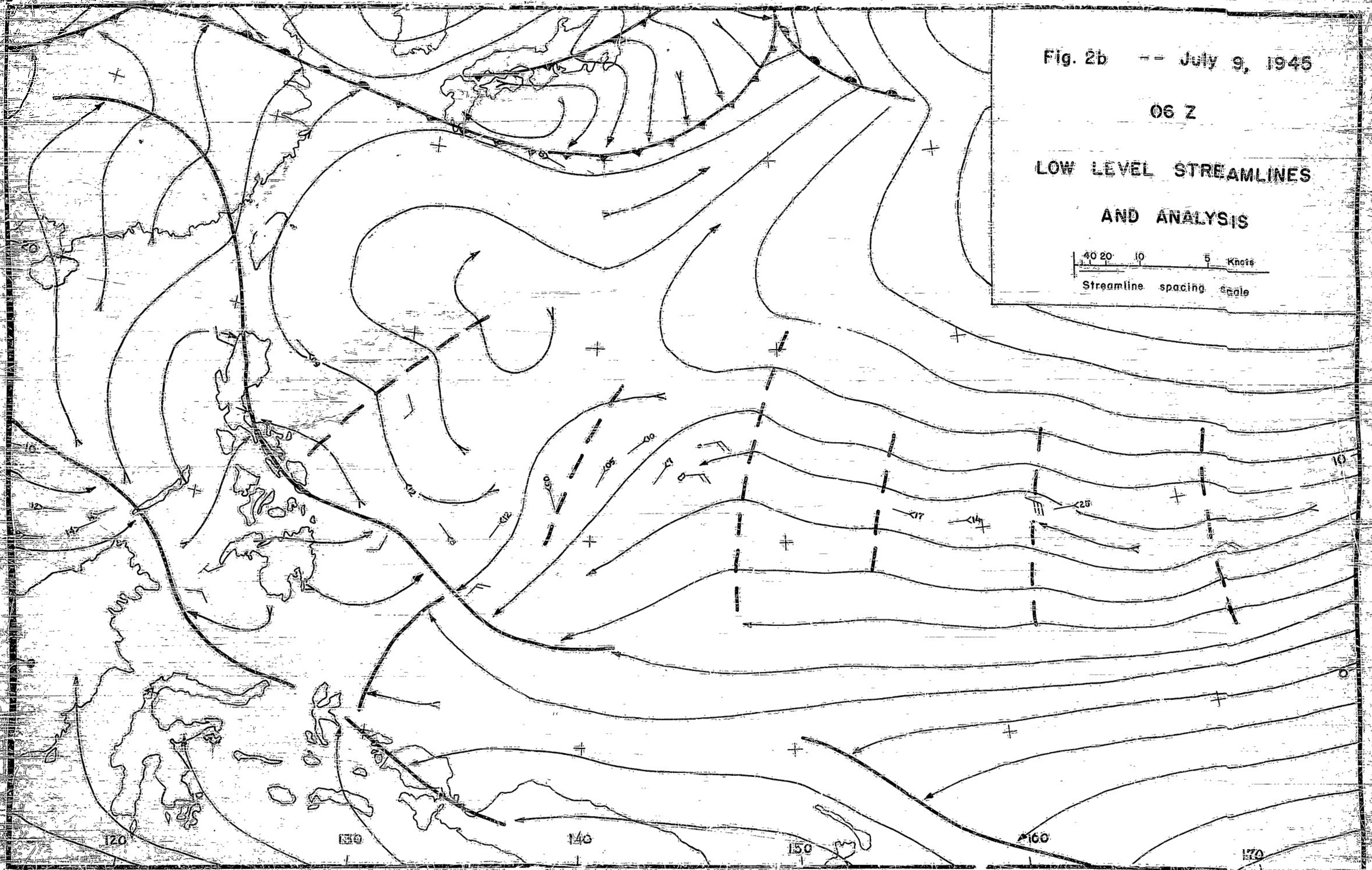

Fig. 2b -- July 9, 1945

06 Z

LOW LEVEL STREAMLINES

AND ANALYSIS

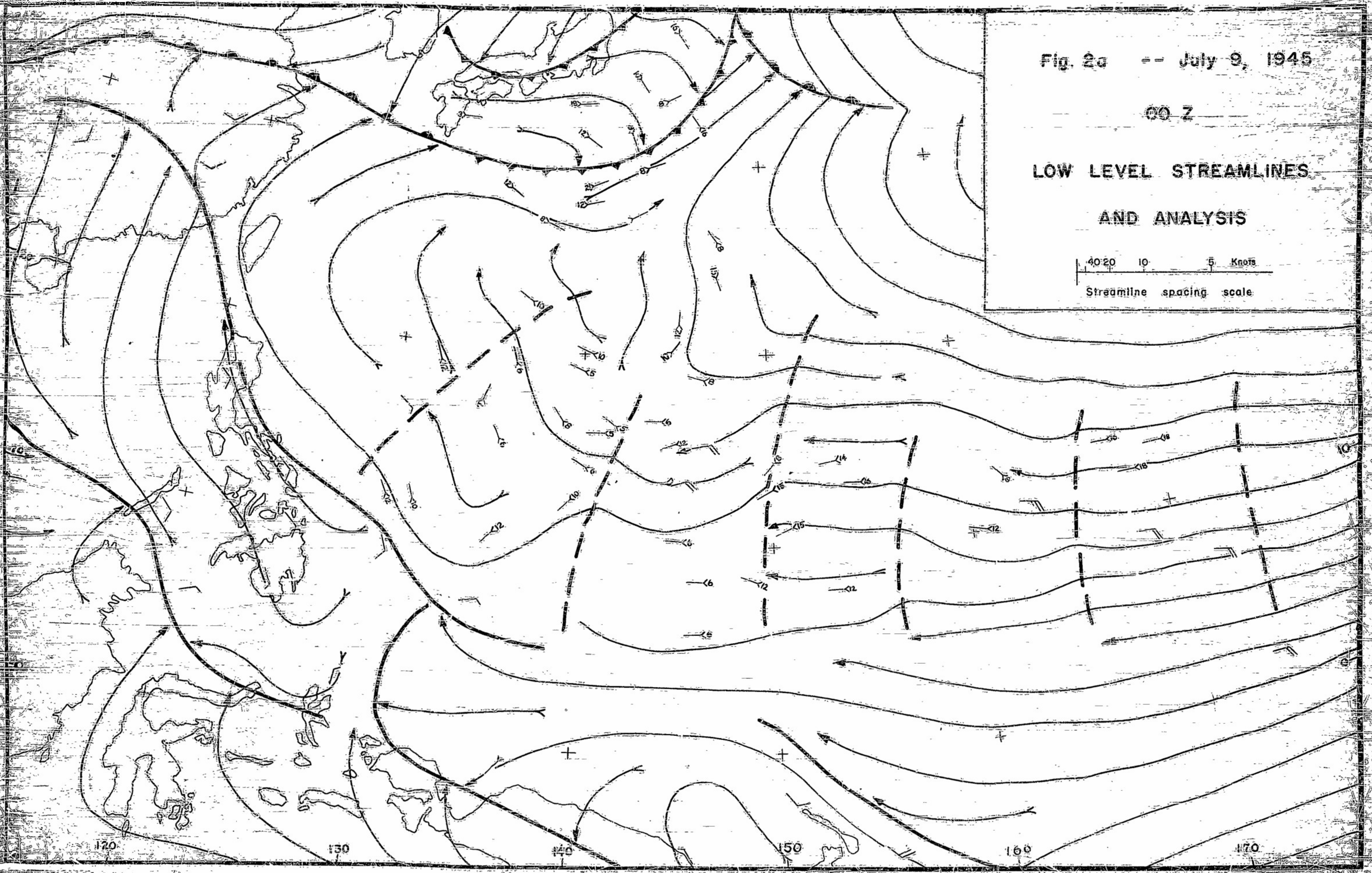

Fig. 2a -- July 9, 1945

00 Z

LOW LEVEL STREAMLINES AND ANALYSIS