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THE USE of ENVIRONMENTAL SATELLITE DATA FOR MAPPING ANNUAL SNOW-EXTENT DECREASE in the WESTERN UNITED STATES

FINAL REPORT

JUNE 1970
CONTRACT NO. E-252-69(N)

JAMES C. BARNES
CLINTON J. BOWLEY

prepared for
DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

ALLIED RESEARCH ASSOCIATES, INC.
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FOREWORD

The research described in this report was performed by Allied Research Associates, Inc., Concord, Massachusetts, for the Environmental Science Services Administration, under Contract No. E-252-69(N). The authors wish to acknowledge the technical assistance provided throughout the study by Mr. Donald Baker of the National Environmental Satellite Center, Environmental Sciences Group.

The environmental satellite photographs were provided by ESSA, the Nimbus data by the Nimbus Data Utilization Center of NASA, and the Apollo-9 photographs by the Manned Spacecraft Center of NASA. Aerial-survey snow data collected by the Army Corps of Engineers were obtained through the courtesy of the Sacramento and Portland River Forecast Centers. Other aerial-survey data were kindly provided by the Salt River Project in Arizona. Snowfall information and snow-depth reports are from the Basic Data Summaries published by the Soil Conservation Service, the publications of the California Department of Water Resources, and Climatological Data Summaries published by the Environmental Data Service of ESSA.

ABSTRACT

Techniques to map areal snow extent from environmental satellite photography are tested in three regions of the western United States during the 1967 and 1969 snowmelt seasons. The three regions, each with characteristically different terrain, forest cover, and snowfall climatologies, are: (1) The Southern Sierra Nevada in California, (2) the Upper Columbia Basin in Idaho and Montana, and (3) the Salt River Project Area in Arizona. The principal data sample is AVCS photography from the ESSA satellites; in addition, IDCS photography and Daytime HRIR data from the Nimbus III satellite are also examined. Snow-extent measurements from aerial surveys are used as ground-truth data.

The results of these investigations indicate that of the three regions tested satellite imagery provides the most reliable measurements of snow extent in the southern Sierras. For typical river basins in this region, snow extent in terms of percentage of basin covered can be determined from satellite photographs to within ± 5% of the aerial-survey measurement. In the Kings River Basin, the satellite snow-line elevation is within 500 feet of the aerial-survey snow-line elevation, with the satellite value being higher in 10 of 11 cases analyzed.

In the Upper Columbia Basin satellite snow mapping is less reliable because the region consists of more densely forested mountain ranges, each with a relatively small horizontal snow-cover extent. Furthermore, spring-time cloudiness is more prevalent in this region. In the Arizona mountains considerably smaller snow depths than in the other two regions can be mapped because of the sparse vegetation.

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1. INTRODUCTION

1.1 Purpose

Considerable research has been carried out recently to determine hydrologic applications of environmental satellite data. The current status of the use of photographic and radiometric data for these purposes is well documented in reports such as McClain (1970) and Ramey (1970). One hydrologic application of satellite photography is the measurement of areal snow extent. Through studies performed during the past few years techniques to enable the operational use of existing satellite data have been developed for both flat and mountainous terrain regions (Barnes and Bowley, 1968 and 1969). A computer product has also been devised as a means of suppressing transient cloudiness and enhancing major snow and ice features in satellite imagery (McClain and Baker, 1969).

The study described in this report is a continuation of the initial research on satellite surveillance of mountain snow (Barnes and Bowley, 1969). In that study, using data from a single winter-spring season (1966-1967), techniques for identifying and mapping snow were developed, background charts of winter and spring snow distributions were prepared, and the snow-line retreat in selected areas was monitored. Because of the lack of suitable ground-truth data, however, the accuracy of the satellite snow maps was difficult to determine.

The purpose of the continuation of that work was to test the mapping techniques on a second year of data, to develop improved techniques where applicable, and using better ground-truth sources to evaluate more precisely the mapping accuracy. It was also hoped to perform objective analysis of brightness variations within forested and non-forested snow areas; however, the digitized brightness values necessary for this phase of the study were not available.

1.2 Satellite Data Sample and Regions Studied

The satellite data sample consisted primarily of operational ESSA-AVCS photography acquired during the winter and spring seasons of 1967 and 1969. In 1967 ESSA-3 operated through May and ESSA-5 after the 1st of June; in 1969 ESSA-7 provided data through March with ESSA-9 going into operation on 1 April. No significant differences in picture quality were observed throughout the sample period (during 1968, the data were not of sufficient quality to permit their use for snow mapping purposes). The general characteristics of these cameras are discussed in various reports such as Schwalb and Gross (1969); particular characteristics affecting snow surveillance are discussed in the previous reports by Barnes and Bowley (1968 and 1969).

Because the hydrologic interest in snow extent in the western mountains is greatest during the snow-melt season, analyses were concentrated on the period extending from late winter through the month of June. The analyses were performed for three specific regions, selected because of the availability of aerial-survey snow data for use as ground truth. The three regions, which also have characteristically different terrain, vegetation, and snowfall climatologies, are: (1) The southern Sierra Nevada in California, (2) the Upper Columbia Basin in northern Idaho and northwestern Montana, and (3) the Salt River Project Area in Arizona. The major emphasis was placed on the southern Sierras region primarily because the aerial-survey data from the Sierras were more abundant and were in a more suitable format.

A summary of the principal results of the study is presented in Section 2. The analyses for the three regions are described in detail in Sections 3, 4 and 5, respectively. In Section 6, analyses of Nimbus III IDCS and daytime HRIR data are discussed; examples of the computer-produced Augmented Resolution Chips and Composite Minimum Brightness charts evaluated by McClain and Baker (1969) are also presented. Satellite photographs and accompanying maps are given in the Appendix. Elevation contours for each region are given on the base maps.

2. SUMMARY OF RESULTS

In a report on the management of California's snow-zone lands for water, Anderson (1963) discusses two important characteristics of the Sierra Nevada snowpack: (a) Maximum accumulation of snow, and (b) rate of melt of snow water from the pack. The first characteristic is a good indicator of total water yield, and the second of when the resulting water is delivered. Both of these characteristics may be related in some degree to the snow extent. In a study using aerial photographs, Leaf (1969) found that for each of three Colorado watersheds a functional characteristic exists between extent of snow cover during the melt season and accumulated runoff. He reports that snow-cover depletion relationships are useful for determining both the approximate timing and the magnitude of seasonal snowfall peaks.

Thus, areal extent of mountain snow is an important hydrologic consideration in the western United States. The results of the study described in this report further substantiate that valuable information on snow extent can be acquired from existing environmental satellite data. Of the three regions examined, satellite imagery appears to provide the most reliable data for the southern Sierra Nevada.

The southern part of the Sierra Nevada is not densely forested, so snow appears very bright and can be reliably identified. Furthermore, an abundant number of cloud-free pictures can be anticipated during the snow-melt season. Geographic referencing of the data is not a serious problem; after the identifiable features are initially located, relative changes in the snow pattern can be mapped fairly easily from subsequent pictures.

For the river basins of the southern Sierras snow extent can be mapped from satellite photographs with an accuracy of within ± 5% (of basin snow covered) of that obtained from aerial-survey observations. Moreover, as seen from the graphical results, the rates of snow decrease are similar to those derived from the aerial-survey data. In the Kings River Basin, the basin for which the agreement in total snow extent between the two data sources was the poorest of the four basins tested, the satellite value was consistently less than the aerial-survey value. Because of this consistency, the rates of snow-extent decrease computed from the satellite data were in excellent agreement with those computed from aerial-survey data. In the Kings Basin, the mean difference in snow-line elevation computed from the corresponding satellite and aerial-survey snow extents is about 500 feet.

Snow mapping in the Upper Columbia Basin region is more difficult because of three factors: (1) The mountainous terrain consists of numerous but smaller ranges, so that late-season snow covers less horizontal area and, therefore, cannot be as easily identified (2) The region is more densely forested reducing the overall albedo of the snow-covered terrain; and (3) terrain-associated cloudiness is more prevalent, especially during the late spring. Nevertheless, for three cases tested the mean difference in snow-line elevation within several river basins estimated from the satellite data and measured by aerial survey was less than 1000 feet. The snow-line was consistently estimated to be at a higher level than the aerial-survey measurement, probably due to forest effects.

Although comparative data were not available for the Lower Columbia Basin, snow appears to be more easily identifiable in that region. Despite the mountains also being densely forested, a heavier snowpack at the higher elevations apparently increases the overall albedo. Cloud contamination also seems to be less of a problem in the Pacific Northwest during the late spring. In the Salt River Project area in Arizona, because of the lack of dense forest, snow depths of only a few inches can be mapped from the satellite observations.

For purposes of snow mapping, the Nimbus III IDCS photography does not appear significantly different from the ESSA AVCS photography. In the pictorial display of the Nimbus III Daytime HRIR data, mountain snow is virtually undetectable. In these longer wavelength measurements, however, the contrast between land and water features is greatly enhanced. The computer-produced Composite Minimum Brightness Charts are excellent for identification of large-scale snow features, but obscure the small-scale features important for accurate mapping in smaller river basins.

The aerial-survey data in the form of horizontal snow-extent charts were easier to work with than the data in the form of snow-line elevation. Furthermore, because even relatively small grid-location errors in the satellite data can be significant when comparing the snow line with elevation contours, exact determination of snow-line elevation from satellite snow maps is difficult. When considering the overall snow extent within an entire river basin, however, many of the small mapping errors cancel out. Thus, when analyzing satellite data in mountains such as the Sierras, areal extent of snow cover (in percent of basin covered) is concluded to be a more meaningful parameter than snow-line elevation. This parameter is the one that is inherently measurable from satellite imagery.

3. REGION I: SOUTHERN SIERRA NEVADA

A major part of the study was devoted to an analysis of the southern part of the Sierra Nevada in California. The hydrologic importance of snow accumulations in this region, in which annual stream flow is the most variable of any California watershed, is well documented (Anderson, 1963; Court, 1963). The stream flow variability in the areas adjacent to the southern San Joaquin Valley is due mainly to a large variability in the number and intensity of the winter storms crossing the region. Thus, accurate monitoring of snowpack distribution in the southern Sierras is essential for water management and flood forecasting.

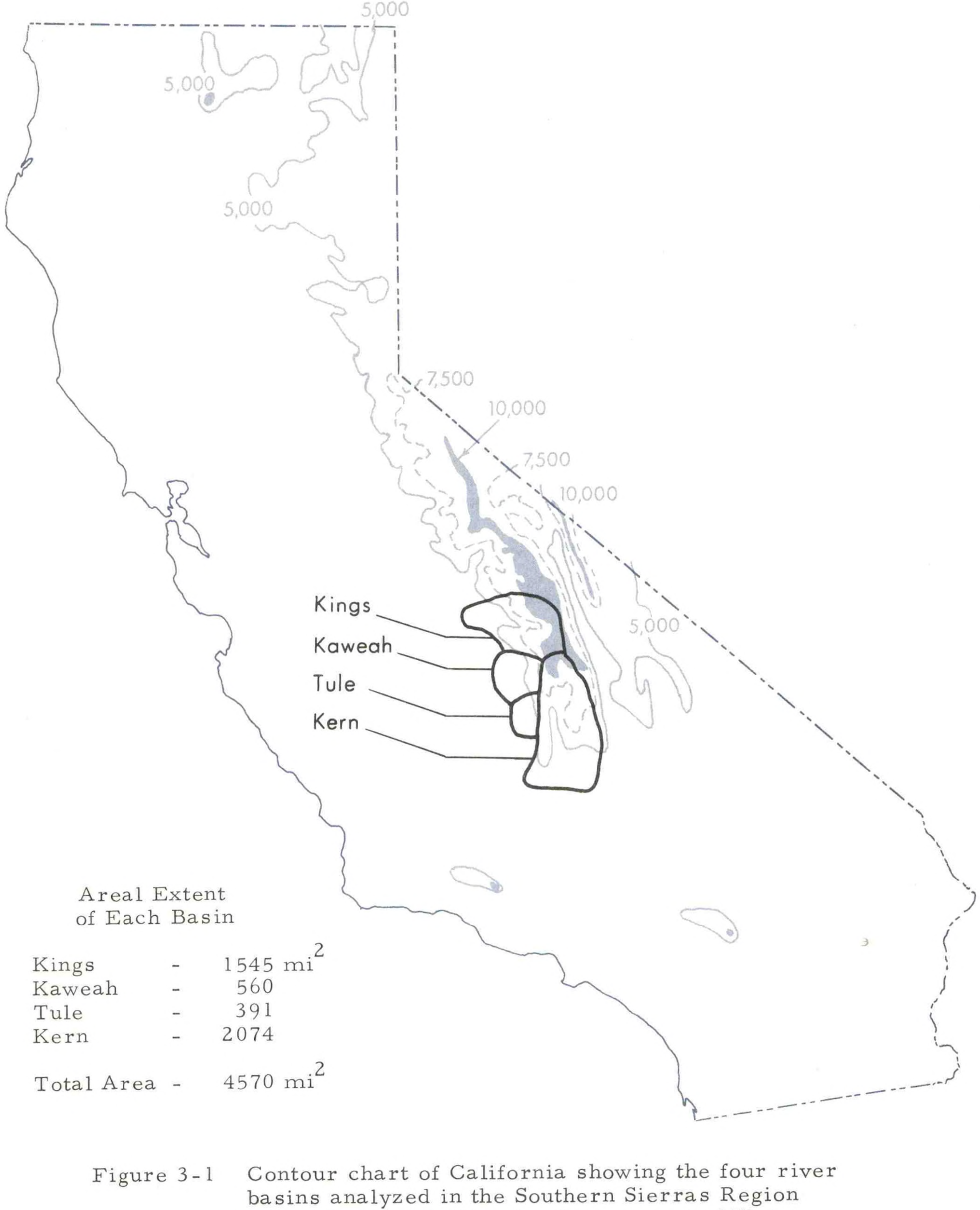
The results of an earlier study (Barnes and Bowley, 1969) indicated the Sierra Nevada to be a mountainous region for which satellite snow surveillance is particularly promising. Since much of the southern Sierras is not heavily forested, the mountain snowpack can be readily identified in satellite photographs; cloud-free observations are also plentiful during the spring snow-melt season. Moreover, because of the great hydrologic interest, considerable snow information is available from the southern Sierras. The river basins within the region are, therefore, appropriate for the evaluation of satellite data.

Aerial snow-survey charts prepared by the Corps of Engineers are especially useful for comparative analyses with snow-extent maps prepared from satellite photographs. Aerial surveys are flown regularly after the first of April of each year, the date when the snowpack accumulation is considered to be maximum. These data for four river basins, the Kings, Kaweah, Tule, and Kern, were used extensively in the analyses described in the following sections.

3.1 Characteristics of Southern Sierra Nevada Region

3.1.1 Terrain and Vegetation

The drainage boundaries of the four river basins studied are indicated in Figure 3-1. The areal extent of each basin is also given; of the total area (4570 mi^2), the Kings Basin comprises 34%, the Kaweah 12%, the Tule 9%, and the Kern 45%. As seen in Figure 3-1, the Kings Basin has the highest mean elevation of the four, with approximately half of the basin being above 8500 feet; the lowest point is approximately 1000 feet, at Pine Flat Reservoir. The altitude of the Kern Basin ranges from about 2500 to greater than 10,000 feet. The Kaweah and Tule Basins are both lower, with the entire Tule Basin lying below 7500 feet.



Areal Extent
of Each Basin

Kings	-	1545 mi^2
Kaweah	-	560
Tule	-	391
Kern	-	2074
Total Area	-	4570 mi^2

Figure 3-1 Contour chart of California showing the four river basins analyzed in the Southern Sierras Region (from State of California, Department of Water Resources).

Land usage charts depict the Southern Sierras as consisting primarily of "forest and woodland mostly ungrazed," with some "forest and woodland grazed." Specific forest types (from a California forest-type map of 1953) are shown in Figure 3-2. In a slightly different classification scheme, Anderson (1963) designates the higher elevation as "Alpine" and "Commercial Forest." In this scheme, a narrow band of "Lower Conifer Zone" borders the commercial forest zone along the western slope of the Sierras, with the lower elevation designated as "Woodland-Brush-Grass Zone." Despite the apparent abundance of forest-covered land, however, Court (1963) points out that in total area the Kings River Basin is only 28% forested; furthermore, trees are so sparse in the forested area that only about 17% of the basin is covered by the tree canopy. For the Sierras as a whole, Court reports that 76% of the area is exposed to the sky.

3.1.2 Snowfall Climatologies in 1967 and 1969

In the fall of each year, as part of the California Cooperative Snow Survey Program, a general summary of water conditions during the preceding water year is pusblished by the California Department of Water Resources. The factors of water supply used to summarize water conditions include precipitation, stream flow, snowpack, carryover reservoir storage, and ground water elevations.

Seasonal and monthly normals (averages) of precipitation are based on a 30-year period from 1931 to 1960. The total contents of selected major reservoirs are related to their aggregate capacities and to their combined 10-year average supply. Stream flow is the computed unimpaired runoff as it would be if unaltered by upstream development. Stream flow averages are based on the 50-year period from 1911 to 1960.

Precipitation and runoff in the region of the southern Sierras during the 1966-1967 and 1968-1969 water years was reported as well above average with record-breaking stream flows occurring in some drainage basins. The following paragraphs briefly summarize this annual publication for both years.

3.1.2.1 1966-1967 Snowfall Summary

The water year began with a very dry October and only light storms through November. In December, however, a 10-day storm gave the southern Sierra watersheds recordbreaking amounts of precipitation over the Kern, Tule,

Figure 3-2 Forest types within Southern Sierras Region (from "Forest Types of California," 1953).

and Kaweah drainages. A series of storms in January was halted by a high-pressure ridge off the coast which diverted subsequent storms to the north. For the most part, February was quite dry, but by early March a low-pressure trough developed off the coast which triggered six weeks of storms. It was this series of storms which boosted the water year precipitation well above average and deposited heavy snows in the Sierras. Because of these late season storms, May 1 surveys were made at an unprecidented number of snow courses. Of the 211 courses measured, 139 had the greatest water contents ever observed for that date. The total runoff for this season in the southern Sierra drainages was reported as about 250% of normal. The greatest runoff in over 50 years was reported in the Kaweah River (265% of normal), Tule River (295% of normal), and the Kern River (245% of normal).

3. 1. 2. 2 1968-1969 Snowfall Summary

Major snowfall did not occur over the Sierras until the storms of the 11th and 26th of December when increases of from 20 to 40 inches were reported. Two additional major storm systems over the Sierras during January deposited from 30 to 70 inches of new snow. During February and March, however, amounts were somewhat less than in January with increases averaging about 30 inches for each month. The April snowfall was light.

The overall season was reported to have precipitation amounts of from 220 to 340% of normal over the southern Sierras. Consequently, record-breaking stream flows and prolonged flood control problems were produced in the San Joaquin Valley area. The June 1 measurements in the southern Sierras indicated that a substantial snow cover remained at higher elevations with many courses retaining water content in excess of their April 1 averages. Precipitation during May was fortunately well below normal in most areas, as above normal temperatures produced a record snow-melt runoff. The April-July predicted runoff in percent of normal was reported as 271% for the Kings River, 307% for the Kaweah River, 393% for the Tule River, and 439% for the Kern River.

3.2 Analysis Procedures

Based on techniques developed previously (Barnes and Bowley, 1969), cloud-free satellite photographs were selected for days as close as possible to the dates of the available aerial-survey charts. In some instances, cloudiness or poor-quality photographs necessitated the use of a satellite observation two or three days prior to or following the aerial-survey date. The greatest discrepancy was four days, except for a case in late March 1967, which had a 7-day difference between the observations. The latter case, however, was not included in the tabulated results. For the purpose of comparing snow extent, the variations within individual river basins during a two- or three-day period were not considered significant. Also, in one situation in early June 1969, satellite pictures two days apart both appeared cloud-free and yet showed an apparently significant difference in snow extent. In this situation, the snow extent was mapped from both pictures with the mean values being used in the tabulated results.

A base map of the four river basins was prepared to the same scale as that of the aerial-survey charts. The four-basin region, which is just over one degree in latitude and longitude extent, was gridded for the eventual transfer of snow distributions determined from the satellite photographs. In each case the photograph was enlarged such that the $1^{\circ} \times 1^{\circ}$ area was approximately one inch on a side (with a single satellite frame printed on an 8 x 10 inch sheet, the corresponding $1^{\circ} \times 1^{\circ}$ area is slightly less than one-quarter inch on a side). This degree of enlargement, which permitted more precise mapping, was found to be the upper limit, after which features became to "fuzzy" for mapping purposes. The picture grids were carefully checked against recognizable landmarks, and corrections applied when necessary.

In order to insure that the satellite-derived snow extent was not biased by the aerial-survey data, the satellite picture was analyzed separately. This analysis, together with the aerial-survey snow limit, were then transferred to the same base map. Although brightness variations were noted within the snow patterns of several pictures, only a single snow line encompassing the total snow extent was mapped. After transfer of both data to the base map, the areal extents of the snow cover within each basin were measured using a compensating polar planimeter. The resulting values from both data sets were tabulated in "percent of basin covered," and through reference to the given areas of each basin (Figure 3-1), in total square miles. Although these aerial-survey values were often slightly different from the given values, due apparently to different measuring techniques, the differences were usually no more than one or two percent (percent of basin covered).

On six days (4 in 1969 and 2 in 1967) aerial-survey charts prepared by two observers were provided. For these six days, the mean difference in snow extent (for the four basins combined) between the two charts was 2.7%. The charts for 15 May 1967 were in greatest disagreement, with a difference of 5.0%; of the four basins, the disagreement was consistently greater in the Kaweah, which had an overall mean difference of 4.5%. Typical discrepancies can be seen in the charts for 7 June 1967, shown in Figure 3-3. Thus, a certain amount of subjectivity exists in the charts mapped from aerial surveys.

Whenever two charts were given on the same day, the satellite value was compared to the average areal snow-extent value of the two charts. Since it would be difficult to derive graphically an average chart, however, the charts given in the illustrations of this report are those that were closest in value to the satellite-derived snow extent.

3.3 Southern Sierras as Viewed by ESSA-7 and Apollo-9, March 1969

Apollo-9 provided the first opportunity to acquire high-resolution color photographs of parts of the United States with snow on the ground. One such photograph, an oblique shot looking northward along the Sierra Nevada and across the state of Nevada on 12 March 1969, is shown in Figure 3-4a. This photograph together with the ESSA-7 photograph taken three days later (Figure 3-4b) provides an excellent "general picture" of the Sierras region and a better understanding of what is actually being "seen" by the ESSA satellite. Although the snow cover was not mapped from the Apollo photograph because of the difficult perspective, many snow features can be identified in both of the pictures. At this March date the snow extent in the Sierras was near its winter maximum.

In Figures 3-5a and 3-5b, corresponding features in the two pictures are designated by letter. The Kings, Kaweah, Tule, and Kern Basins are also indicated on the ESSA picture. Lake Tahoe, to the north (A) can be identified, but Mono Lake is cloud covered in the Apollo picture; cloud also obscures part of the Owens Valley (B) in the 12 March observation. The southern Sierras is completely cloud-free in both photographs, however, and both the Kings and Kern Rivers can be seen (C and D). To the east of the Sierras, the White Mountains (E) can be identified; similarly, many distinct snow features, some of which are designated by corresponding letters, can be identified in Nevada.

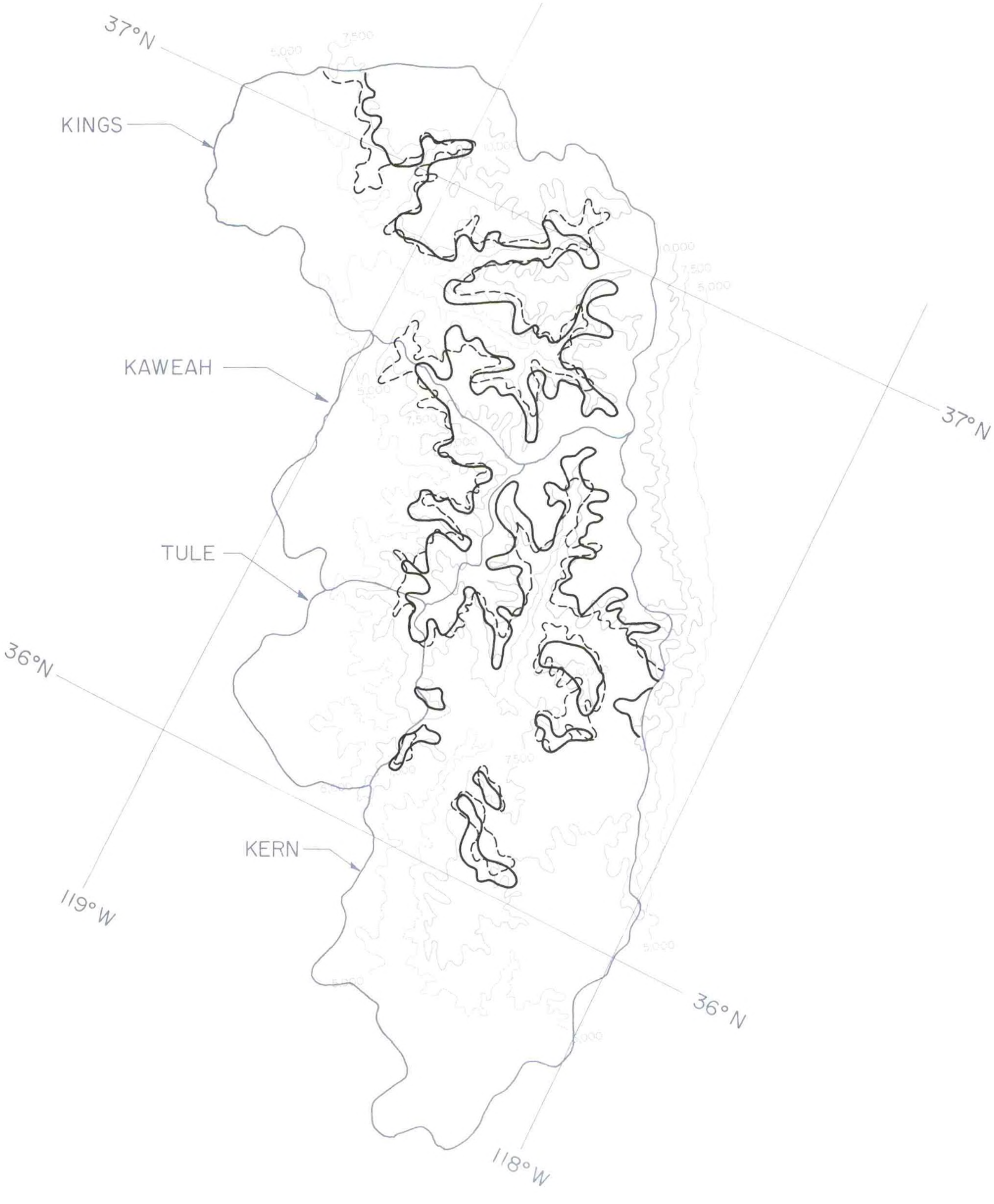


Figure 3-3 Composite of aerial-survey snow extent charts prepared by two observers, 7 June 1967.

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The high albedo of the snow-covered terrain in this entire region, including the higher elevations of the Sierras, is clearly evident in the Apollo photograph (the "brightness" is even more evident in the original color photograph). In the southern part of the Kern Basin, the snow does not appear quite as bright, and contrast between snow and non-snow covered terrain is less.

In the ESSA observation, from which the four-basin region was estimated to be about 70% snow covered, the snow line in the Kern Basin would likely be established along a line at about the southern end of the Owens Valley (Position K). The higher resolution photograph, however, shows isolated areas of snow south of this line. A reexamination of the ESSA photograph reveals that the apparent "sharp" snow line may be due in part to an enhanced raster line, and that lighter gray tones south of this line likely represent snow. From the ESSA photograph alone, though, these isolated snow areas could not be mapped confidently because the gray level is not much different from the tone of areas farther south, which are known to be snow-free. Although the lower contrast in the Kern Basin does cause mapping problems, these isolated snow areas do not constitute the major part of the basin's snow cover.

3.4 Comparative Analyses of Satellite and Aerial-Survey Snow Extent

Snow extent was mapped for the four-basin southern Sierras region from eight satellite photographs in 1967 and 12 in 1969. Of these, three in 1967 and five in 1969 were during the winter and very early spring before aerial-survey data are available; these cases were mapped so that the winter snow distribution can be compared with the spring distributions. One of these cases in late March 1967 was plotted graphically but not included in the tabulated results because of the 8-day interval between satellite and aerial-survey data. Also, the mean value of the 3 and 5 June 1969 satellite observations was used, because both pictures appeared cloud-free and yet indicated a considerable difference in snow extent. Thus, a total of 11 direct comparisons were tabulated, five in 1967 and six in 1969. The dates of these cases are given in Table 3-1.

The measured snow extents for each river basin and for the total area, in "square miles" and in "percent of basin covered," are given in Tables A-1 through A-3 of the Appendix. In Figures A-1 through A-11 the satellite pictures and corresponding maps are given for each case with aerial-survey data. For selected dates, snow depths obtained from California Cooperative Snow Survey reports are also plotted. Pictures and maps for cases without aerial-survey data are not given.

Figure 3-4a Apollo-9 photograph of Southern Sierras Region, 12 March 1969 (Note, original photograph is in color).

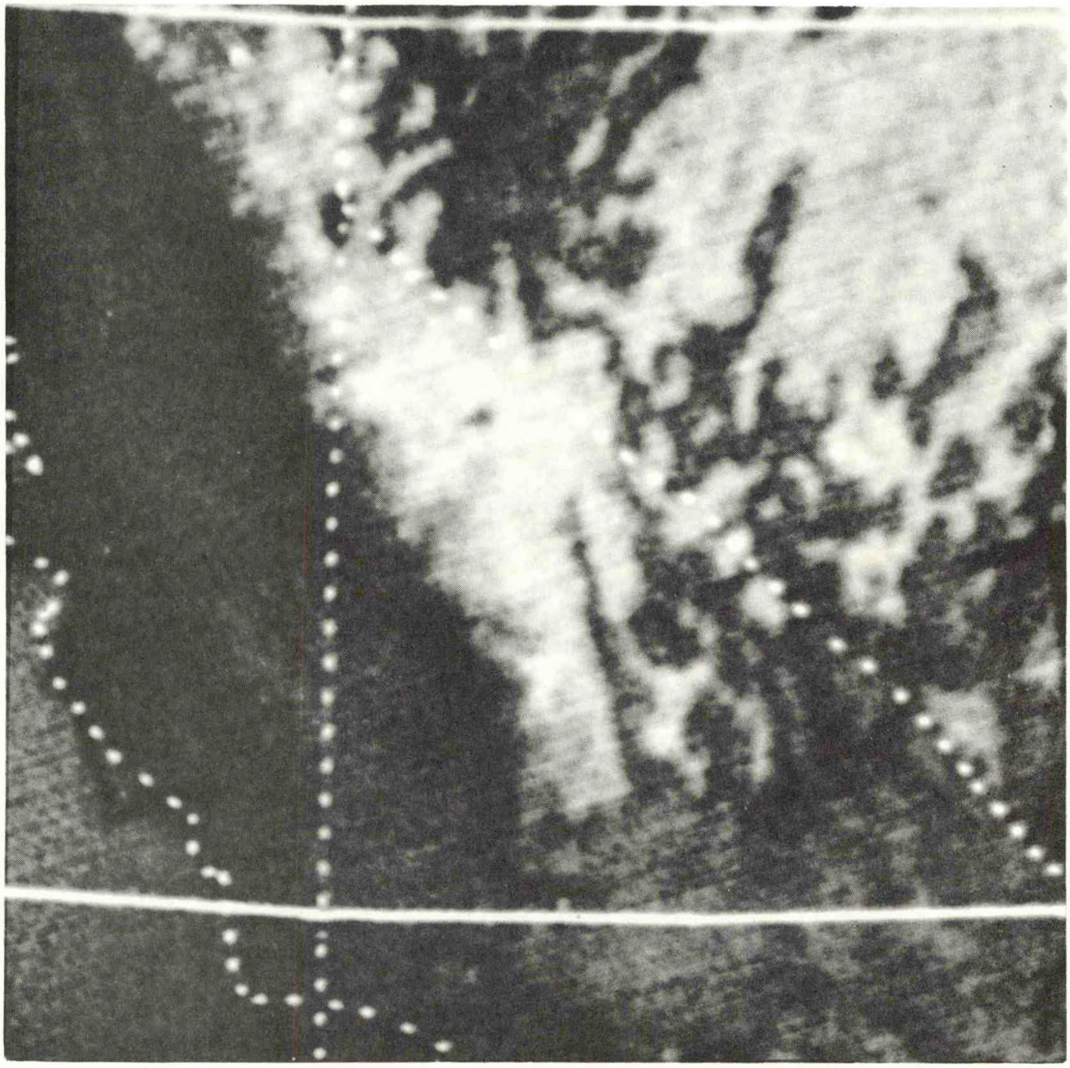

Figure 3-4b ESSA-7 photograph of Southern Sierras Region, 15 March 1969.

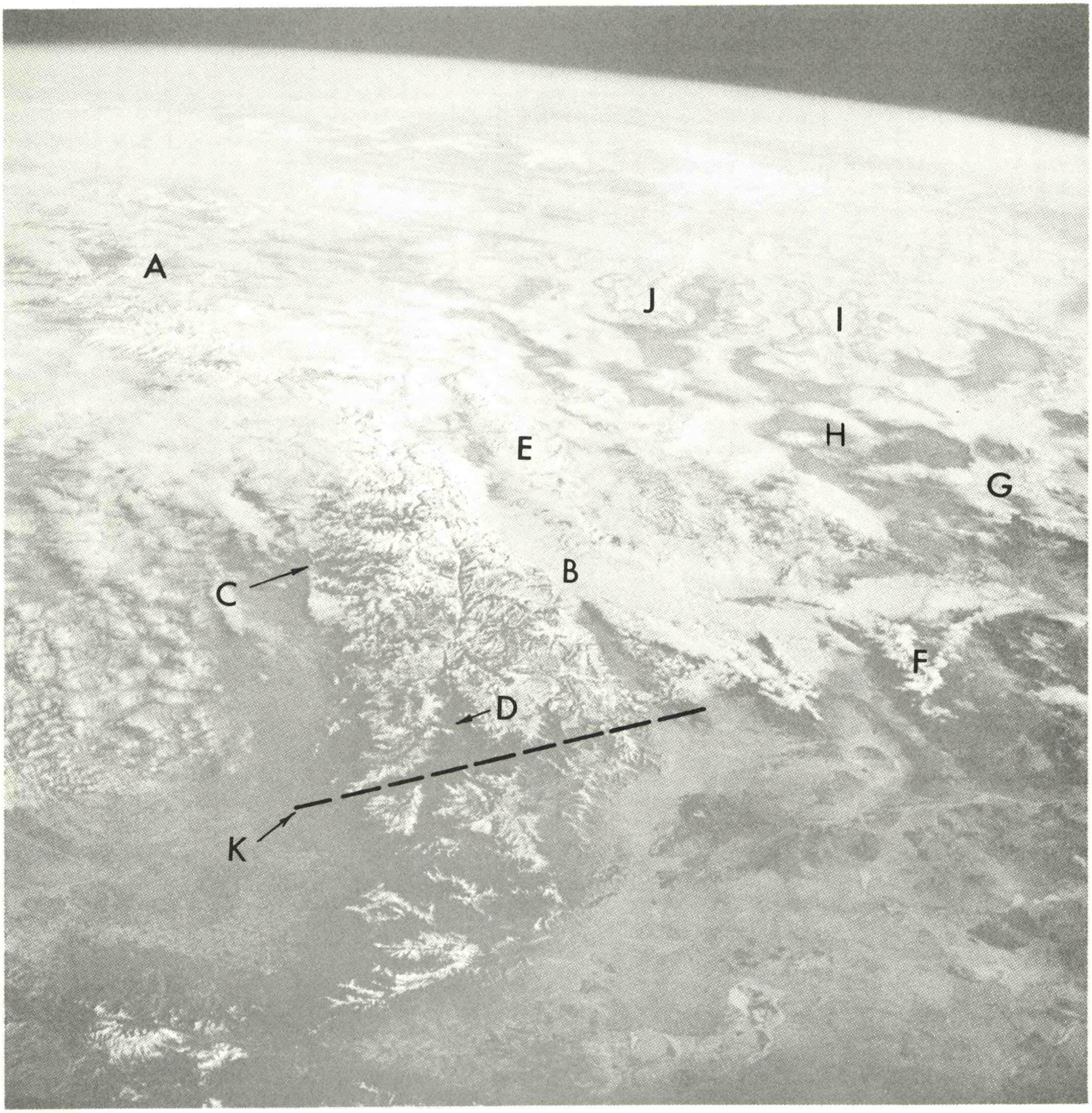

Figure 3-5a Apollo-9 photograph, 12 March 1969, with features also identifiable in ESSA-7 photograph indicated by letter.

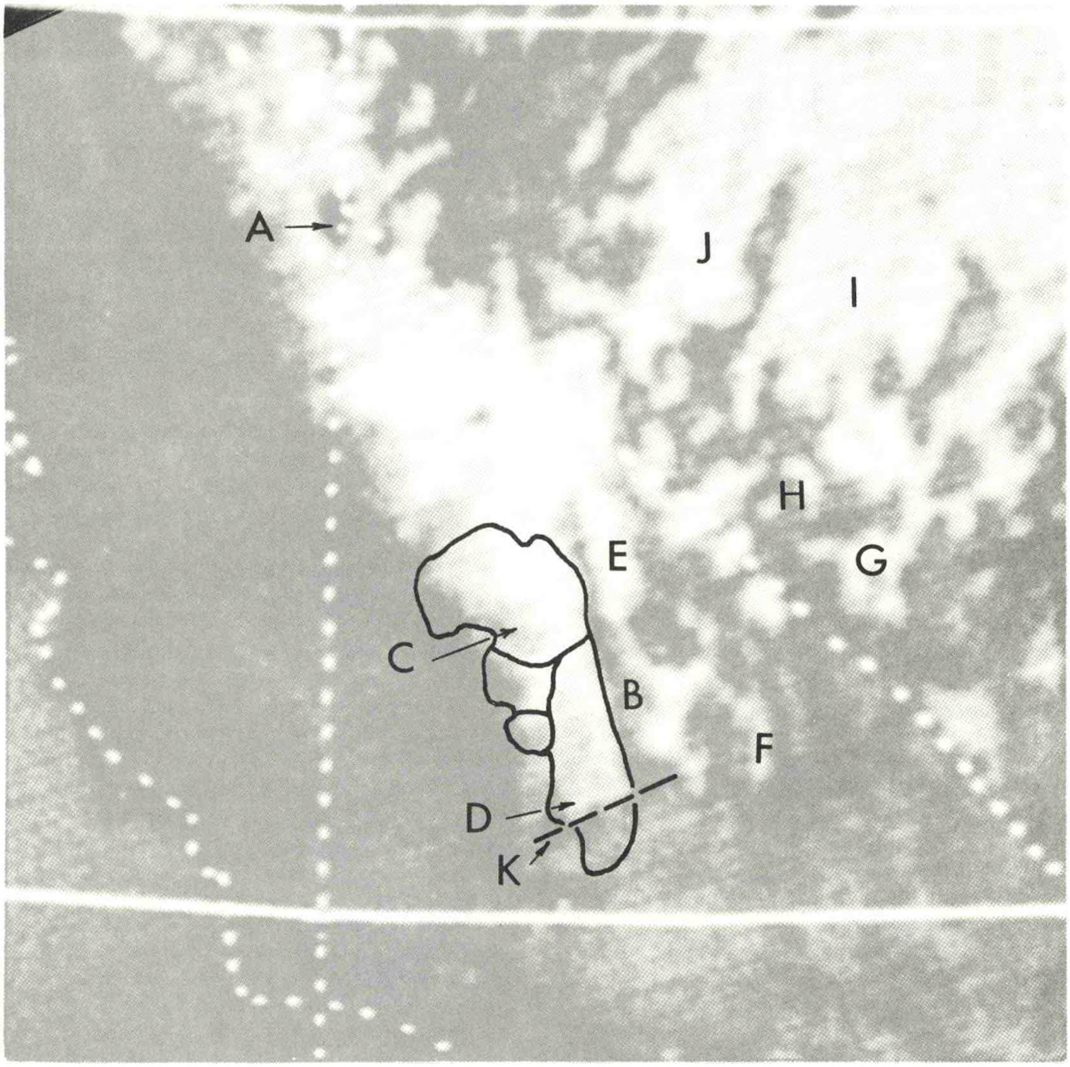

Figure 3-5b ESSA-7 photograph, 15 March 1969, with features also identifiable in Apollo-9 photograph indicated by corresponding letters. River basins of Southern Sierras Region are outlined.

TABLE 3-1

DIFFERENCE BETWEEN SATELLITE AND AERIAL-SURVEY SNOW EXTENT FOR RIVER BASINS OF SOUTHERN SIERRAS REGION

(Satellite value minus aerial-survey value in percent of basin snow covered)

	Kings	Kaweah	Tule	Kern	Total Area	Mean for 4 Basins By Date
1967						
15 May	-3	-13	-7	-11	-9	8.5
21-23 May	-6	3	2	4	3	3.8
3-7 June	-3	12	12	5	3	8.0
22 June	-8	3	4	8	1	5.8
28-29 June	-1	6	5	5	3	4.3
Mean of Absolute Difference	4.2	7.2	6.0	6.6	3.8	6.1
1969						
29 April	-9	-4	-2	-6	-6	5.3
8-9 May	-8	-5	-2	4	-2	4.8
15-16 May	-12	-4	6	2	-4	6.0
25-26 May	-9	4	0	-2	-3	3.8
3-5 June	-6	-6	-4	-4	-5	5.0
25-26 June	2	2	0	4	2	2.0
Mean of Absolute Difference	7.7	4.2	2.3	3.7	3.7	4.5

Note: Raw data given in Appendix, Tables A-1 and A-2.

TABLE 3-2

SUMMARY FOR 1967 AND 1969 COMBINED

(11 Cases given in Table 3-1)

	Kings	Kaweah	Tule	Kern	Total Area	Mean for 4 Basins By Date
Mean of Absolute Difference	6.1	5.6	4.0	5.0	3.7	5.2
Median of Absolute Difference	6	4	4	4	3	-
Greatest Difference	-12	-13	12	-11	-9	-
Number of Cases:						
Positive Difference	1	6	5	7	5	-
Negative Difference	10	5	4	4	6	-
No Difference	0	0	2	0	0	-

In Figures 3-6 and 3-7, the snow-cover extent (in square miles) for each river basin as derived from satellite and from aerial-survey observations is plotted by date for 1967 and 1969. In Figures 3-8 through 3-10, the snow extents in terms of "percent of basin snow covered" are plotted. The relative sizes of the river basins are clearly evident in Figures 3-6 and 3-7, but the graphs in "percent of basin covered" are more meaningful for hydrologic considerations. The latter results will, therefore, be discussed in more detail than the former.

The differences between the satellite and aerial-survey values (in percent of basin covered) are tabulated for 1967 and 1969 in Table 3-1 and for the two years combined in Table 3-2. In these analyses, the absolute differences are given; plus values indicate that the satellite snow extent is greater than the aerial-survey snow extent. Mean values are computed directly for the total area (the four basins combined) and are computed from the individual differences for each basin; because the four basins vary considerably in size, the resulting values are different for most cases (see Table 3-1).

The mean absolute difference for the overall area for all 11 cases is 3.7%. The means are not significantly different for the two separate years, but in 1967 the satellite value exceeds the aerial-survey value in four of the five cases, while in 1969 nearly the opposite is true. For the individual basins, the mean absolute difference for the 11 cases ranges from 3.9% for the Tule to 6.1% for the Kings. In the Kings Basin, the satellite value is less than the aerial-survey value of 10 of the 11 cases; in the other three basins the signs of the differences are about equally distributed.

In addition to the mean for the overall area, mean values were computed from the individual basin values. The resulting means are greater than the overall mean in most cases, with the mean for all 11 cases being 5.2% as compared to 3.7%. For each basin, the median value of the difference between satellite and aerial-survey snow extent was also computed (Table 3-2). In all but the Kings Basin, the median is less than the mean.

3.5 Additional Analyses for Kings River Basin

In a paper by Court (1963), snow-cover relations in the Kings River Basin are discussed in considerable detail. Court selected the Kings Basin for study because of the hydrologic interest in the snowpack in the southern Sierras and because more varied information on snow was available there than for any other basin. For comparison with Court's analyses of similar aerial-survey snow

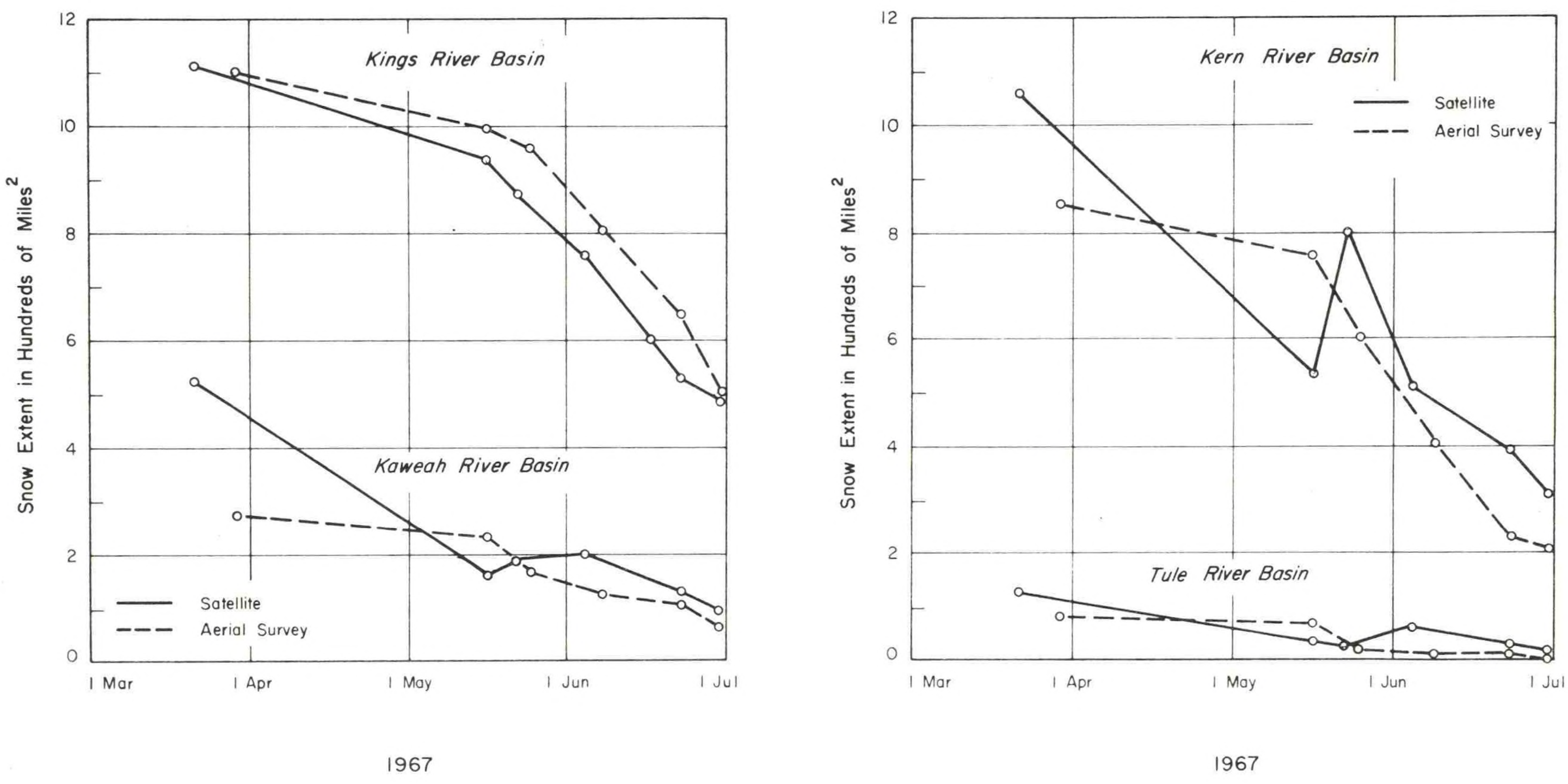

Figure 3-6 Snow-extent decrease (in sq. mi.) for each river basin of the Southern Sierras Region during the 1967 snowmelt season.

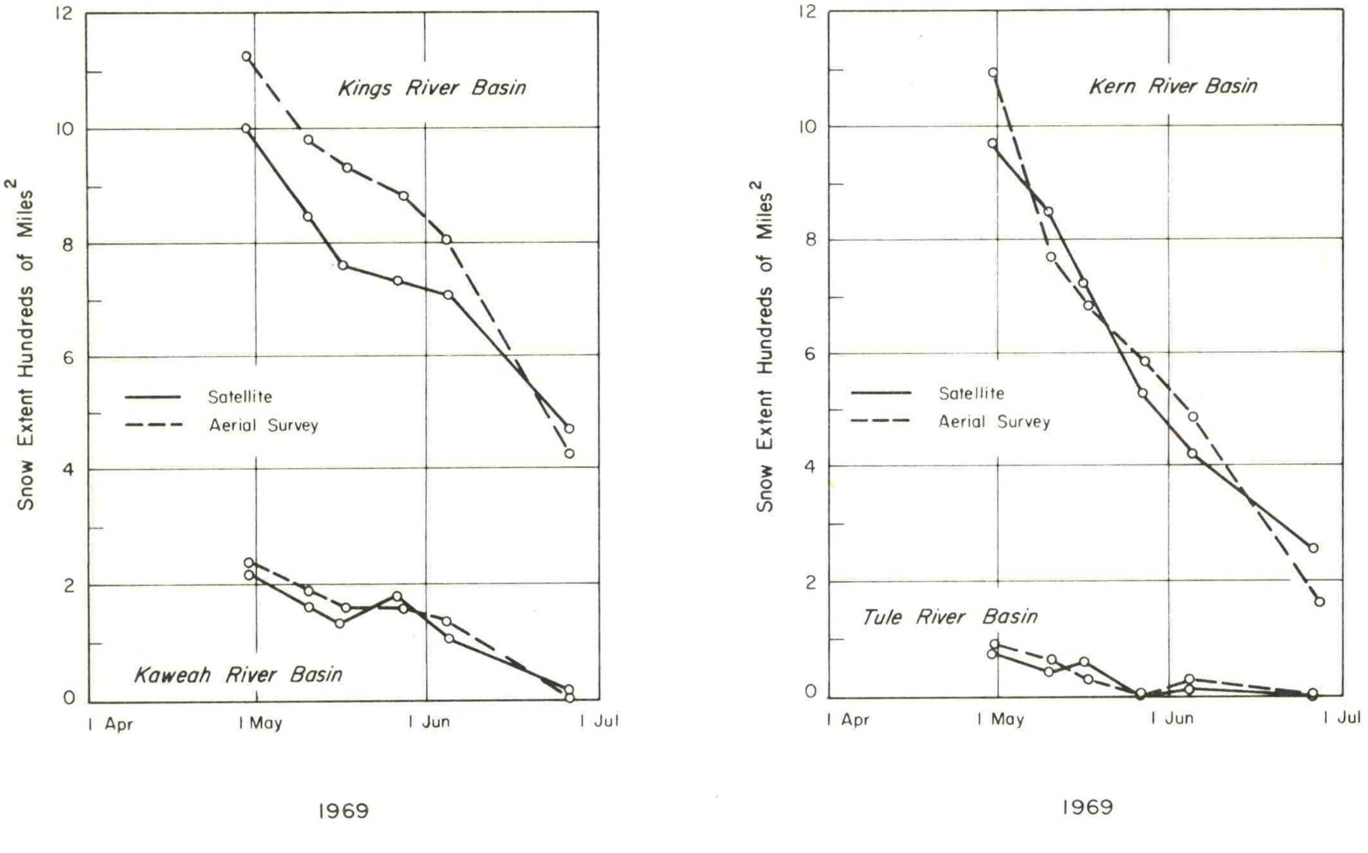

Figure 3-7 Snow-extent decrease (in sq. mi.) for each river basin of the Southern Sierras Region during the 1969 snowmelt season.

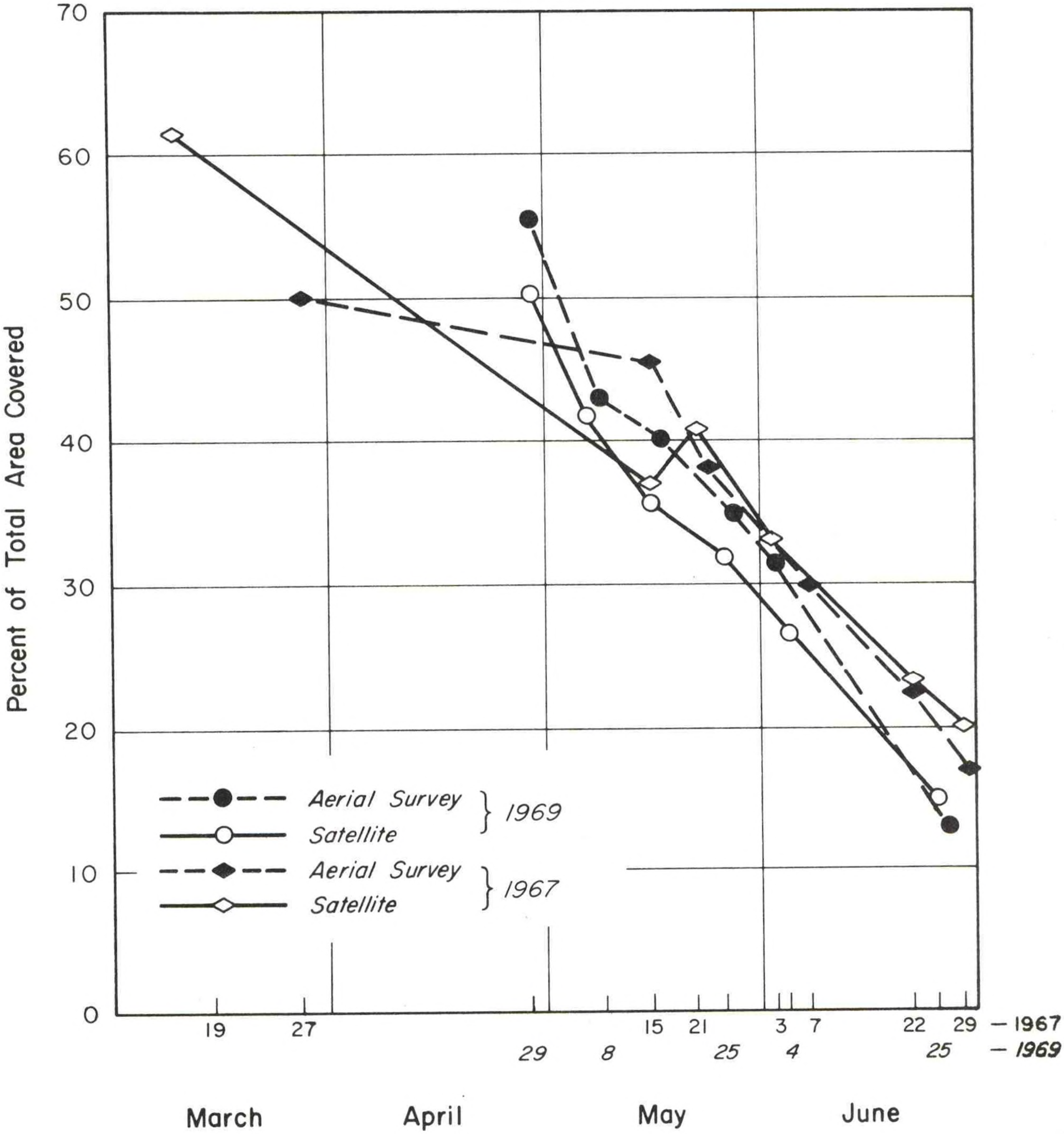

Figure 3-8 Snow-extent decrease (in percent) for the total Southern Sierras Region during the 1967 and 1969 snowmelt seasons.

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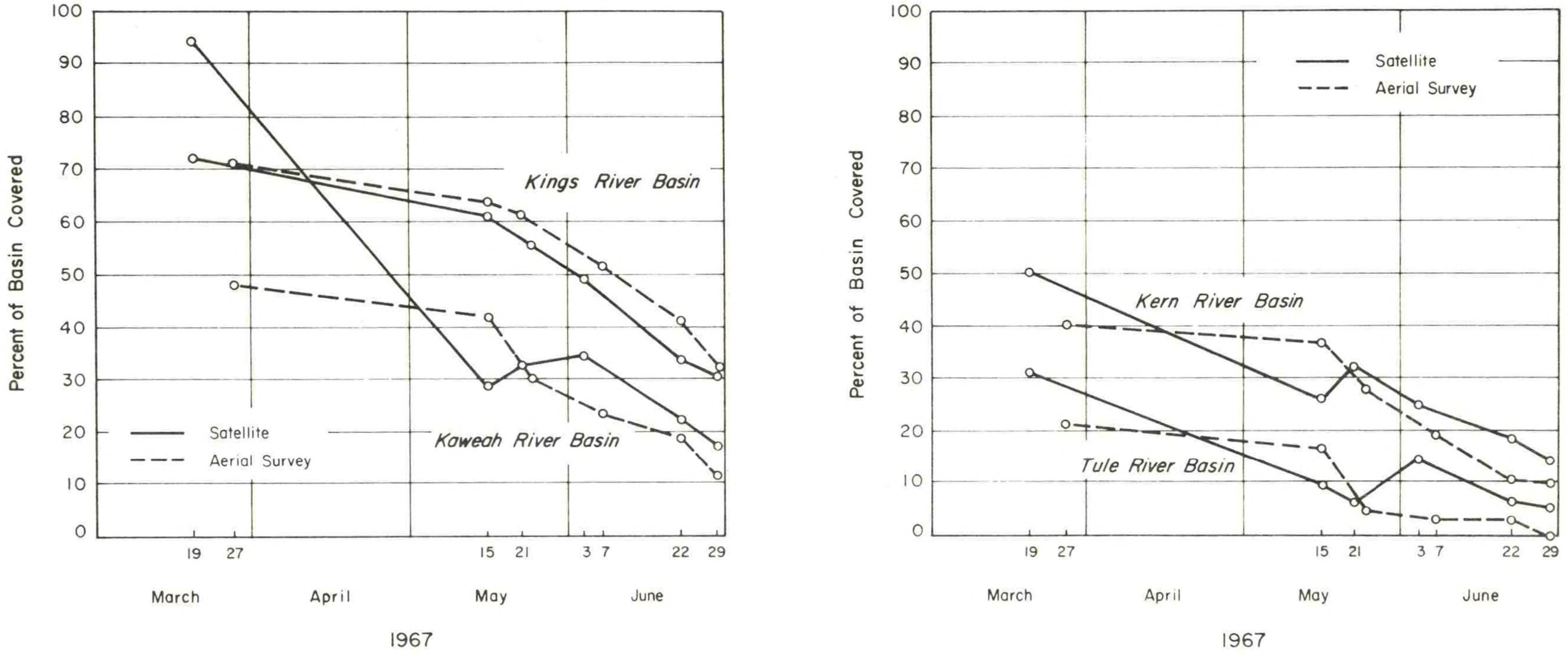

Figure 3-9 Snow-extent decrease (in percent) for each river basin of the Southern Sierras Region during the 1967 snowmelt season.

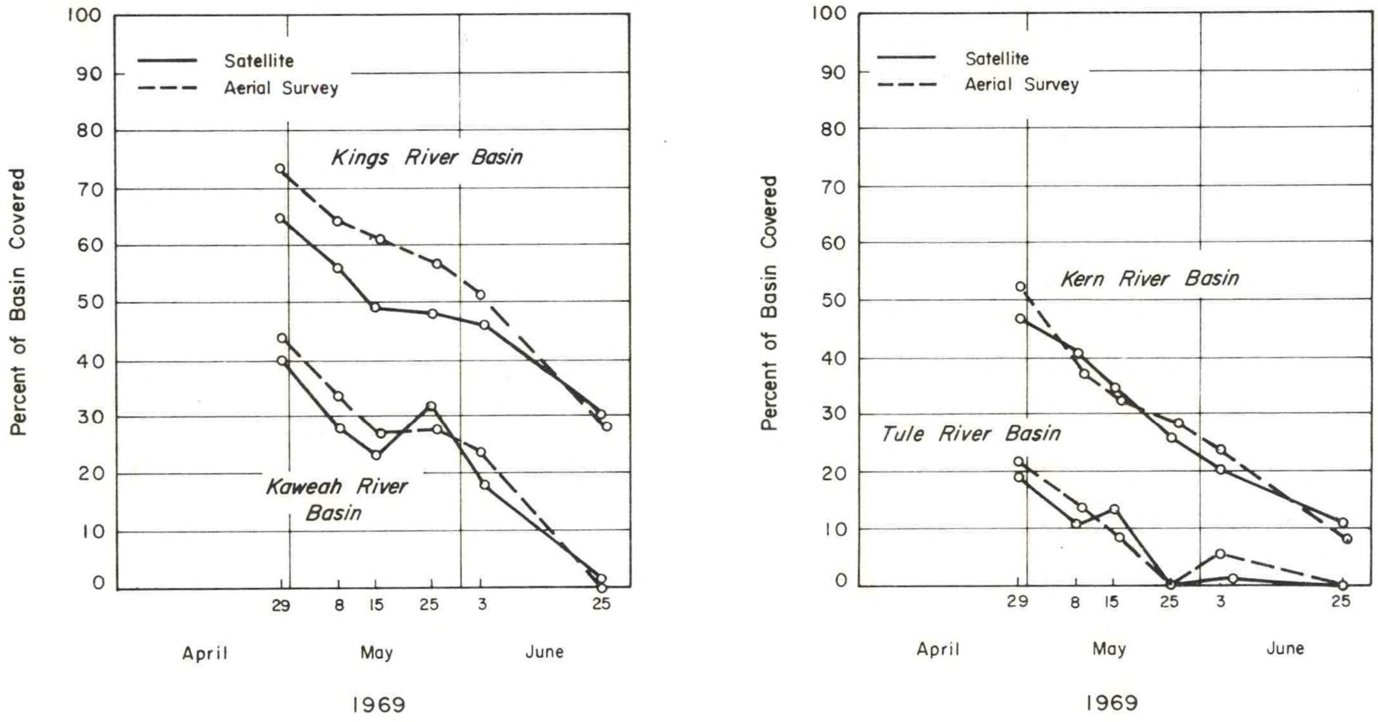

Figure 3-10 Snow extent decrease (in percent) for each river basin of the Southern Sierras Region during the 1969 snowmelt season.

charts, more extensive analyses of the satellite snow maps were carried out for the Kings Basin.

Based on the hypsometric (area-elevation) curve used by Court, equivalent snow lines were determined for the satellite and areal-survey snow-extent values (Table 3-3). The results are plotted in Figure 3-11, which also shows the hypsometric curve. Court also determined the dates when the areal snow extent decreased to 600 mi^2 (about half the total basin area above 5000 feet) and the rate of snow decrease during the interval including this day. Similar analyses for the satellite data are given in Table 3-4.

3.6 Discussion of Results

3.6.1 General Results

The tabulated and graphical results (the latter being more easily interpreted in many instances) indicate that the positive and negative differences associated with the individual basins tend to smooth out somewhat when the overall area is considered. For hydrologic considerations, however, it is more meaningful to discuss the individual basins since the snowpack within each contributes only to that basin's runoff. On the other hand, the differences from basin to basin do not appear related to size; in fact, the smallest mean difference between the satellite and aerial-survey values occurs in the smallest basin, the Tule.

The mean difference between satellite and aerial-survey snow extent computed from the individual basin values is 5.2%. The median of the difference for the 11 cases tested is 6% in the Kings Basin and 4% in the other three basins. Based on these results, it is concluded that snow extent in the river basins of the southern Sierras can be mapped from satellite photographs to within ± 5% (of basin area covered) of the snow extent charted from aerial survey flights. For the overall area, no significant evidence exists to indicate that the satellite either consistently overestimates or underestimates the snow extent as compared to the aerial survey values. In the Kings Basin, however, the satellite value is consistently less in areal extent than the aerial-survey value. No obvious reason can be found as to why this basin differs from the other three. Since the vegetation does not vary greatly among these four basins, the amount of detail in the elevation contours may be a factor. On many of the aerial-survey charts, small "fingers" are mapped along the western edge of the snow cover. Because of the lower resolution of the satellite pictures, these are often not detected, possibly accounting for some of the resulting differences in the snow extent values.

TABLE 3-3

DIFFERENCE IN SATELLITE AND AERIAL-SURVEY SNOW-LINE ELEVATION FOR KINGS RIVER BASIN

(Values determined from hypsometric curve given in Figure 3-11)

	Satellite		Aerial Survey		Satellite Minus Aerial-Survey Value (ft)
	Extent (mi^2)	Elevation (ft)	Extent (mi^2)	Elevation (ft)	
1967					
19-27 March	1112	6100	1097	6200	(-100)*
15 May	941	7400	990	7100	300
21-23 May	865	7800	958	7300	500
3-7 June	757	8300	804	8100	200
22 June	525	9400	648	8800	600
28-29 June	479	9600	494	9500	100

1967 Mean Absolute Difference = 340

1969					
29 April	1004	7000	1136	6000	1000
8-9 May	850	7900	988	7100	800
15-16	758	8300	935	7400	900
25-26	742	8400	881	7700	700
4-3 June	704	8600	803	8100	500
25-26 June	463	9600	433	9800	-200

1969 Mean Absolute Difference = 683

Summary for 1967 and 1969 (11 Cases)

Mean of Absolute Difference = 527 feet

Median of Absolute Difference = 500 feet

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*(19-27 March Difference not used in tabulation because of interval between observations.)

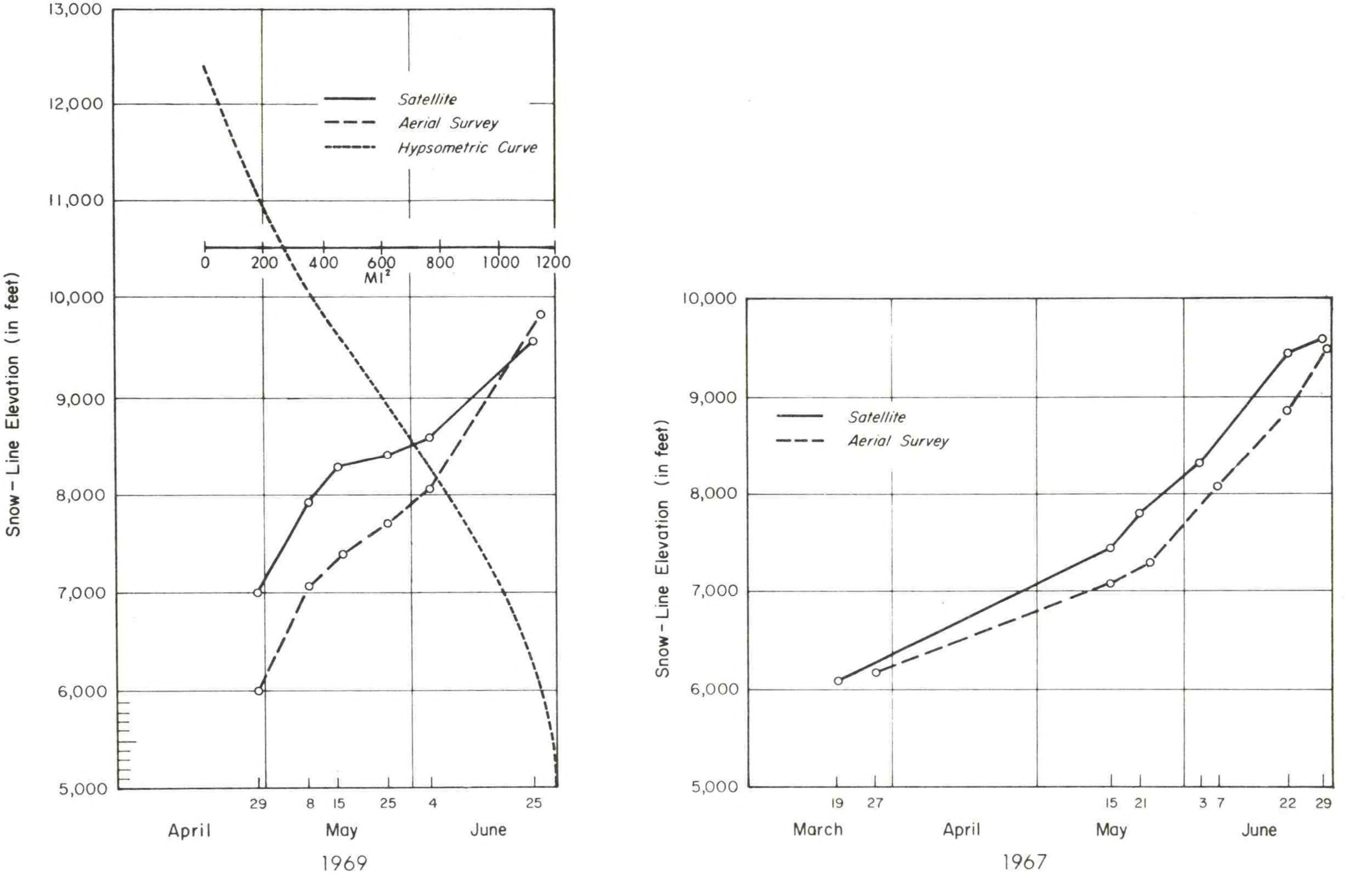


Figure 3-11 Change in snow-line elevation within the Kings River Basin during the 1967 and 1969 snowmelt seasons. Hypsometric curve from Court, 1963.

TABLE 3-4

RATE OF SNOW-COVER DECREASE (AREAL-EXTENT) IN KINGS RIVER BASIN DURING INTERVAL INCLUDING DATE WHEN SNOW COVER DECREASED TO 600 MI^2 (ABOUT ONE-HALF OF BASIN COVERED), AND DATE OF OCCURRENCE

	Satellite	Aerial Survey	Difference Satellite Minus Survey
1967			
Date	17 June	24 June	-
Days after 1 April	77	84	-7 Days
Interval	3-22 June	7-29 June	-
Rate (mi^2/Day)	$\frac{232}{19} = 12.2$	$\frac{310}{22} = 14.1$	-1.9 mi^2/Day
1969			
Date	13 June	15 June	-
Days after 1 April	73	75	-2 Days
Interval	3-25 June	3-26 June	-
Rate (mi^2/Day)	$\frac{327}{22} = 14.9$	$\frac{355}{23} = 15.4$	-0.5 mi^2/Day

Values from Court (1963)

	Days after 1 April	Rate
Mean	53	18.2 mi^2/Day
Median	60	17.5
Greatest Value	71	-
Least Value	-	12.0

Although some indication exists of a better agreement between satellite and aerial-survey values late in the spring, the seasonal variation does not appear significant. Similarly, variations between the two years do not appear significant; as seen from the snow extent maps, plotted snow depths, and discussions in Section 3.1.2, both 1967 and 1969 were exceptionally heavy snow years in the Sierras with later than normal snow-melt seasons. In fact, the aerial-survey snow extents for comparable dates in 1967 and 1969 are very similar (Tables A-1 and A-2 in Appendix).

3.6.2 Discussion of Specific Cases

The graphical results shown in Figures 3-6 through 3-10 indicate that in the Kern and Kaweah Basins an average value of the snow extents mapped from the 15 and 21 May 1967 satellite pictures would fall almost exactly on the aerial-survey curve. As in the 3 and 5 June 1969 pictures, which were averaged, the apparent discrepancies may be due to factors such as picture angle and exposure; the discrepancies do not appear to be due to clouds. On 3 June 1967, on the other hand, some cloud may be present over the Kaweah and Tule Basins. The increase in snow extent in the Kaweah Basin from 25 May to 3 June 1969, indicated in ~~both~~ both the satellite and survey data, presumably is due to new snowfall.

In the March 1967 case, which is plotted graphically but not used in the tabulated results, a large difference in snow extent is observed in the Kaweah Basin (Figures 3-6 and 3-9). Although a part of the apparent discrepancy may be due to cloud contamination, a part is probably due to the rapid snow-melt that occurred during late March, particularly at lower elevations, following the large storm earlier in the month. (This case is discussed, with the pictures, in Barnes and Bowley, 1969.) After 19 March a period of relatively mild weather prevailed in the Sierras; during this period temperatures at lower-elevation stations reached to near 60°F on several days. Thus, during the 7-day interval between the satellite and aerial-survey observations, considerable snow may have disappeared from the Kaweah Basin, with much less melting having taken place at higher elevations, such as the Kings Basin.

3.6.3 Visual Map Analysis and Estimation of Snow-Line Elevation

The satellite snow maps are considerably smoother than the aerial-survey maps, but do retain the major features (Figures A-1 through A-11 in Appendix). The snow-free areas within the Kings Basin, produced by the Kings and Middle Fork Rivers, are prominent in the satellite maps. Later in the spring, a snow-free area along the South Fork River appears in the aerial-survey maps, but is less easily detected in the satellite pictures. Similarly, the Kern Basin is easily identified; as the season progresses, however, the South Fork Kern River (snow-free area to the east of the Kern) shows up better in the aerial-survey data.

A visual inspection of the concurrent maps indicates that in the 15 May 1967 case, considerable snow in the Kern Basin was not detected in the satellite photograph. In the June cases, on the other hand, the satellite maps have considerable positive values in the southern sections. In 1969, the isolated patches of snow in the Kern Basin are often not detected in the analysis of the satellite picture (see Section 3.3). In many of the cases, a discrepancy between the two snow lines can be seen in the northwest portion of the Kings Basin. This area most likely accounts for much of the negative difference observed consistently in the results for the Kings Basin.

Approximate snow-line elevation can be determined by comparing the snow-extent maps with the elevation contours. Although snow-line elevation is not given in the aerial-survey data, the elevations listed below were estimated from three satellite maps in 1969.

SNOW-LINE ELEVATION WITHIN EACH BASIN

Date	Kings	Kaweah	Tule	Kern
29 April	5000-7500 ft	5000-7500 ft	5000-7500 ft	7500 ft
25 May	7500	7500	No snow	7500-10,000
25 June	7500-10,000	10,000	No snow	10,000

In general, the aerial-survey charts exhibit better agreement with elevation contours than do the satellite-derived charts. Small gridding errors in the satellite data can be significant, making exact determination of snow-line elevation difficult. When considering the overall snow extent within an entire river basin, however, many of the small mapping errors cancel out. In the Kings Basin, for example, the snow line of 29 April 1969 appears to be below the 5000 foot contour in the northwest part of the basin. The extent of the snow-free areas along the rivers, however, is greater than the extent of the 5000 foot contour, approximating more closely the extent of the 7500 foot contour. The overall snow line within the basin is, therefore, estimated to be between 5000 and 7500 feet (the more detailed snow-line analyses carried out for the Kings Basin are discussed in the following section). Thus, when analyzing satellite data in mountains such as the Sierras, areal extent of snow cover (in percent of basin covered) appears to be a more meaningful parameter than snow-line elevation.

3.6.4 Kings River Basin Analysis

Despite the fact that the overall agreement between the satellite and aerial-survey snow extents is lower in the Kings Basin than the other three, the results of the additional analyses for this basin are in fairly good agreement. For the 11 dates tested, the mean difference in snow line elevation is 528 feet and the median 500 feet. In all but one case, the satellite snow-line is at a higher elevation than the aerial-survey snow line. The plotted values (Figure 3-11) indicate that despite the differences in elevation, the rates of snow-line retreat in both years are remarkably similar.

The close agreement in the rates of snow-line retreat are substantiated in the analyses of the rates of snow-cover decrease in areal extent (Table 3-4). The differences in the rates derived from the satellite and aerial-survey data (in miles^2/day) are only 0.5 and 1.9 for the two years. Similarly, the dates when the snow cover decreased to 600 mi^2 are very close, being only two days apart in 1969. In comparison with Court's values (given in Table 3-4), the rates derived from both data sources are very low. Of greater interest, however, is the fact that in both years the dates of snow decrease to 600 mi^2, whether derived from satellite or aerial survey observations, are later than for any year in Court's 1952 to 1960 data sample. These results most certainly emphasize the magnitude of the phenomenal snow packs in the southern Sierras in both 1967 and 1969.

4. REGION II: COLUMBIA RIVER BASIN

4.1 Upper Columbia Basin

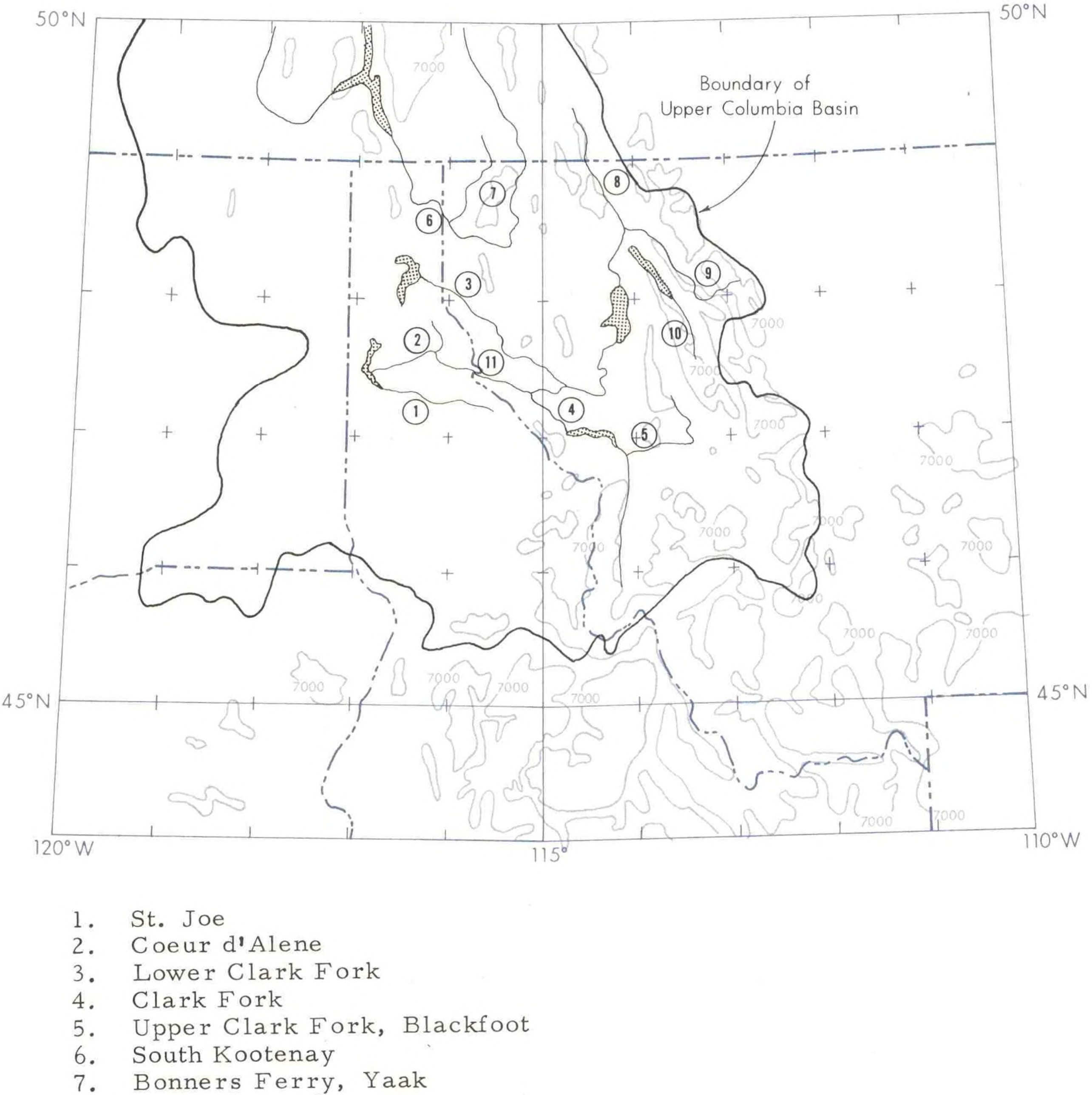
The Columbia River Basin is a second region in which aerial-survey snow data are collected during the snowmelt season. Data in a usable format were available only from the Upper Columbia Basin, so detailed satellite analyses were concentrated in that region. The Upper Columbia Basin of northern Idaho and northwestern Montana, together with the individual river basins for which aerial-survey observations were taken, are shown in Figure 4-1.

This region consists of mountain ranges intersected by numerous river valleys. In areal extent the individual ranges are considerably smaller than the Sierras, and only a few isolated areas exceed 10,000 feet in elevation. The terrain in the region more closely resembles the Canadian Rockies just to the north than it does the Sierras. The Upper Columbia Basin is also more densely forested than is the southern Sierras region. Except for some lower elevation grassland and farmland, land-usage charts indicate most of the region to consist of "forest and woodland, mostly ungrazed."

4.1.1 Snowfall Climatologies for 1967 and 1969

The snowfall climatology of the Upper Columbia Basin region is also different from that of the southern Sierras. In general, snowfall is more consistent and distributed over a longer season. Although maximum depths may exceed 100 inches, total water content is usually less than that contained in the maximum snowpack areas of the Sierras.

In the 1966-1967 winter season, the upper Columbia River basin reported below normal snow amounts during October and November 1966. The first significant snowfall during this water year did not occur until December. January and February snowfall was again reported as well below normal, with only light amounts recorded over most of the region. During March, snow amounts were reported as slightly above normal, while three heavy snow periods in April resulted in a number of record snowfall amounts and reports of water content. Reports of snowfall in Helena, Montana, added up to the greatest for any April dating back to 1880, while Great Falls, Montana, broke its record by a wide margin. By the end of May, the Montana snowpack carried a record water content.



1. St. Joe
2. Coeur d'Alene
3. Lower Clark Fork
4. Clark Fork
5. Upper Clark Fork, Blackfoot
6. South Kootenay
7. Bonners Ferry, Yaak
8. North Fork } Flathead
9. Middle Fork } Flathead
10. South Fork } Flathead
11. St. Regis

Figure 4-1 Upper Columbia River Basin Region with elevation contours. River basins for which aerial-survey snow data available are indicated.

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Only small snowfall amounts were reported over the upper Columbia Basin during the early part of the 1968-1969 season. The first significant snowfall over the region was reported during December when the percentage of mean monthly snowfall over the region was reported as about 200%. January was also reported as a very snowy month with a number of storms adding considerable snow depth to the entire basin area. February and March amounts were once again reported as relatively light. Further reports of significant snowfall did not occur until late April, when up to 36 inches of new snow was reported.

4.1.2 Analysis of Satellite Photographs

Satellite photographs were analyzed using the same techniques as for the Sierras region for identifying and mapping the snow extent. For each case, total snow extent without regard to the tonal brightness, was mapped onto a base map containing grid-points and elevation contours. Three cases for each year are presented in the Appendix, Figures A-12 through A-17. Although only one photograph is shown for each case, two pictures were used in several instances to establish pattern continuity and to eliminate cloud contamination. For purposes of clarity, the accompanying maps contain elevation contours in a subdued tone. For selected cases, representative snow depths are plotted.

During 1969 very few good satellite photographs were found after the early part of May, mainly due to cloud contamination. Convective-type cloudiness over the mountainous areas was present nearly continuously during late May and June. During 1967 a greater number of uncontaminated photographs were available, with several good cases as late as the middle of June. Even when the region appears to be cloud-free in the late spring of 1969, however, little snow is visible. In pictures taken on 13 and 14 June (not shown), only the Lewis and Flathead Ranges can be identified at all, and even in these areas the patterns are not sufficiently distinct to permit the snow to be mapped reliably. As late as 19 June 1967, the Cabinet Mountains and Purcell Range in the Kootenay Basin and the Lewis Range in the Flathead Basin can be easily identified (Figure A-14).

In contrast to the June observations, the snow extent measured in 1969 in the early spring is greater than that of 1967. On 25 March 1969, nearly the entire region appears snow-covered; in this picture as well as in the 7 April 1967 picture, the non-forested, lower elevation areas are significantly brighter than the mountains. These differences in snow distribution between the two years can be attributed to the record April snowfall in 1967. Whereas snow reports show a steady decrease in snow depths from April to June 1969, amounts remained about equal or even increased from early April to mid-May 1967. In mid-June 1969, the aerial-survey data indicate that snow does remain on most ranges, although at snow-line elevations from 500 to 1000 feet higher than in 1967.

4.1.3 Comparative Analyses of Satellite and Aerial-Survey Data

Aerial-survey data were available for three dates in both 1967 and 1969. Instead of snow extent being mapped as is done in the southern Sierras, the snow cover is reported by snow-line elevation. For each river basin flown, the lowest, highest, and average snow-line elevation is given; normally the lowest value applies to a north or east-facing slope while the highest is a south or west-facing one. Suitable satellite photographs were available on or near only three of the aerial-survey dates, one each in May and June 1967 and one in May 1969. In the May 1969 case the satellite and aerial-survey observations are 7 days apart; during the intervening period, which was relatively warm, some snowmelt may have occurred.

Because of the format of the aerial-survey data, the comparative analyses were performed by estimating snow-line elevations from the satellite snow-extent maps. Since the aerial-survey snow-line elevations are given only by river basins, each corresponding satellite estimate was made for an area believed to approximate the area flown. The results cannot, therefore, be considered exact comparisons. The corresponding snow-line elevations are given in Table A-4 of the Appendix.

When estimating the snow-line elevation from the satellite maps, difficulties similar to those experienced when working with the Sierras data were encountered. Often, the snow extent did not follow elevation contours, and it was found easier in many places to estimate by the relative sizes of the snow and non-snow covered areas rather than by attempting to align a snow boundary with a contour.

The results of the analyses, which are tabulated in Table 4-1, show a mean overall difference between the satellite snow-line elevation and the aerial-survey "average" snow-line elevation of approximately 600 feet. The overall median value is also about 600 feet, and the greatest single discrepancy is 1200 feet. Because of the inherent methods used to estimate the snow-line elevations from the satellite data, the only comparison believed meaningful was with the

TABLE 4-1

DIFFERENCE BETWEEN SATELLITE AND AERIAL-SURVEY SNOW-LINE ELEVATION FOR UPPER COLUMBIA BASIN REGION

(Values given are satellite minus aerial-survey "average snow line")

Basin Number	6-14 May 1969	13-18 May 1967	19-21 June 1967
1	600	-	-
2	500	-300	-
3	1200	-400	0
4	-700	1100	500
5	700	1100	500
6	300	100	-500
7	-	-	1200
8	800	700	900
9	1100	900	100
10	600	600	200
11	-	-	-
Mean =	722	650	488
Median =	700	650	500

Summary for all three dates: Mean = 624 feet
(25 Cases) Median = 600 feet

NOTES:

(a) Raw data given in Table A-4 of Appendix.

(b) River Basins are identified in Figure 4-1.

(c) Missing value indicates that snow was not detected in satellite picture or that no Aerial-Survey Value was given (see Table A-4).

"average" snow-line elevation. Hence, the lowest and highest values were disregarded.

The results were tabulated for a total of 25 cases (about eight basins for each of the three dates). Of these, the satellite value exceeded the aerial-survey value in 21 cases. The agreement is better in some basins than others; for example, in Basin 7 (Yaak and Moyie Rivers) a substantial snow cover in both of the May cases is not detected in the satellite pictures. With regard to the mean values for the basins tested on each date, the best agreement is for the 19 June 1967 case and the worst for the 6 May 1969 case.

4.1.4 Discussion of Results and Comparison with Results for Southern Sierras Region

The results obtained for the Upper Columbia Basin cannot be considered as reliable as those for the Sierras region since comparative satellite and aerial-survey data were available on a total of only three days in the two-year sample period. Based on these three cases, it is concluded that the satellite snow-line elevation can be determined to within about 600 feet of the aerial-survey value. This compares with a value of about 500 feet for the Kings River Basin in the Sierras. In the Upper Columbia Basin, the satellite snow-line is consistently at a higher elevation than the aerial-survey snow line, and hence may actually be in better agreement with the "highest" reported value rather than the "average" value. The same was found true in the Kings Basin, but not in the other three Sierras basins examined.

In general, however, satellite mapping of snow extent in the Upper Columbia Basin during the late spring is not as reliable as in the southern Sierras. In some instances, snow cover is only poorly visible or not identifiable at all, such as in mid-June 1969. For this particular case, the error in snow-line elevation derived from the satellite data would, of course, be considerably greater than 600 feet. Snow also appears more difficult to detect in certain river basins, such as the Yaak and Moyie.

The reason that late season snow can be detected more reliably in the Sierras is concluded to be due primarily to the less-dense forest cover of that region. The extent of the terrain at higher elevations is also considered to be a factor; because the Upper Columbia Basin consists of several individual ranges, the snow remaining at the high elevations may not have a sufficient areal extent to be as reliably identified as in the single, larger in-extent, Sierra Nevada.

Furthermore, some ranges are so narrow that even when the snow-line elevation is reported to have decreased, the areal extent as viewed by the satellite does not appear to decrease significantly enough for the change to be detected.

Cloud contamination in the late spring, especially due to terrain-induced cloudiness, is a significantly greater problem in the Upper Columbia Basin than in the southern Sierras. This factor would also tend to make the Sierras a more suitable region for satellite snow surveillance. Finally, since the satellite is photographing snow extent, the aerial-survey snow-extent charts available for the Sierras were easier to work with than the snow-line elevation data available for the Upper Columbia Basin.

4.2 Lower Columbia Basin

Aerial-survey snow data were not available for the Lower Columbia Basin region. Nevertheless, snow cover was mapped from several satellite photographs during the period from 10 March to 17 June 1969. Four of these photographs are shown in the Appendix, Figures A-18 and A-19. Three analyses were prepared both to compare characteristics of the region with those of the Upper Columbia Basin and to compare the 1969 snow distribution with the 1967 distribution discussed in the previous study of satellite surveillance of mountain snow.

In comparison with data from two years earlier, a much greater extent of lower elevation snow existed during March 1969. This snow cover is the result of the record snowfalls during late December and January throughout the Pacific Northwest. Because of the heavy spring snowfalls during 1967, however, the late spring snow distributions do not appear significantly different in the satellite observations from the two years; in fact, the snow extent in Washington observed on 16 and 18 June 1967 appears greater than the extent observed on 17 June 1969. Thus, the 1967 and 1969 snow climatologies of the region, as reported and as derived from satellite photography, are similar to those of the Upper Columbia Basin region.

In comparison with the Upper Columbia Basin, a greater number of cloud-free observations were obtained during the 1969 snowmelt season. In general, late-spring contamination by convective cloudiness appears to be less of a problem in the Pacific Northwest than in the region farther east. Furthermore, although the snow in the forested mountain areas does not appear as bright as the snow in the lower elevation farmland, it does seem easier to identify during the late spring than does the snow in the mountains of northern Idaho and Montana. Snow identification is probably easier because the Cascade Range covers a greater area than do the more isolated ranges farther east, and contains several higher peaks that retain snow above the tree-line well into summer.

Although no comparative data were available, snow-line elevation were estimated in a similar manner to that described in the previous section. For the observations shown in the Appendix, the snow-line elevations (in feet) were estimated to be as follows: (a) 12 March, 3000 in Oregon and less than 3000 in Washington; (21 March, about 4000 in southern Washington and Oregon, and still 3000 or lower in northern Washington; (c) 5 May, 4000-5000 in Washington and 6000-7000 in Oregon; and (d) 1 June, 5000-7000 in Washington (except lower in the Olympic mountains) and 7000 in Oregon. In the Basic Data Summary, snow cover was reported at only seven locations within the Lower Columbia Basin on about 1 June. Two of these locations were below 4000 feet, two were between 4000 and 5000 feet, two between 5000 and 6000 feet, and one above 6000 feet.

5. REGION III: ARIZONA - SALT RIVER PROJECT

A third region of the western United States for which aerial-survey snow data are available is in Arizona. Aerial-survey flights are made throughout the snow season in the Salt River Project area, outlined in Figure 5-1. These mountains are indicated to be "forest and woodland, grazed" or "open woodland, grazed," and thus are even less forested than the southern Sierras. In this region, however, snowfall is considerably lighter, with depths of only a few inches usually reported, except at the highest elevations.

Satellite and aerial-survey data were analyzed during the late winter and early spring period of 1969. In mid to late February and in a stormy period centered about 10 March, considerable snowfall occurred in Arizona, particularly in the central part of the Salt River Project area. During the period of 9-14 March, more than 25 inches fell at Flagstaff. During the latter half of the month, rapid snow melt occurred with the cover at Flagstaff being reduced from a maximum of 37 inches on the 14th to zero on the 25th. The decrease in snow extent is apparent in satellite pictures on 19, 23, 25 and 27 March. Snow cover was also mapped from an earlier picture on 11 February.

Representative pictures (11 February and 19 and 27 March 1969) together with aerial-survey data from 10 February, 19 March and 2 April are shown in Figures A-20 through A-22 of the Appendix. Snow depths from Climatological Data Summaries are also plotted. As can be seen from these figures, the snow extents mapped from the satellite and aerial-survey observations are not in close agreement in many areas. A reason for the disagreement is that the aerial observations are made only within the project area and do not necessarily indicate the total snow extent. For example, on 19 March Flagstaff reports a substantial snow amount, but since the city is just outside the project area it was not overflown. Thus, the comparative analyses described in this section are somewhat limited.

5.1 Comparative Analyses Between Satellite and Aerial-Survey Snow Extent

5.1.1 10-11 February 1969

The area just to the west of Flagstaff, which is reported to have 85-90% snow coverage, appears fairly bright in the satellite picture. Farther to the southeast, where 70-90% coverage of only a few inches depth is reported, the area appears less bright. The brightest part of the satellite picture is near the New

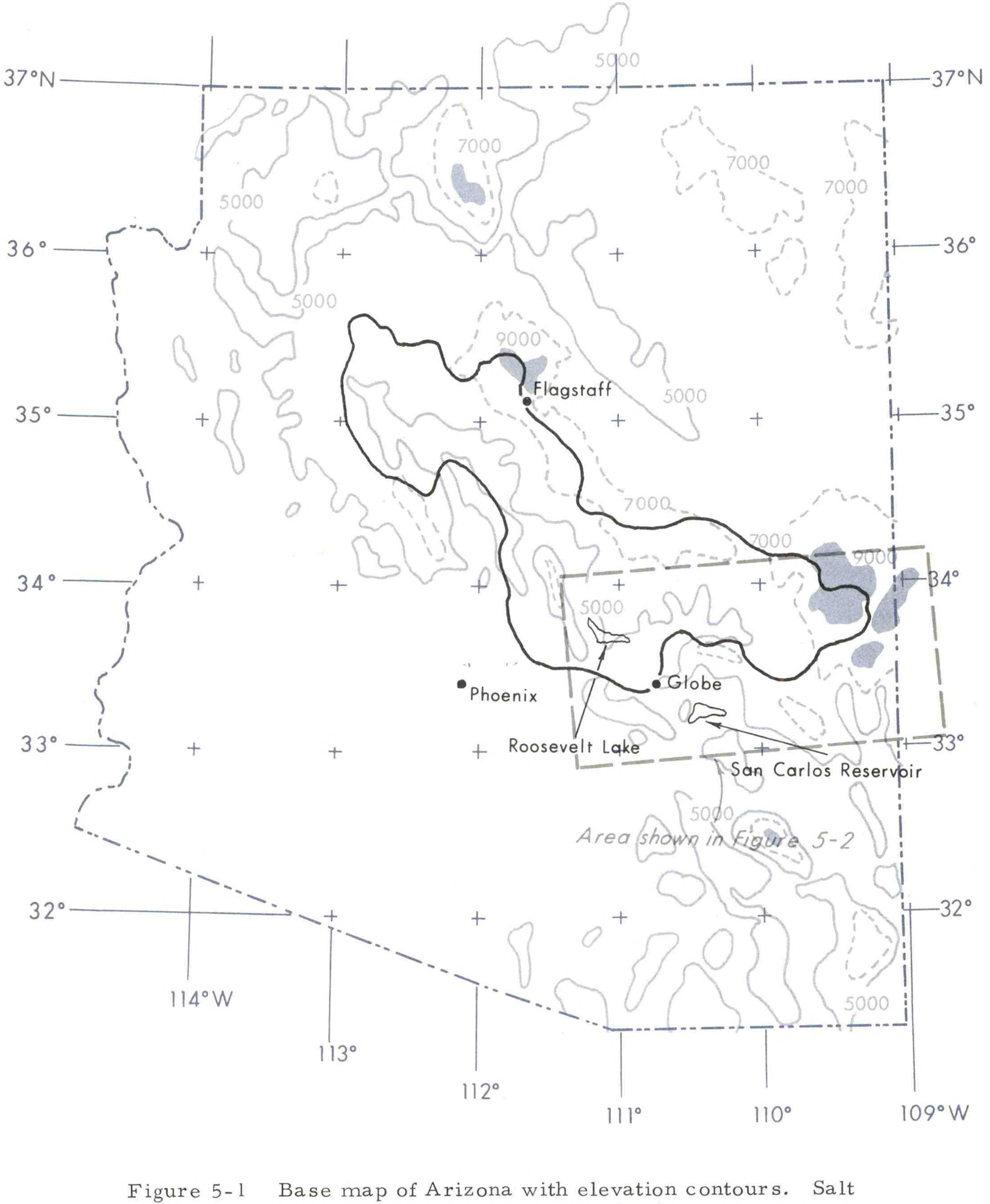

Figure 5-1 Base map of Arizona with elevation contours. Salt River Project Area is outlined. Approximate area covered by Apollo-9 photographs shown in Figure 5-2 is also indicated.

Mexico border, within the White Mountains (Mt. Baldy), where 100% coverage of deep snow is reported. The narrow band with only 20-70% coverage (about 1 inch depth) does not show up in the satellite observation.

5.1.2 19 March 1969

The snow extent and general brightness analyzed from the satellite picture on this date are both greater than in the observation made a month before. The aerial-survey data show an increase in both snow extent and depth, particularly in the North Central Watershed area. Although the areal extent in the White Mountains has not changed significantly, the narrow band of snow between these two principal watershed areas can be detected at this time.

5.1.3 27 March - 2 April 1969

By this date, the only snow cover detectable is in the North Central Watershed and the White Mountain areas. This distribution is in good agreement with the aerial-survey observation a few days later, which reports no significant snow remaining below the 7000 foot elevation. The snow line from the satellite picture would also be estimated at about the 7000 foot level.

5.2 Apollo-9 Photography

Photography from Apollo-9 taken on 12 March 1969 was also available for this region. In the two frames shown in Figure 5-2, the area near and to the east of Globe, Arizona, is viewed (Globe lies about half-way between Roosevelt Lake and San Carlos Reservoir, the two lakes in the picture). The snow cover photographed is that in the Mt. Baldy area of the White Mountains, the area that appears brightest in the ESSA photography.

The Apollo photographs indicate the area to be essentially non-forested, with much of the snow cover appearing very bright. Nevertheless, particular features are difficult to identify in the ESSA picture of 19 March (Figure A-21), and several small snow covered areas, such as those west of Globe, cannot be detected. Two factors, lesser snow depths and less contrast between the snow and surrounding desert terrain, may account for the greater difficulty in identifying the same snow features in both of the photographs, as compared to the Apollo and ESSA photographs analyzed in the California-Nevada Region (Section 3.3).

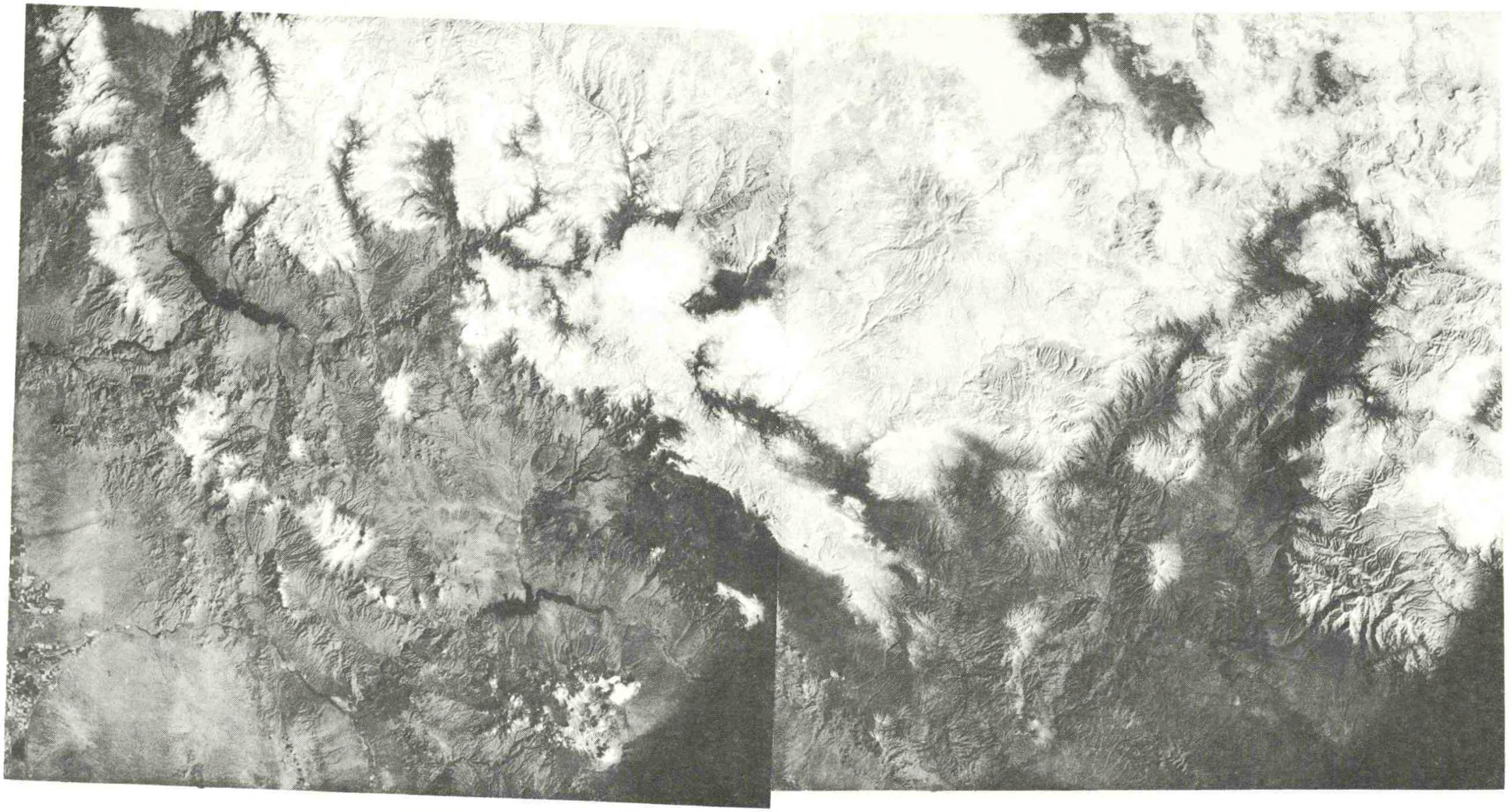

Figure 5-2 Apollo-9 photographs of central and east-central Arizona, 12 March 1969. Photographs are in the 0.68-0.89 μm spectral interval.

6. ADDITIONAL DATA SOURCES

6.1 Nimbus IDCS Photography

A sample of Nimbus III IDCS (Image Dissector Camera System) photography from the spring of 1969 was also examined to determine whether these photographs were significantly different from the ESSA AVCS photographs for purposes of snow mapping. The advantages of the experimental IDCS over the more conventional vidicon camera systems are given as: the ability to sense a greater dynamic range (about 100:1, compared with a value of 40:1 given by Schwalb and Gross (1969) for the ESSA vidicon), high signal-to-noise ratios, direct relationship between light flux input and electron current output, and the avoidance of a mechanical shutter (Sabatini, 1969). The average picture resolution is approximately 2.2 n. mi., about the same as that of the ESSA AVCS cameras.

Nimbus IDCS photographs of the southern Sierras region were analyzed for three dates during the late April to early June period. The dates selected either coincided with or were within a day or two of the dates for which ESSA-9 observations were analyzed. Pictures on the same day were not selected for each case because of variations in the IDCS picture quality. Two of the IDCS photographs are displayed in the Appendix, Figures A-23 and A-24.

For the three cases tested, the snow extent as mapped from the Nimbus did not differ significantly from the values mapped from the ESSA data (Table 6-1). Except for the Tule Basin in the late April case, the differences in percent of basin covered are of the order of 2%. The signs of the differences are about equally distributed. The results of the initial analysis of the April case gave a much lower value from the Nimbus than from the ESSA picture, particularly within the Kings Basin. A reexamination of the pictures indicated that what had been thought to be noise in the Nimbus observation was actually snow cover.

Overall, with the pictures enlarged to a workable size, the IDCS data appear somewhat noisier and "fuzzier" than the ESSA data. The brightness tones for the snow-covered areas appear about the same. Thus, for visual mapping of snow extent, at least in the southern Sierras region, no significant difference was found between the Nimbus IDCS and ESSA AVCS products.

In regions such as the Upper Columbia Basin, where more subtle gray-scale tones are encountered, the increased dynamic range of the IDCS may be to more advantage. Although data for that region were not analyzed in detail, one such picture for 6 May 1969 is shown in Figure A-25 of the Appendix. The snow cover appears somewhat easier to identify than in the corresponding ESSA picture

(Figure A-17). The advantages of the IDCS camera may also be more apparent in products derived through automatic processing techniques.

TABLE 6-1

DIFFERENCE BETWEEN SNOW EXTENT IN SOUTHERN SIERRAS REGION AS MAPPED FROM ESSA-9 AVCS AND NIMBUS III IDCS PHOTOGRAPHS

(ESSA minus Nimbus value in percent of basin snow covered)

	Kings	Kaweah	Tule	Kern	Total Area
29 April - ESSA 28 April - Nimbus	2	0	-12	-4	-2
15 May	-4	1	7	1	5
3 - 5 June - ESSA 1 June - Nimbus	0	0	0	-2	-1
Mean of Absolute Difference	2.0	0.3	6.3	2.3	2.7

6.2 Nimbus Daytime HRIR Data

Nimbus III also carried an HRIR (High Resolution Infrared Radiometer) experiment, the daytime channel of which measured in the 0.7-1.3 μm spectral interval. A detailed discussion of this sensor can be found in Sabatini (1969). Since the radiometer measures primarily reflected solar energy, a sample of HRIR data in the pictorial format was examined to determine whether mountain snow could be detected.

Because of the lack of complete coverage over the western United States and problems with noisy data, the sample available was rather limited. One of the better quality pictures examined is shown in the Appendix, Figure A-26. As indicated by this picture, mountain-snow patterns are essentially undetectable in the daytime HRIR pictorial display. Water bodies, such as Great Salt Lake, Salton Sea, and Lake Tahoe, can, however, be easily identified. In the HRIR data, therefore, contrast between snow and bare ground is apparently less than the contrast between water and ground.

Although other characteristics of the systems undoubtedly have an influence, the difference in the spectral intervals of the Nimbus III Daytime HRIR Sensor and the ESSA AVCS camera apparently have a considerable effect on the detection of snow and water. The AVCS system has a peak spectral sensitivity of 0.5-0.7 μm

(Schwalb and Cross, 1969). In these pictures, whereas contrast between snow and ground is very high, water bodies are difficult to detect.

Similar contrast variations were noted in the Apollo-9 multispectral photographs examined for the Arizona region. The photographs shown in Figure 5-2 are at a spectral interval of 0.68-0.89 μm; high contrast exists between the two water bodies and the surrounding land. In other photographs, taken at an 0.47-0.61 μm, the same two lakes were barely detectable, whereas the snow showed up somewhat brighter.

Thus, it appears that camera systems with a peak spectral response at about 0.5-0.7 μm are the most useful for snow detection. Sensors with a peak response at slightly longer wavelengths (0.7-1.0 μm), although not being as good for snow detection, may be more useful for hydrologic purposes such as flood surveillance.

6.3 ESSA Composite Minimum Brightness Charts

Composite Minimum Brightness (CMB) charts have been found to be a useful product for suppressing transient cloudiness and enhancing major snow and ice features in the satellite imagery (McClain and Baker, 1969). These charts, a computer product derived from digitized and rectified satellite video data, are described in detail in the above report. In the Appendix (Figures A-27 and A-28), examples of an Augmented Resolution Chip and a 5-day CMB chart are presented for comparison with the single-frame photographs used in the analyses carried out in this study.

For visual mapping purposes, the Sierras snow cover does not appear significantly different in the augmented resolution chip than in the original photograph. In the 5-Day CMB chart, a certain amount of detail is lost, presumably due to slight variations in the picture registrations. The fuzziness of Lake Tahoe and of the Kings River Basin are examples. Whereas the current CMB charts give an excellent presentation of the general snow extent, it appears that individual photographs must still be referred to for detailed mapping within river basins similar in size to those of the southern Sierras region.

7. RECOMMENDATIONS FOR FURTHER STUDY

The results of this study further substantiate that valuable information on the annual snow-extent decrease in the mountains of the western United States can be acquired from existing environmental satellite data. Of the three regions examined, satellite imagery appears to provide the most reliable data for the southern Sierra Nevada. Since the two years tested were both exceptionally heavy snow years in the Sierras, the comparative mapping accuracy from future satellite imagery during years with earlier snowmelt seasons will be of interest.

Variations in tonal brightness of snow-covered areas cannot be properly assessed from visual examination of satellite photographs. Objective analyses were not possible in this study, however, because the required digitized brightness data were not available. Since subtle brightness variations may be of significance for accurate snow mapping, particularly in the more densely forested regions such as the Upper Columbia Basin, studies involving the analysis of digitized brightness data should be undertaken.

Further investigations are also required to determine the snow-mapping application of satellite measurements in other than the visual-spectral range. In addition to camera systems, infrared sensors have been flown on several satellites. The spatial resolution of the HRIR (High Resolution Infrared Radiometer) sensor, currently in operation on Nimbus IV and ITOS-1, is nearly comparable to that of the photography used in the studies described above (approximately 5 miles maximum resolution compared with 2 miles for the ESSA cameras). A VHRR (Very High Resolution Radiometer) system, which will have a spatial resolution of 0.5 miles in both a visual and a 10-12 μm channel, is planned for second-generation ITOS in 1972.

An infrared sensing system can complement a video system with nighttime observations and can measure the surface temperature of the snow cover, a significant parameter for predicting snowmelt. A thorough evaluation of existing infrared data is necessary not only to determine whether hydrologically useful information can be derived from these measurements, but to develop analysis techniques applicable for the interpretation of future data such as that anticipated from the VHRR system.

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APPENDIX

Data Analyses

TABLE A-1

SNOW EXTENT MEASUREMENTS - SOUTHERN SIERRAS REGION -1967

(Cases Used in Data Tabulations)

	Kings		Kaweah		Tule		Kern		Total Area	
1967	mi^2	%	mi^2	%	mi^2	%	mi^2	%	mi^2	%
15 May Satellite	941	61	162	29	39	10	539	26	1681	37
15 May Survey A	1020	66	258	46	86	22	830	40	2194	48
15 May Survey B	960	62	205	37	48	12	676	33	1889	43
Mean of A and B	990	64	232	42	67	17	753	37	2042	46
21 May Satellite	865	56	185	33	27	7	809	33	1886	41
23 May Survey	958	62	165	30	20	5	601	29	1744	38
3 June Satellite	757	49	196	35	58	15	518	25	1529	33
7 June Survey A	773	50	117	21	12	3	373	18	1275	28
7 June Survey B	834	54	134	24	12	3	456	22	1315	31
Mean of A and B	804	52	126	23	12	3	414	20	1356	30
22 June Satellite	525	34	123	22	27	7	394	19	1069	23
22 June Survey	648	42	106	19	12	3	228	11	994	22
28 June Satellite	479	31	95	17	19	5	311	15	904	20
29 June Survey	494	32	62	11	0	0	207	10	763	17

TABLE A-2

SNOW EXTENT MEASUREMENTS - SOUTHERN SIERRAS REGION - 1969

(Cases Used in Data Tabulations)

	Kings		Kaweah		Tule		Kern		Total Area	
	mi^2	%	mi^2	%	mi^2	%	mi^2	%	mi^2	%
1969										
29 April Satellite	1004	65	218	40	74	19	975	47	2271	50
29 April Survey A	1112	72	230	41	78	20	1099	53	2519	55
29 April Survey B	1159	75	258	46	86	22	1099	53	2602	57
Mean of A and B	1136	74	244	44	82	21	1099	53	2561	56
8 May Satellite	850	56	157	28	47	12	850	41	1904	42
9 May Survey	988	64	185	33	55	14	767	37	1995	44
15 May Satellite	758	49	129	23	54	14	725	35	1666	36
16 May Survey A	927	60	134	24	27	7	642	31	1730	38
16 May Survey B	942	61	168	30	35	9	726	35	1871	41
Mean of A and B	935	61	151	27	31	8	684	33	1801	40
25 May Satellite	742	48	179	32	0	0	539	26	1460	32
26 May Survey	881	57	157	28	0	0	581	28	1619	35
3 June Satellite	790	51	112	20	12	3	456	22	1370	30
5 June Satellite	618	40	90	16	0	0	373	18	1081	23
Mean (3 and 5 June)	704	46	101	18	6	2	414	20	1225	27
3 June Survey A	818	53	146	26	16	4	477	23	1457	32
3 June Survey B	788	51	123	22	27	7	498	24	1436	31
Mean of A and B	803	52	135	24	22	6	488	24	1448	32
25 June Satellite	463	30	11	2	0	0	249	12	723	15
26 June Survey A	417	27	0	0	0	0	166	8	583	13
26 June Survey B	448	29	0	0	0	0	145	7	593	13
Mean of A and B	433	28	0	0	0	0	156	8	589	13

TABLE A-3

SNOW EXTENT MEASUREMENTS - SOUTHERN SIERRAS REGION CASES FOR WHICH NO AERIAL-SURVEY DATA AVAILABLE

(All Values are Satellite Values Except 27 March 1967)

	Kings		Kaweah		Tule		Kern		Total Area	
	mi^2	%	mi^2	%	mi^2	%	mi^2	%	mi^2	%
1967										
7 March	896	58	196	35	66	17	933	45	2091	46
14 March	1421	92	560	100	391	100	1182	57	3554	78
19 March - Satellite*	1112	72	526	94	125	32	1058	51	2821	61
27 March - Survey	1097	71	269	48	86	22	850	41	2302	50
1969										
3 February	958	62	227	44	99	25	1203	58	2487	54
16 February	1020	66	218	39	145	37	1431	69	2814	62
26 February	1313	85	532	95	364	93	1784	86	3993	87
15 March	1004	65	280	50	211	54	1659	80	3154	69
28 March	865	56	207	37	125	32	1680	81	2877	63

*(Note: This case not used in tabulations because of 7-day interval between observations, but is plotted in graphical results.)

TABLE A-4

UPPER COLUMBIA BASIN:
SNOW-LINE ELEVATION FROM SATELLITE DATA AND AERIAL-SURVEY AVERAGE VALUE

(All Values in Feet)

River Basin*	Satellite 6 May 1969	Aerial Survey 13-14 May 1969	Satellite 13 May 1967	Aerial Survey 17-18 May 1967	Satellite 19 June 1967	Aerial Survey 19-21 June 1967
1	5000	4400	-	None Given	6000	None Given
2	4800	4300	4600	4900	No Snow	5500
3	5400	4200	4000	4400	6000	6000
4	4600	5300	5500		6500	
5	7000	6300	6000	4900	7000	6500
6	5500	5200	5000	4900	6000	6500
7	No Snow	4400	No Snow	4100	7300	6100
8	5500	4700	5000	4300	6500	5600
9	6000	4900	5000	4100	6000	5900
10	6000	5400	5000	4400	6500	6300
11	-	None Given	-	None Given	No Snow	5600

*River Basins are identified in Figure 4-1.

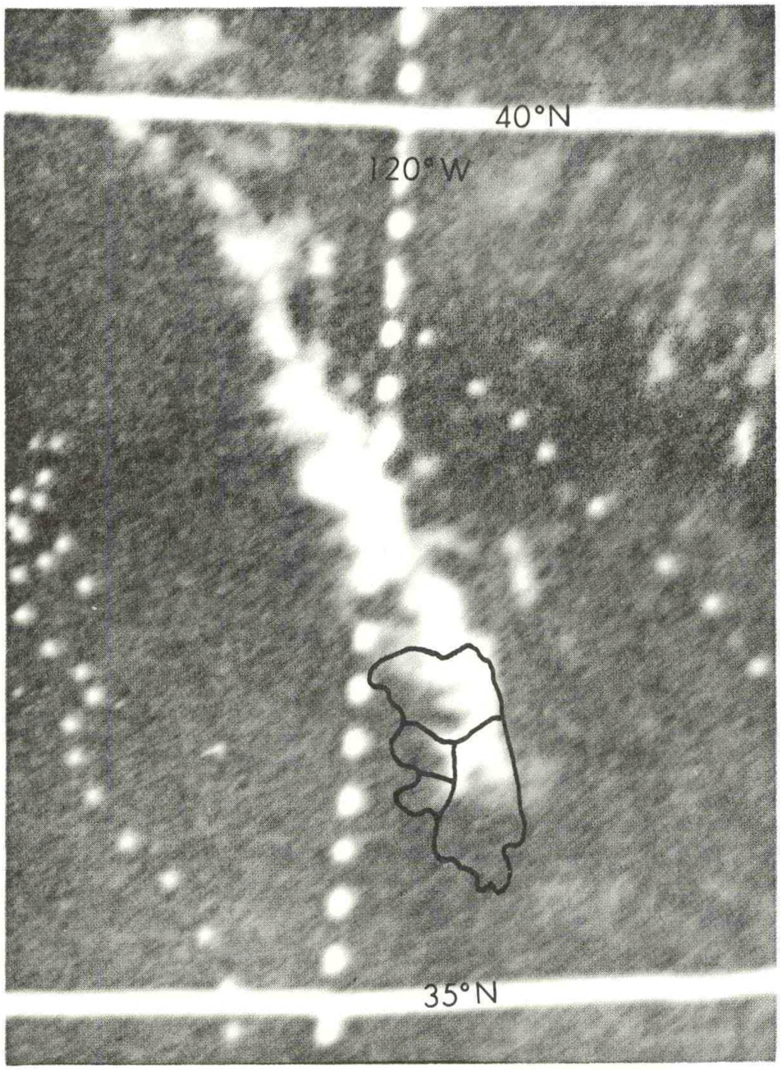


Figure A-1a ESSA-3 photograph of Southern Sierras Region, 15 May 1967. River basins for which snow extent mapped are outlined.

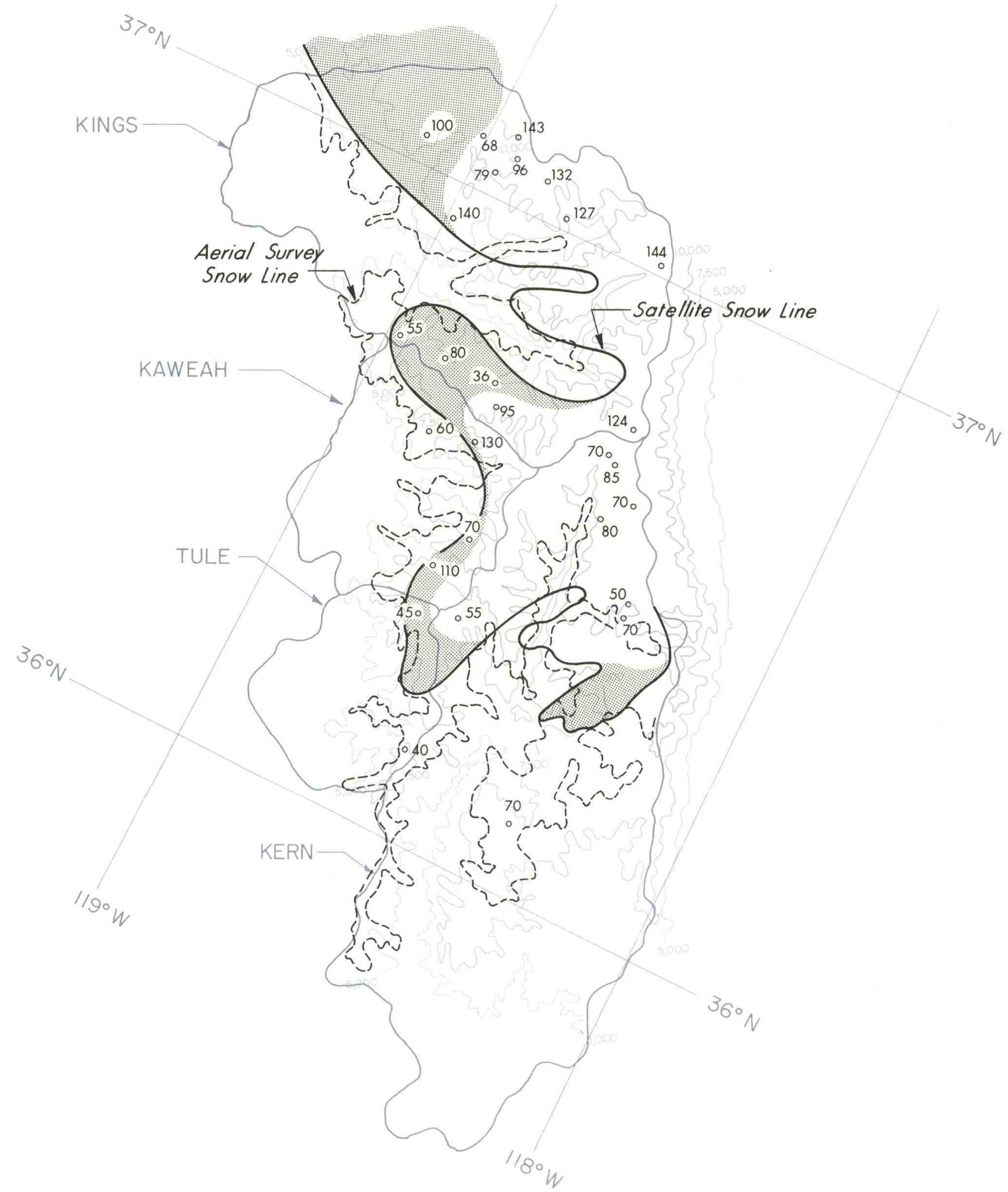


Figure A-1b Satellite snow extent mapped from Figure A-1a and aerial-survey snow extent for 15 May 1967. Shading indicates areas appearing less bright in satellite picture. Snow depths measured in early May are in inches.

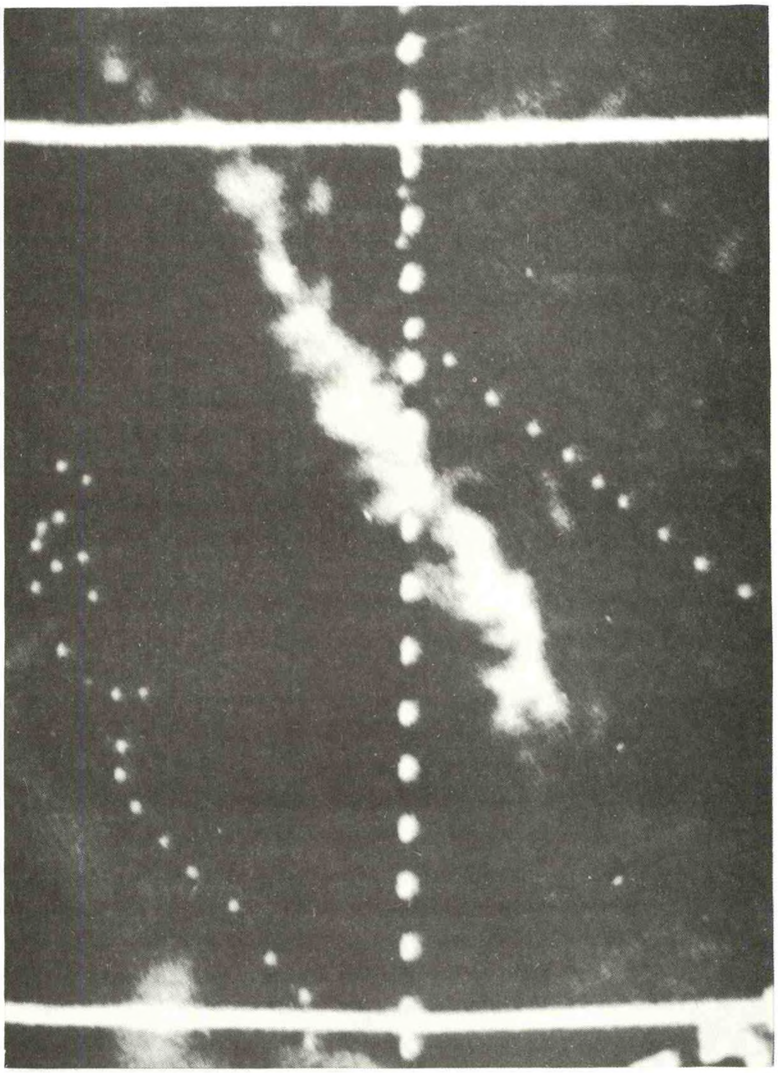


Figure A-2a ESSA-3 photograph of Southern Sierras Region, 21 May 1967. Area for which snow extent mapped is outlined in Figure A-1a.

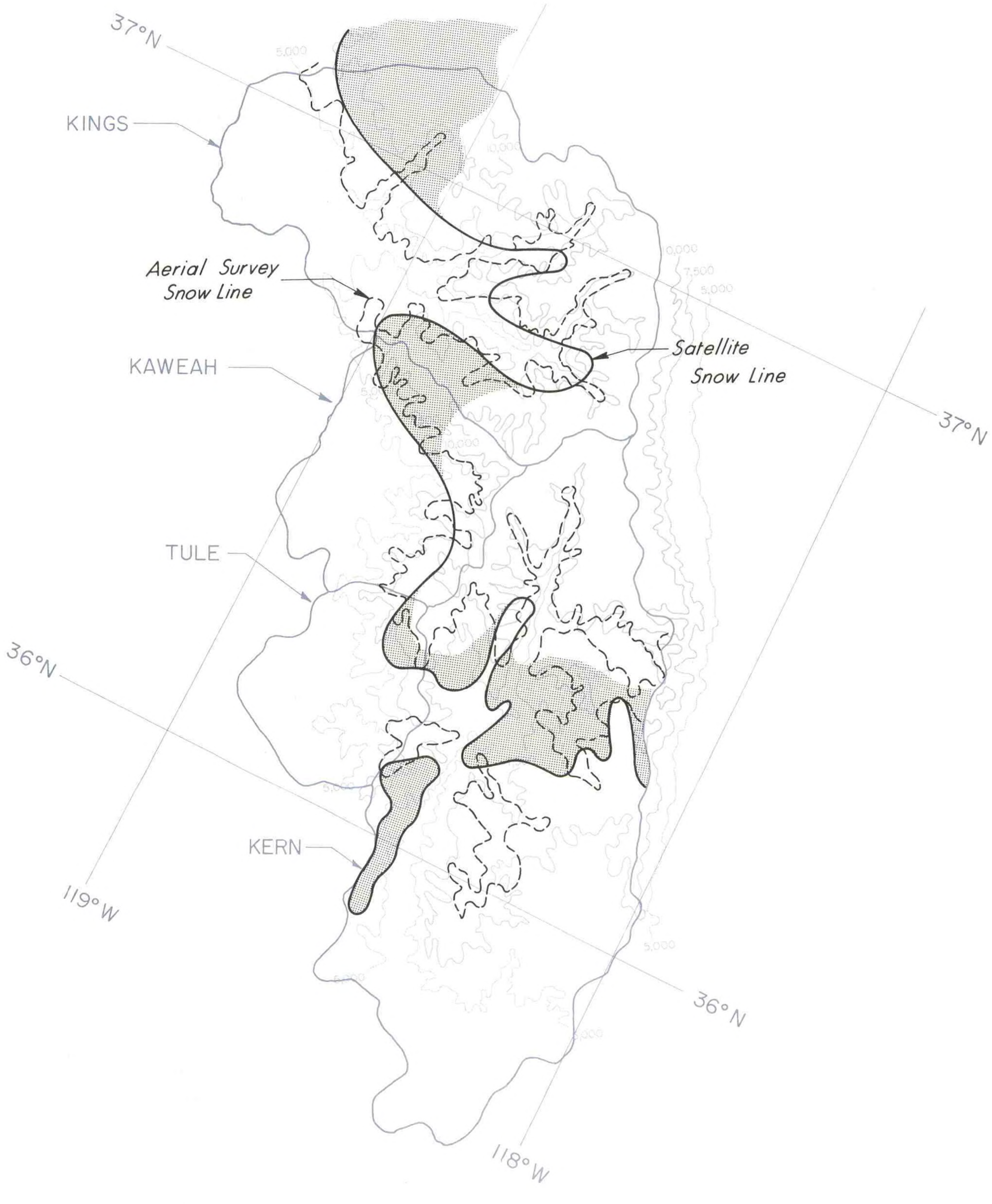


Figure A-2b Satellite snow extent mapped from Figure A-2a and aerial-survey snow extent for 23 May 1967. Shading indicates areas appearing less bright in satellite picture.

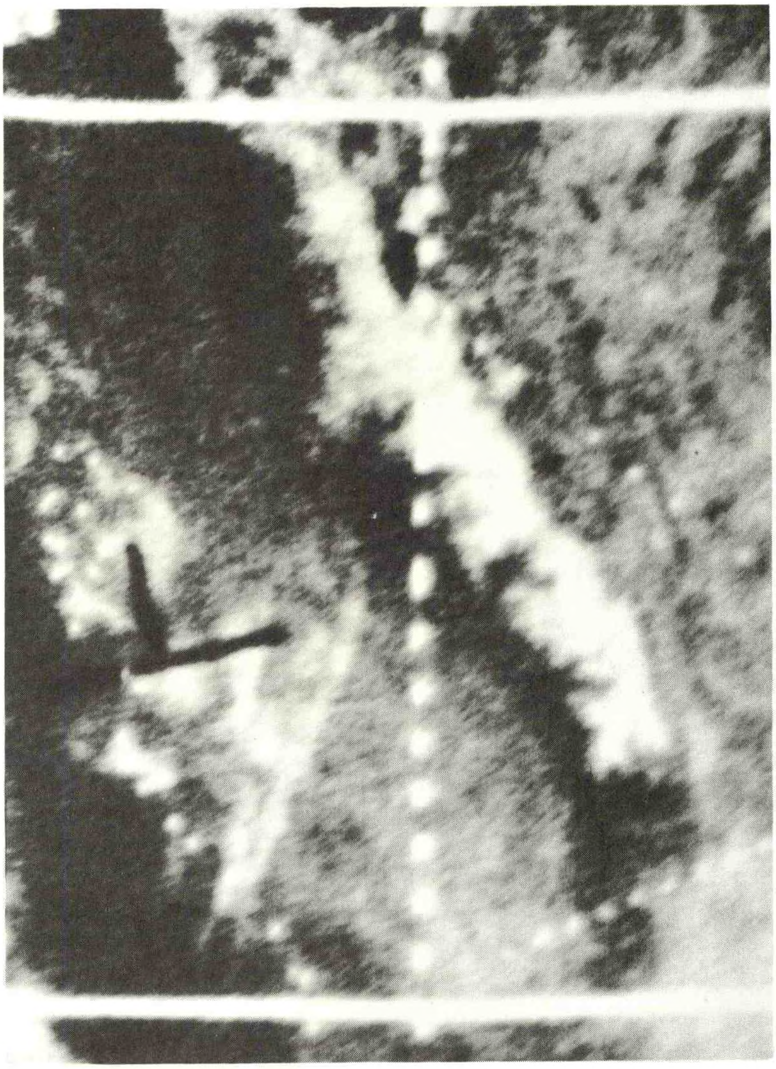


Figure A-3a ESSA-5 photograph of Southern Sierras Region, 3 June 1967. Area for which snow extent mapped is outlined in Figure A-1a.

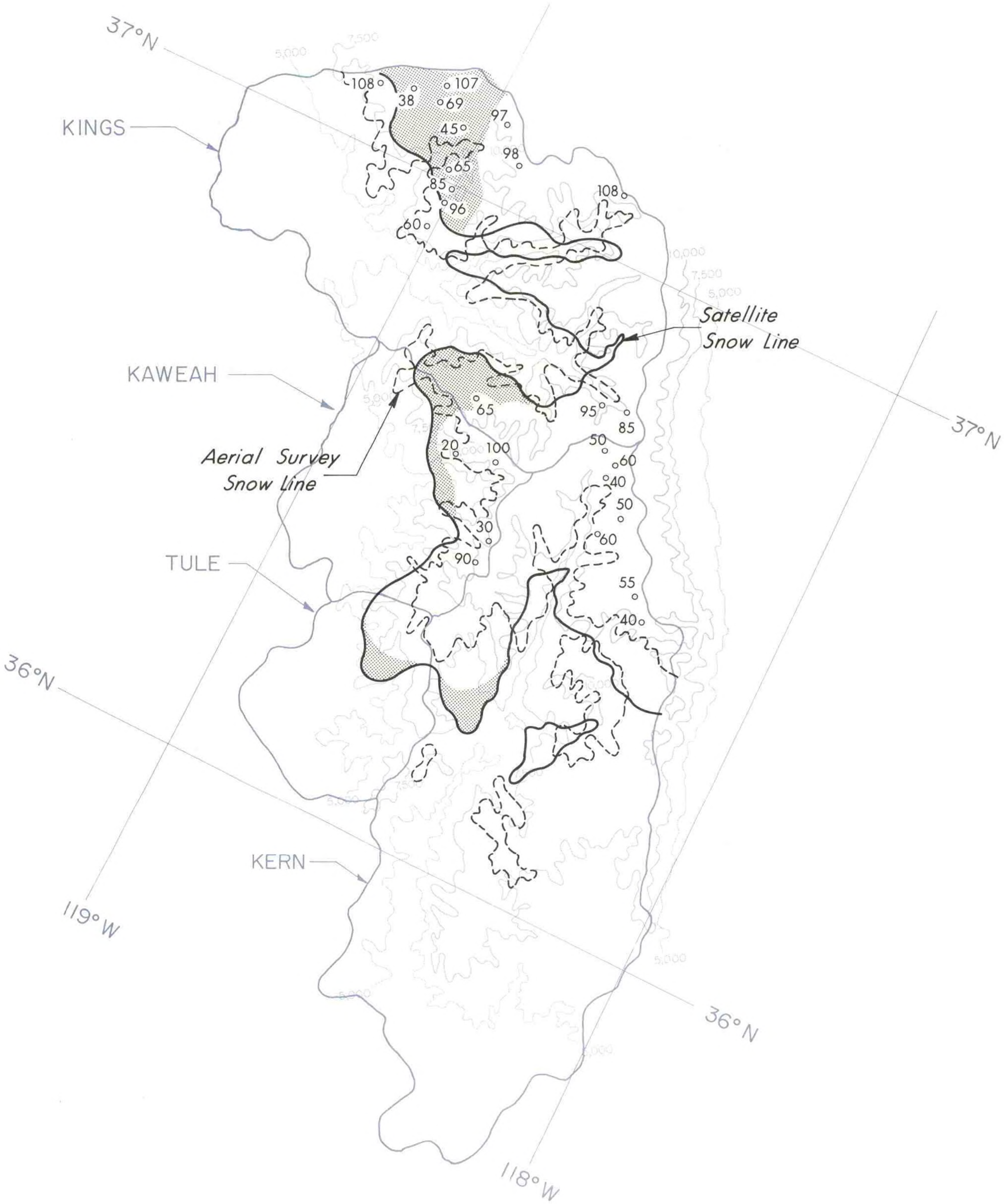


Figure A-3b Satellite snow extent mapped from Figure A-3a and aerial-survey snow extent for 7 June 1967. Shading indicates area appearing less bright in satellite picture.

7469

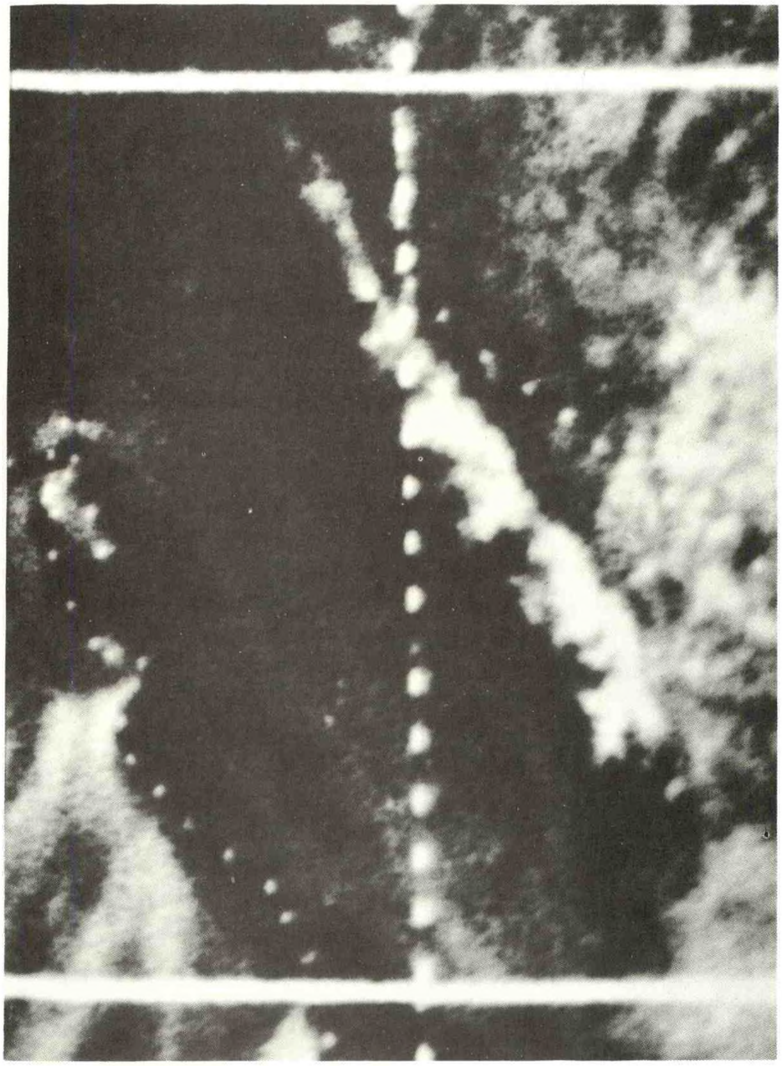


Figure A-4a ESSA-5 photograph of Southern Sierras Region, 22 June 1967. Area for which snow extent mapped is outlined in Figure A-1a.

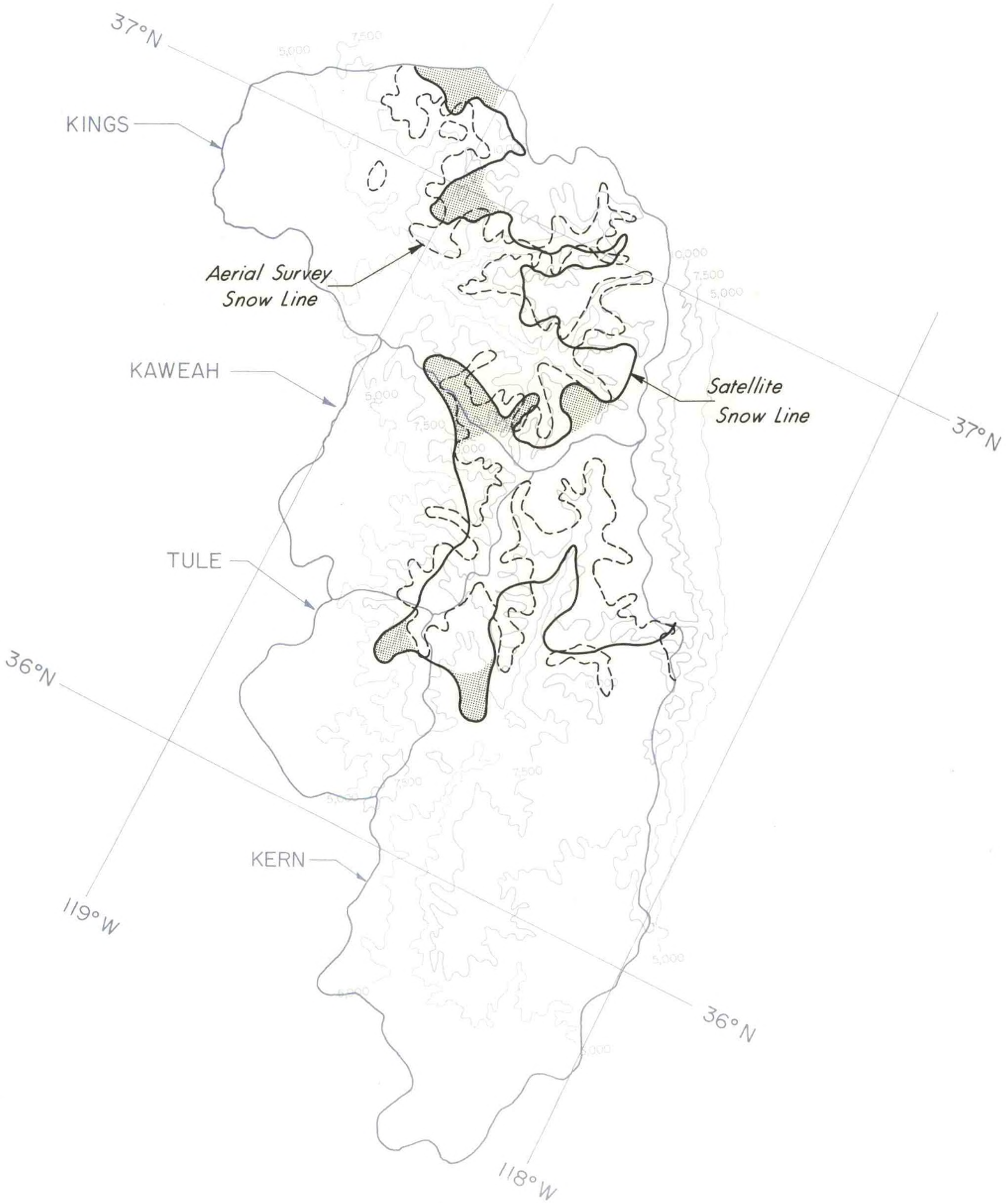


Figure A-4b Satellite snow extent mapped from Figure A-4a and aerial-survey snow extent for 22 June 1967. Shading indicates areas appearing less bright in satellite picture.

7468

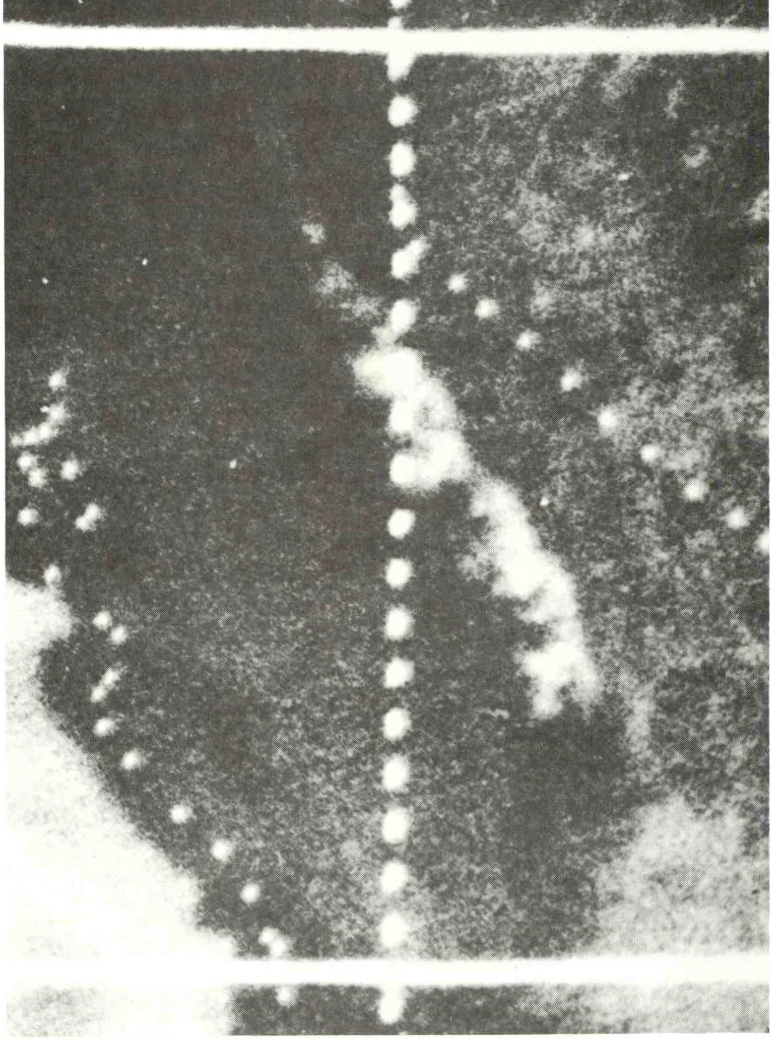


Figure A-5a ESSA-5 photograph of Southern Sierras Region, 28 June 1967. Area for which snow extent mapped is outlined in Figure A-1a.

Figure A-5b Satellite snow extent mapped from Figure A-5a and aerial-survey snow extent for 29 June 1967. Shading indicates areas appearing less bright in satellite picture.

7467

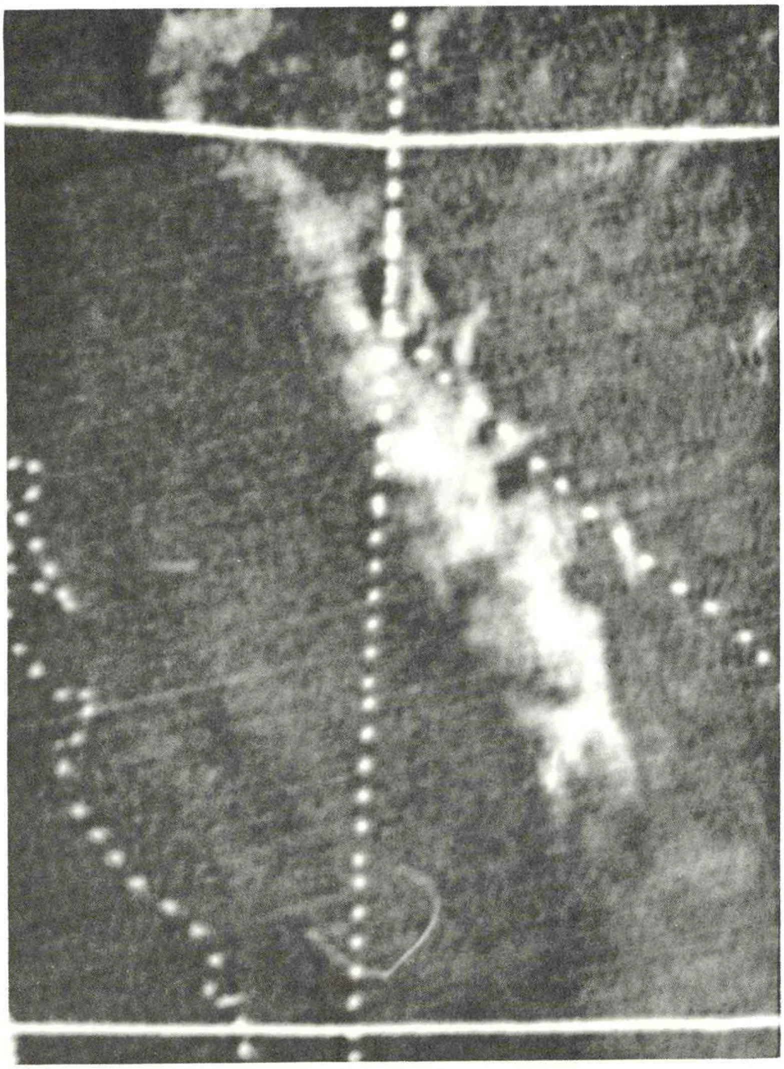


Figure A-6a ESSA-9 photograph of Southern Sierras Region, 29 April 1969. Area for which snow extent mapped is outlined in Figure A-1a.

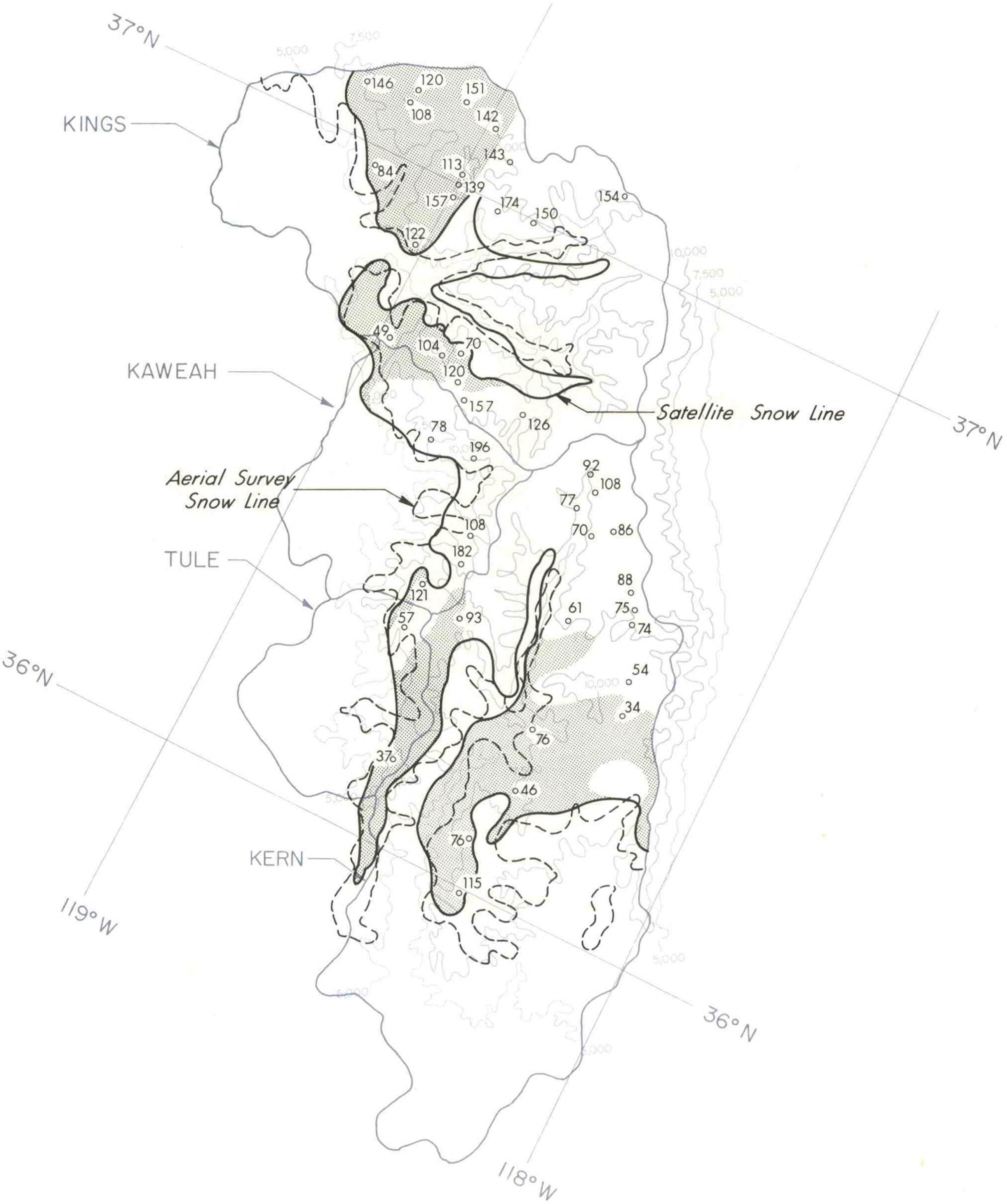


Figure A-6b Satellite snow extent mapped from Figure A-6a and aerial-survey snow extent for 29 April 1969. Shading indicates areas appearing less bright in satellite picture.

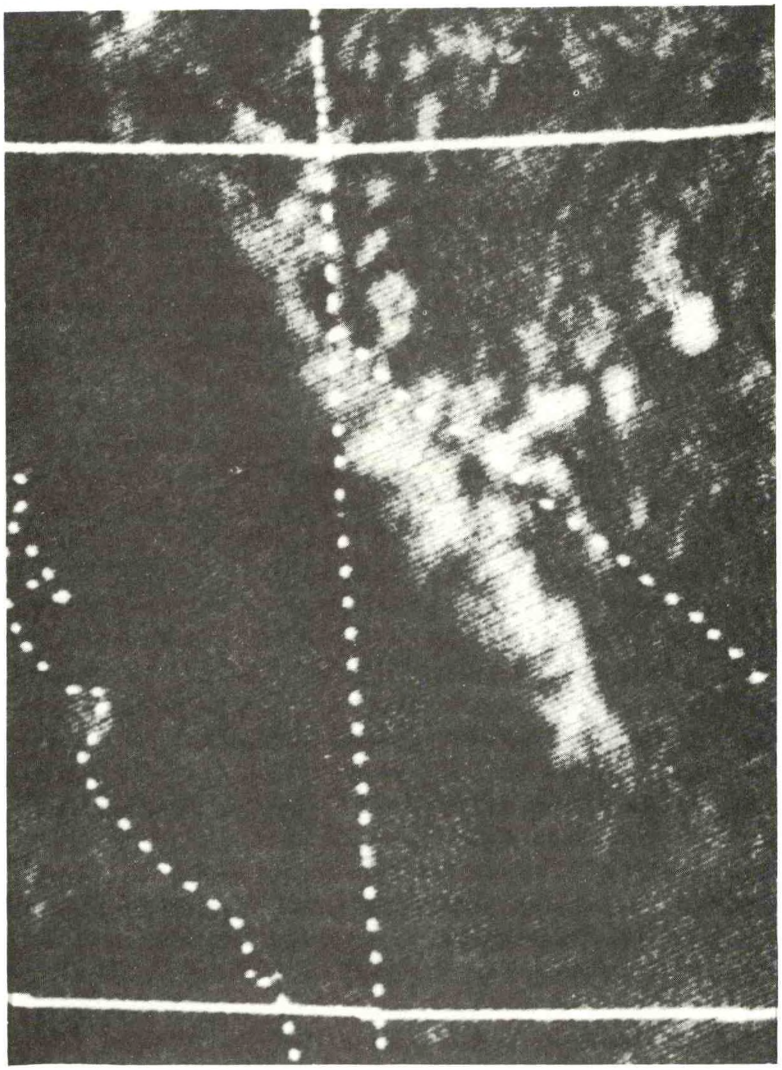


Figure A-7a ESSA-9 photograph of Southern Sierras Region, 8 May 1969. Area for which snow extent mapped is outlined in Figure A-1a.

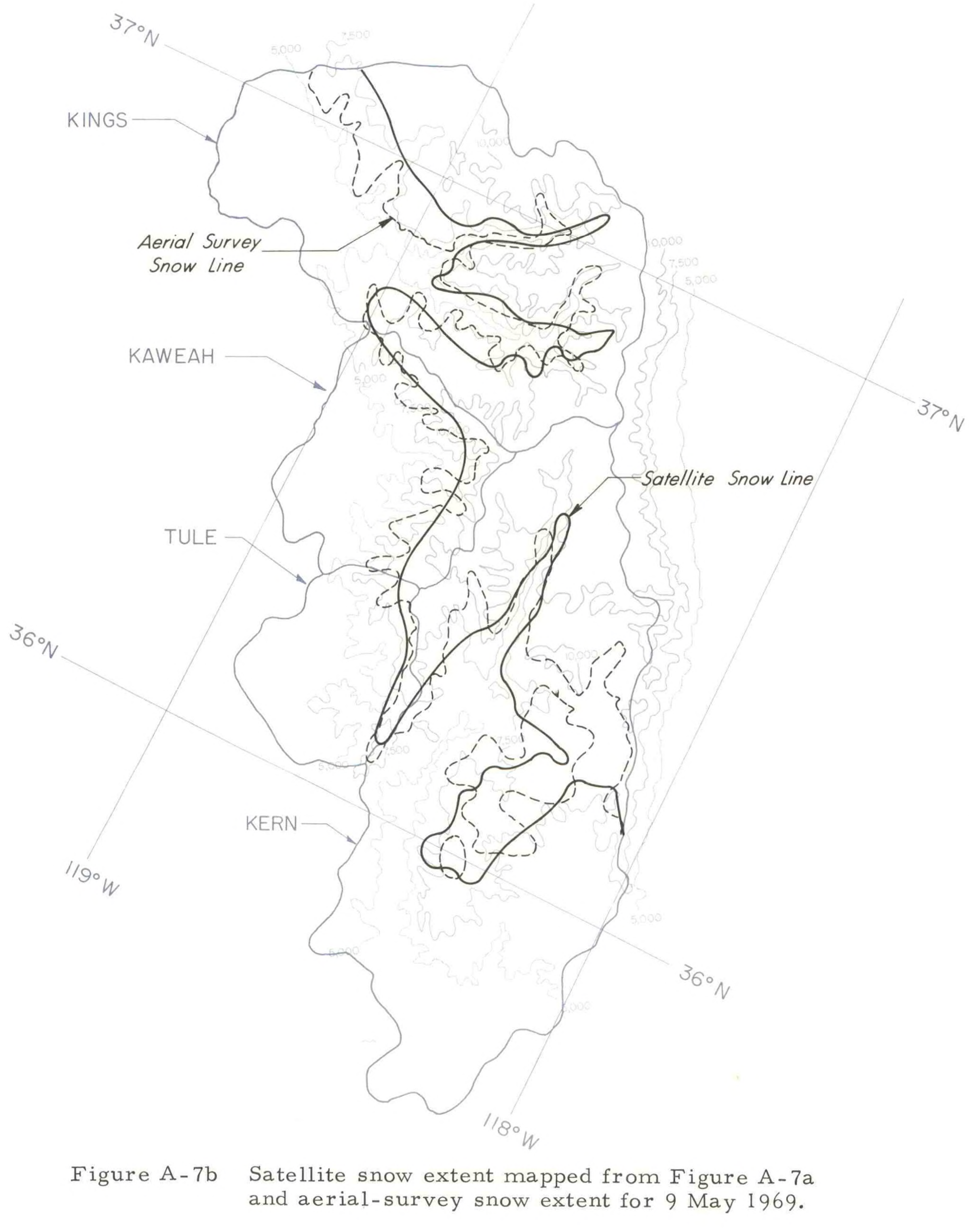


Figure A-7b Satellite snow extent mapped from Figure A-7a and aerial-survey snow extent for 9 May 1969.

7466

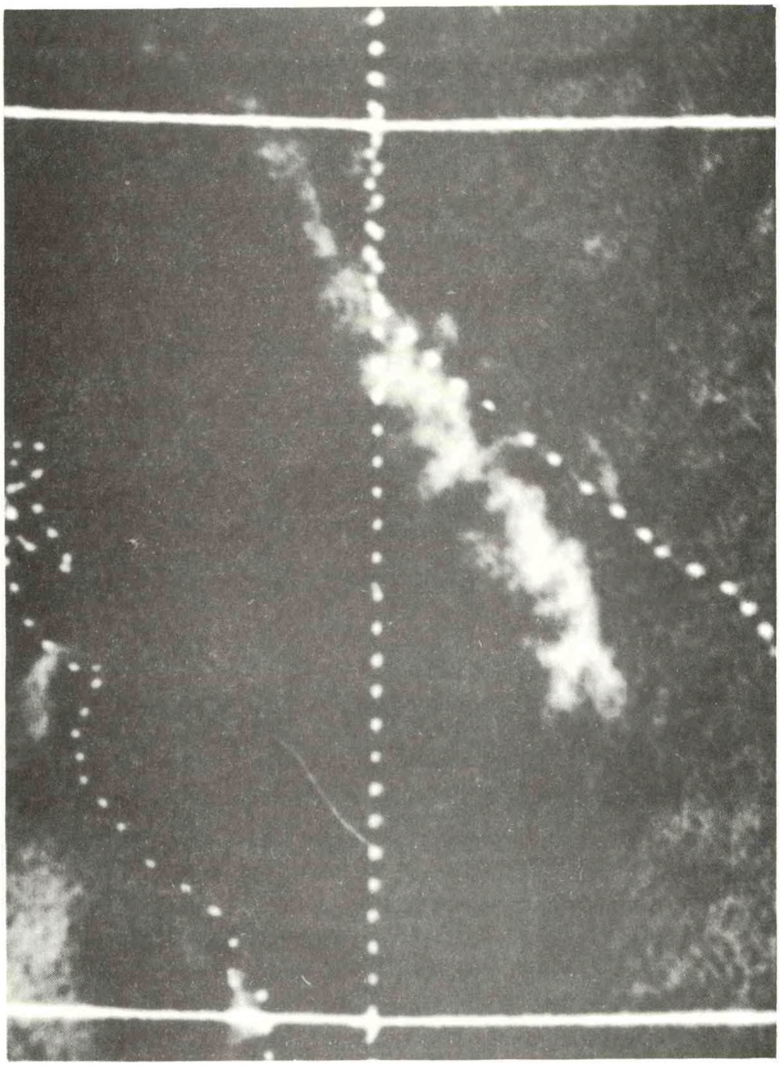


Figure A-8a ESSA-9 photograph of Southern Sierras Region, 15 May 1969. Area for which snow extent mapped is outlined in Figure A-1a.

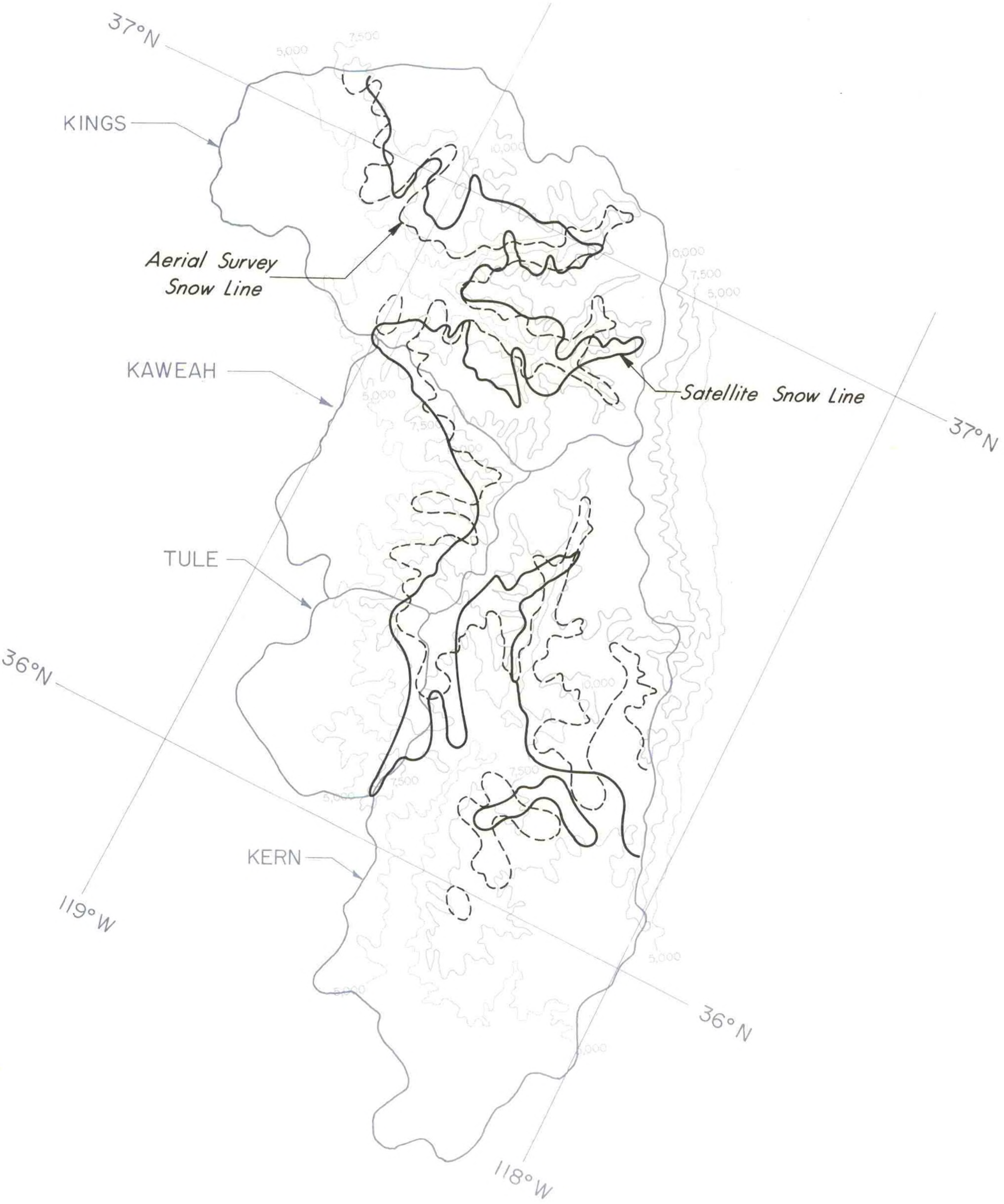


Figure A-8b Satellite snow extent mapped from Figure A-8a and aerial-survey snow extent for 16 May 1969.

7464

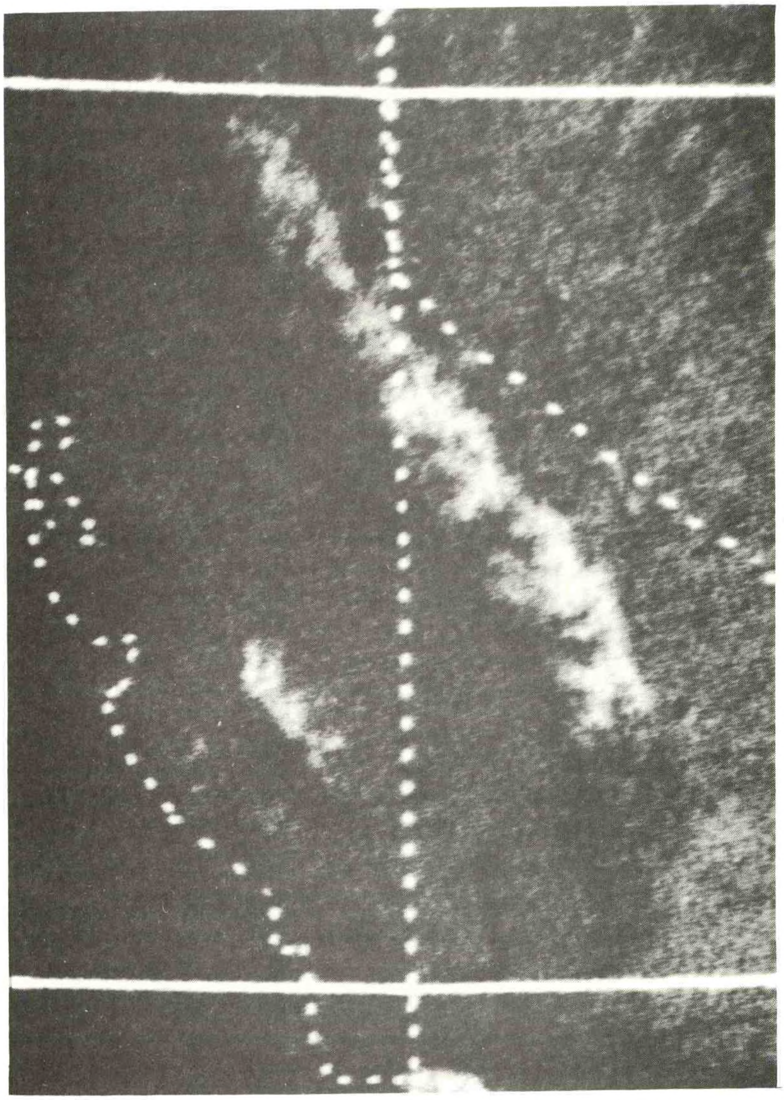


Figure A-9a ESSA-9 photograph of Southern Sierras Region, 25 May 1969. Area for which snow extent mapped is outlined in Figure A-1a.

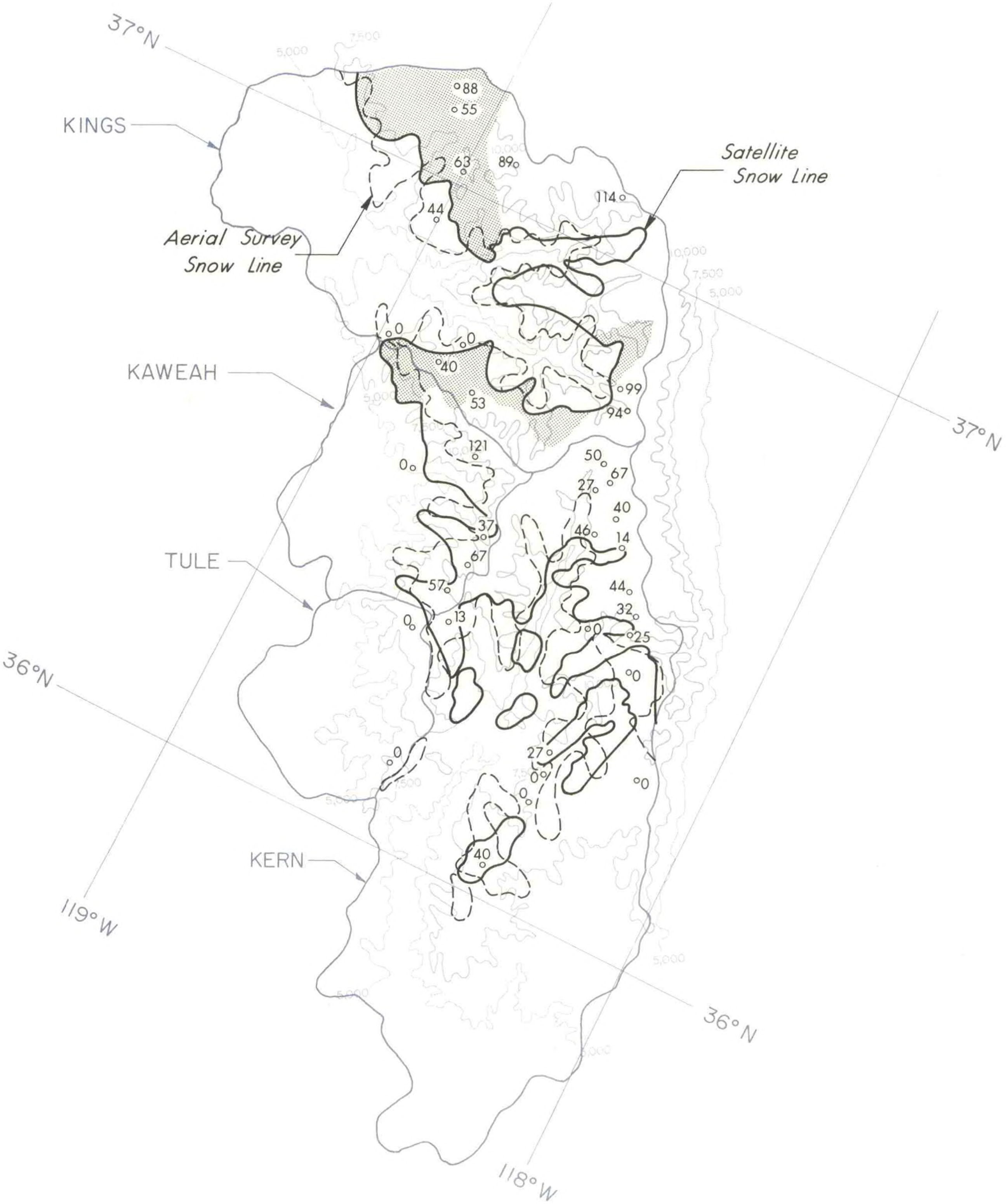
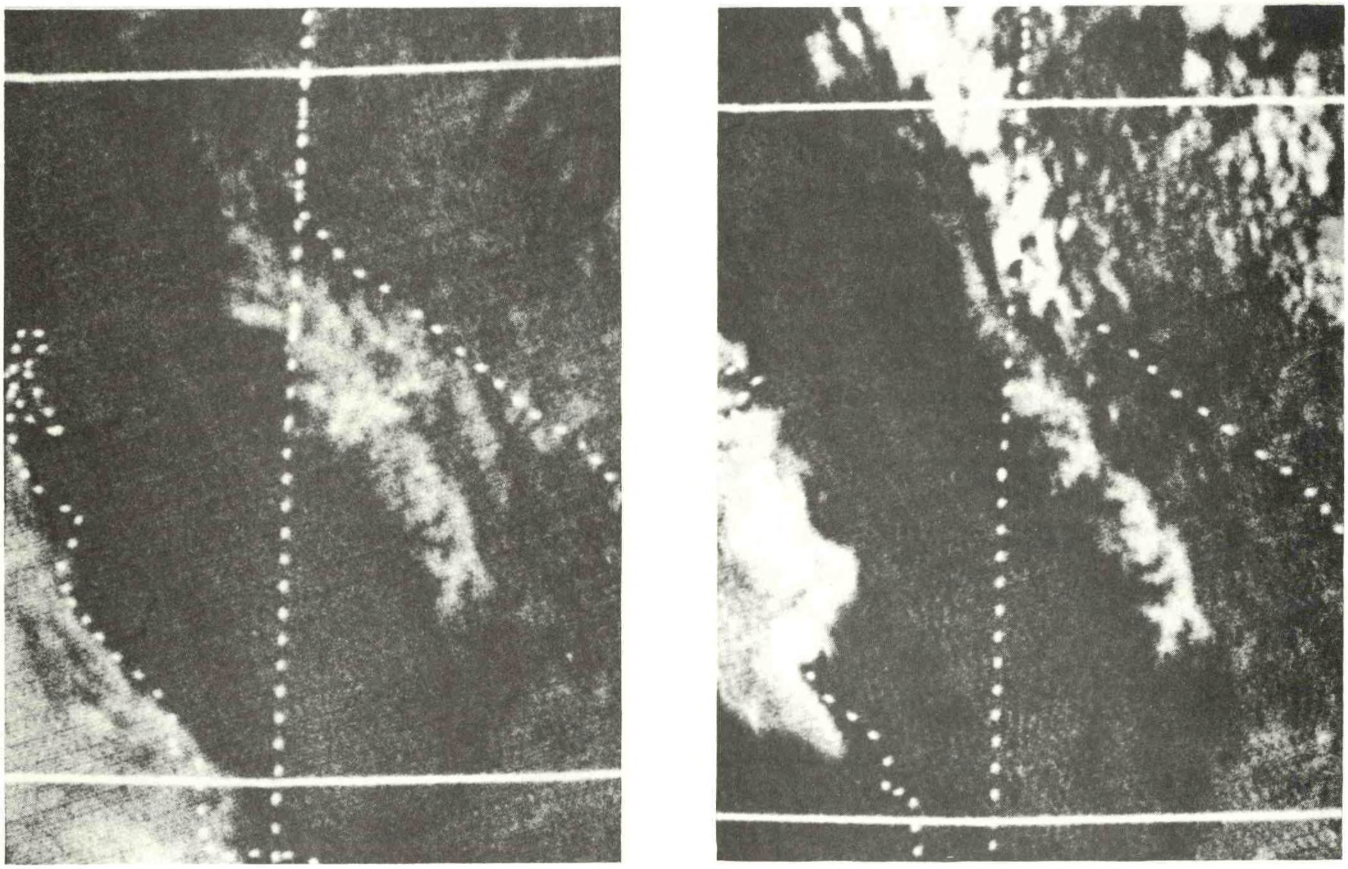


Figure A-9b Satellite snow extent mapped from Figure A-9a and aerial-survey snow extent for 26 May 1969. Shading indicates areas appearing less bright in satellite picture. Snow depths measured about 1 June are in inches.



3 June 1969

5 June 1969

Figure A-10a ESSA-9 photographs of Southern Sierras Region for 3 and 5 June 1969. Area for which snow extent mapped is outlined in Figure A-1a.

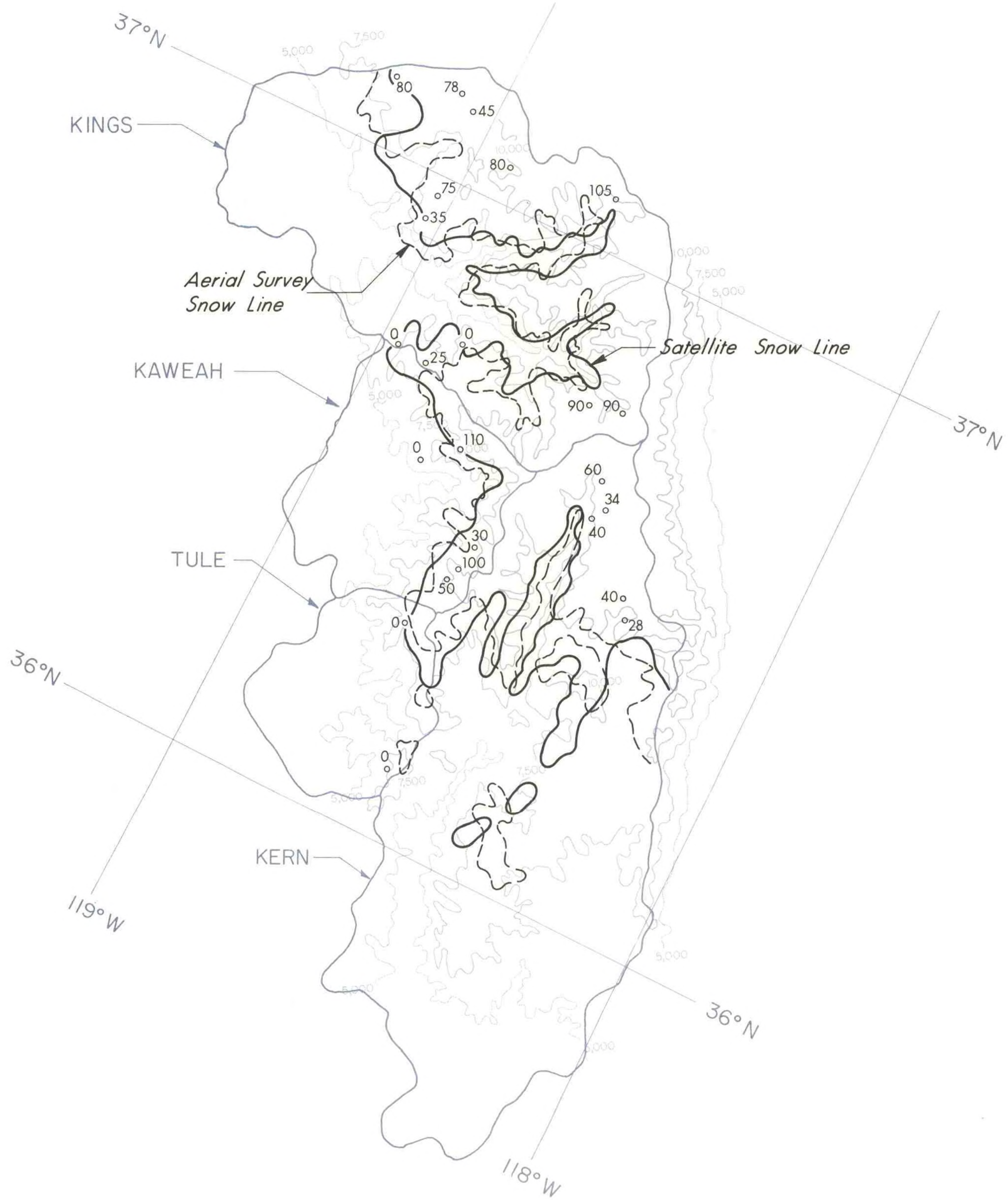


Figure A-10b Satellite snow extent mapped from Figure A-10a (3 June) and aerial-survey snow extent for 3 June 1969. Snow depths measured in mid-June are in inches.

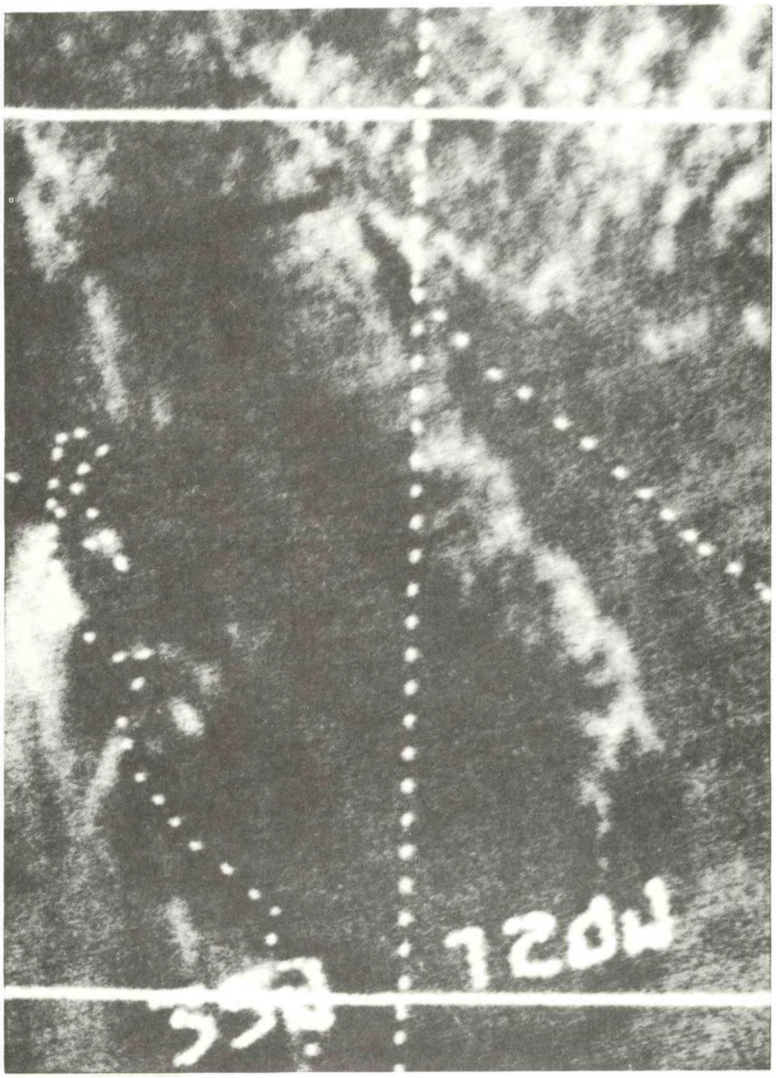


Figure A-11a ESSA-9 photograph of Southern Sierras Region, 25 June 1969. Area for which snow extent mapped is outlined in Figure A-1a.

Figure A-11b Satellite snow extent mapped from Figure A-11a and aerial-survey snow extent for 26 June 1969.

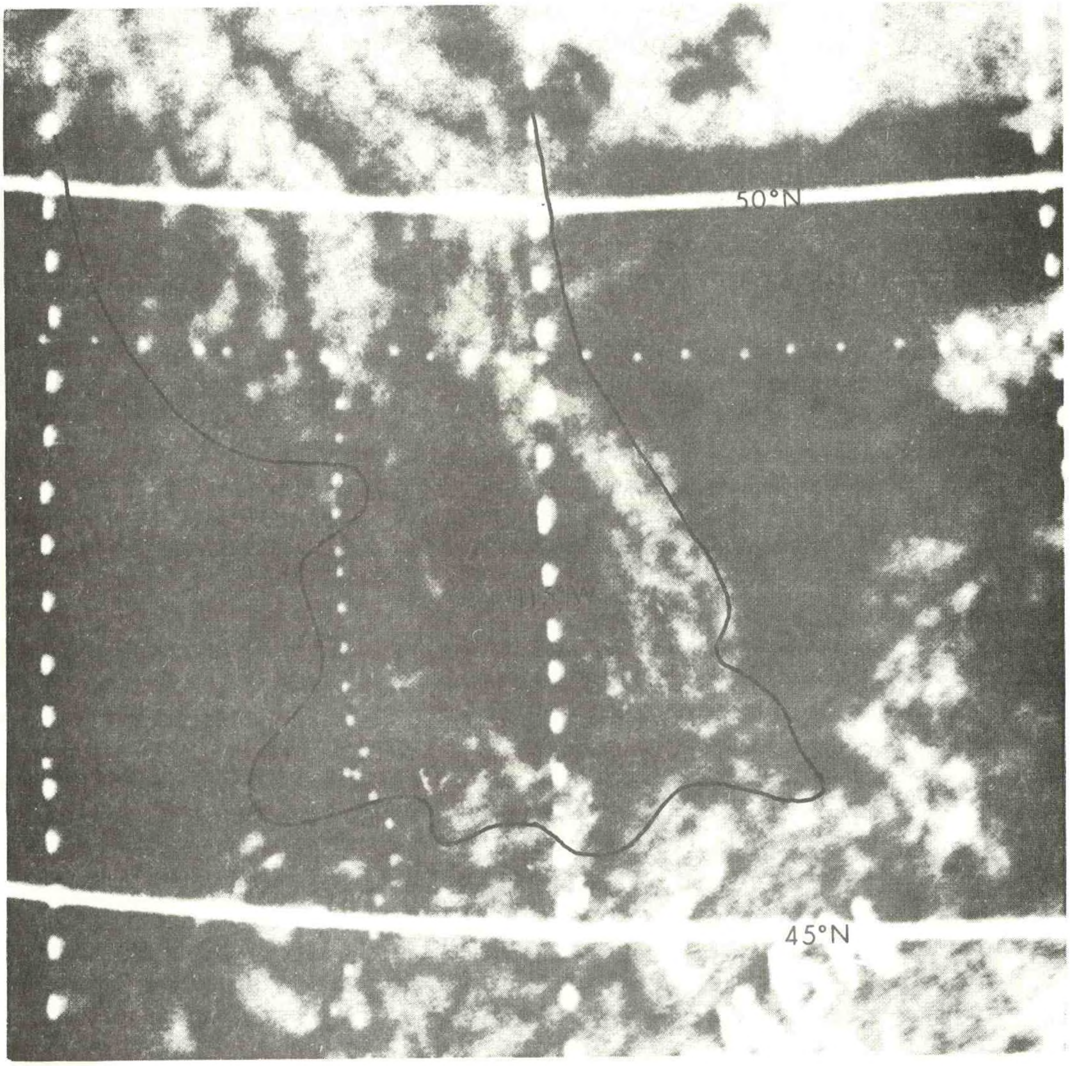


Figure A-12a ESSA-3 photograph of Upper Columbia Basin Region, 7 April 1967. Area for which snow extent mapped is outlined.

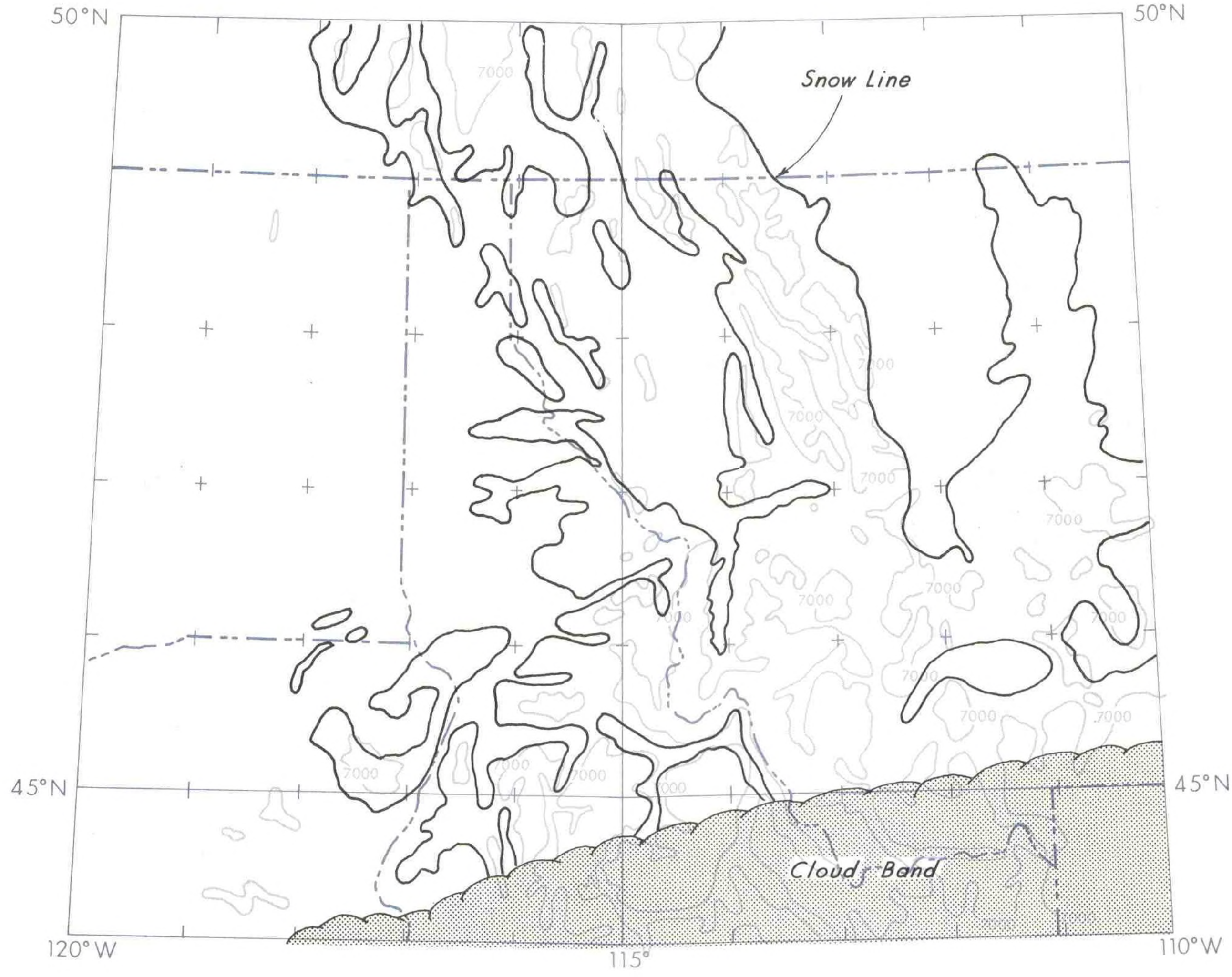


Figure A-12b Satellite snow extent mapped from Figure A-12a.

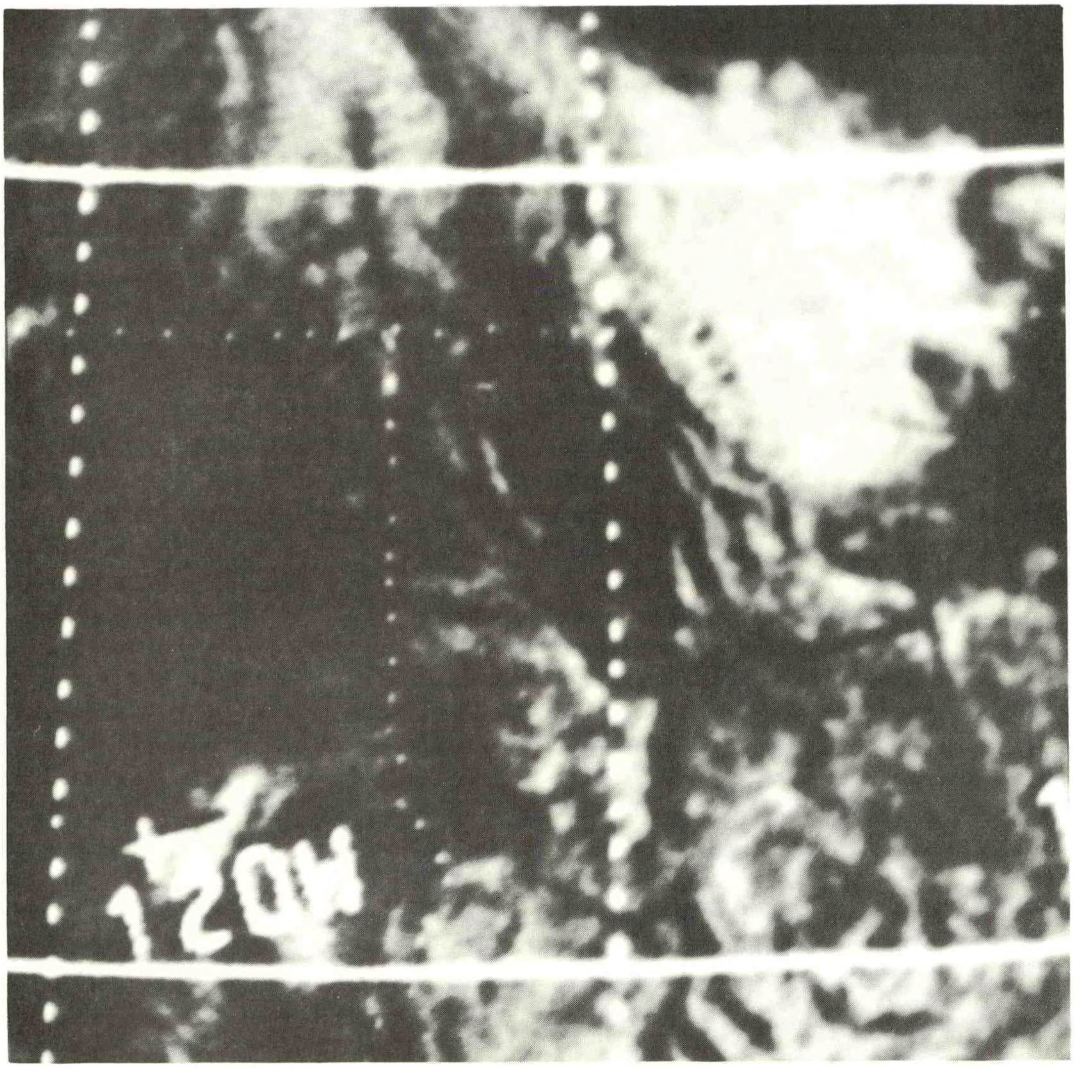


Figure A-13a ESSA-3 photograph of Upper Columbia Basin Region, 13 May 1967. Area for which snow extent mapped is outlined in Figure A-12a.

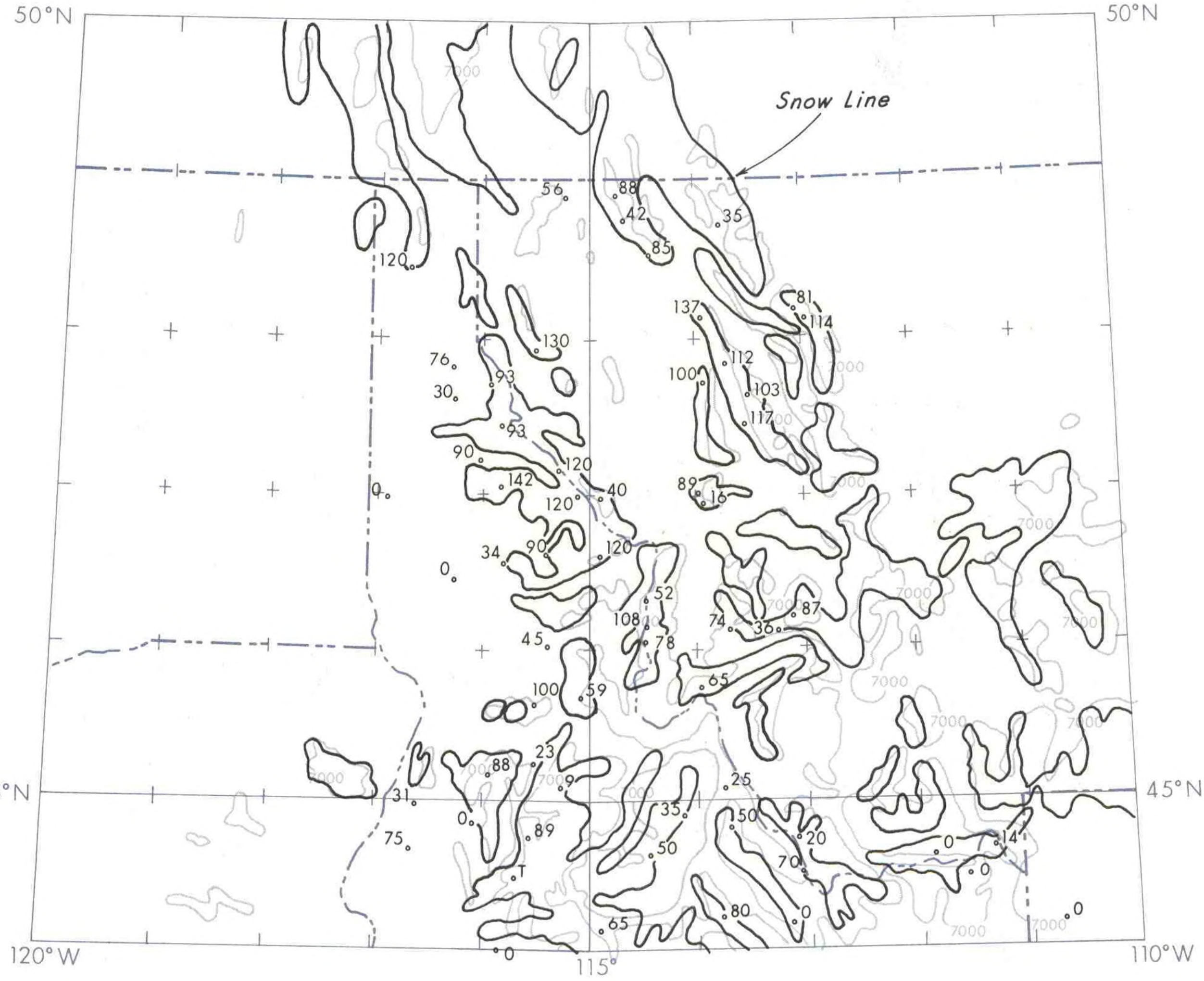


Figure A-13b Satellite snow extent mapped from Figure A-13a. Snow depths measured in early May are in inches.

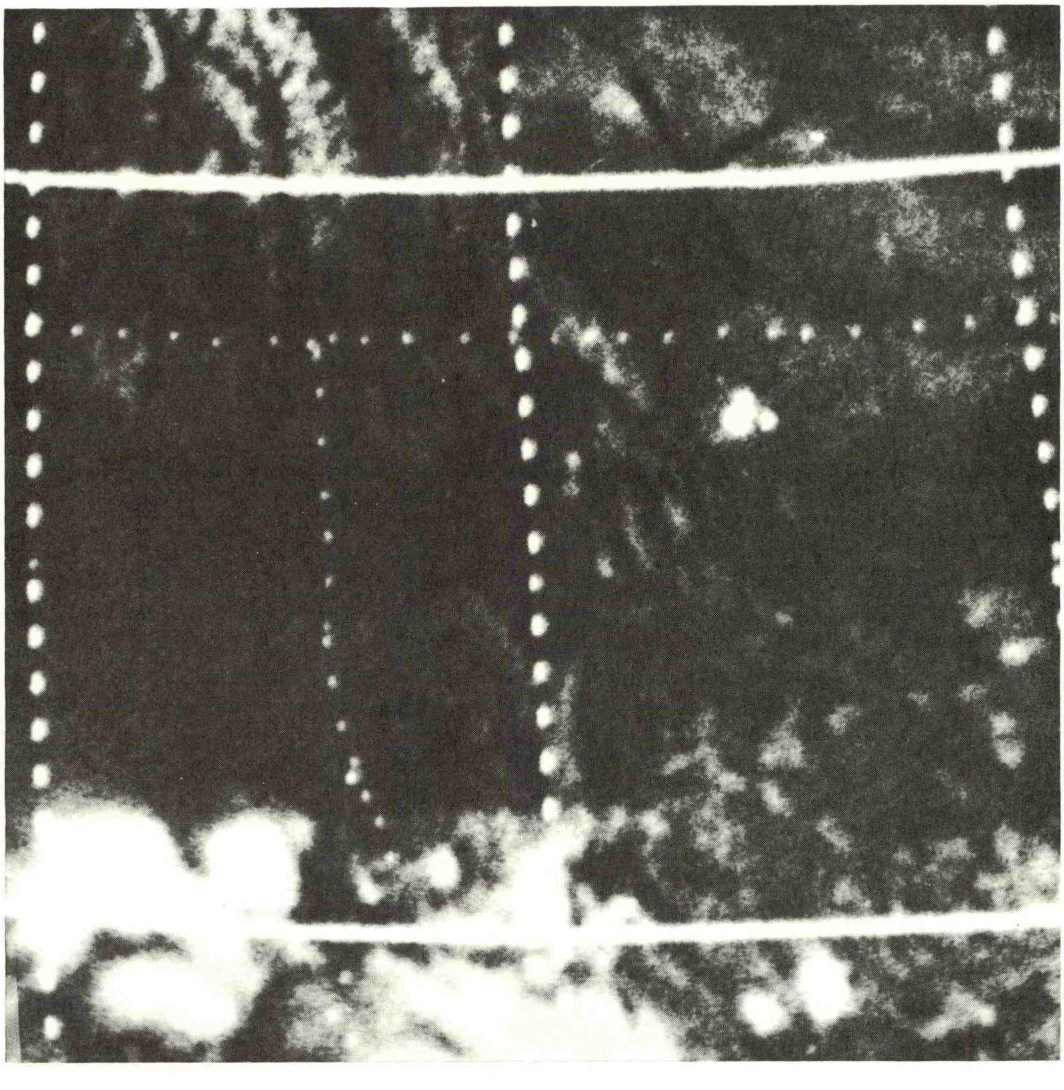


Figure A-14a ESSA-5 photograph of Upper Columbia Basin Region, 19 June 1967. Area for which snow extent mapped is outlined in Figure A-12a.

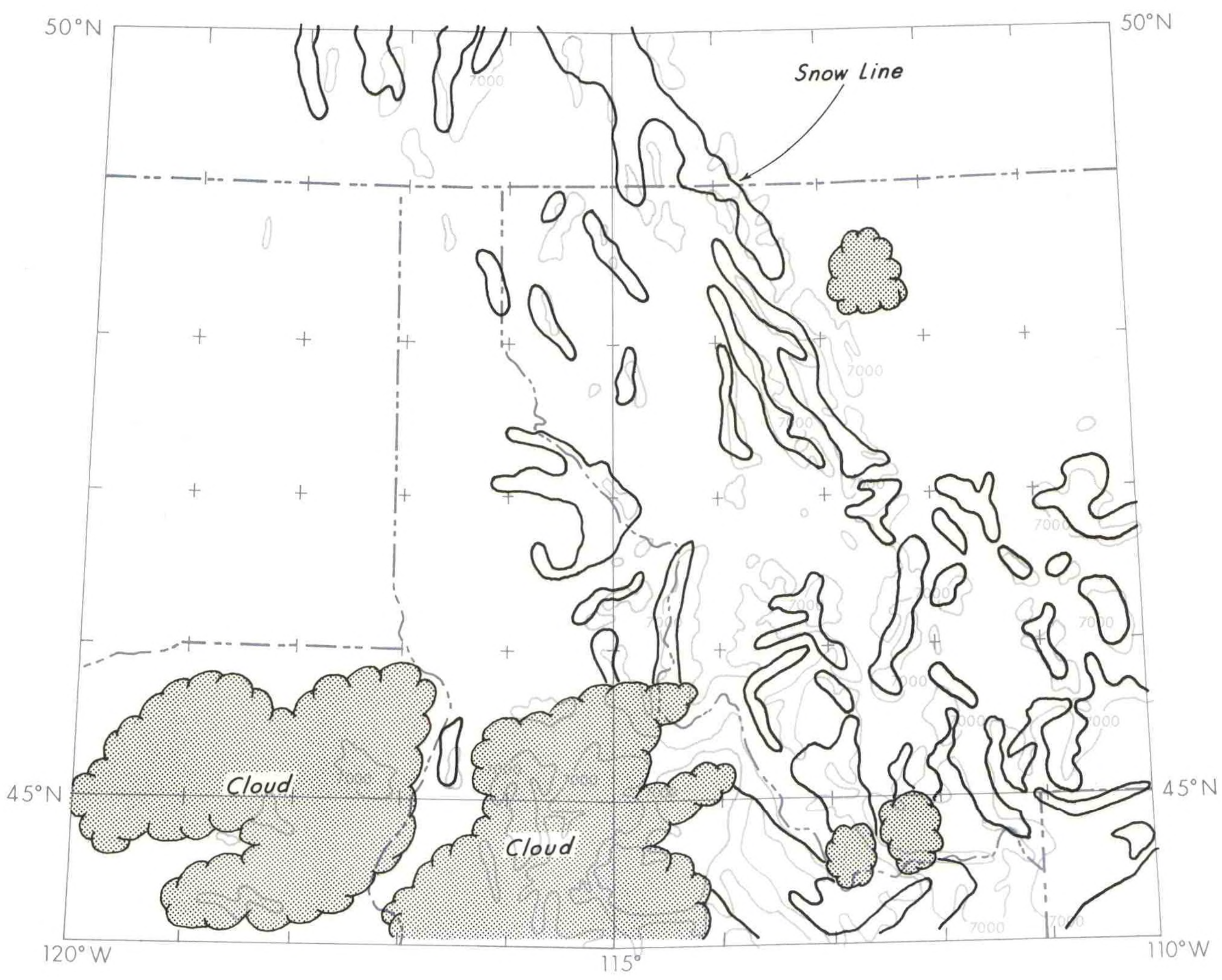


Figure A-14b Satellite snow extent mapped from Figure A-14a.

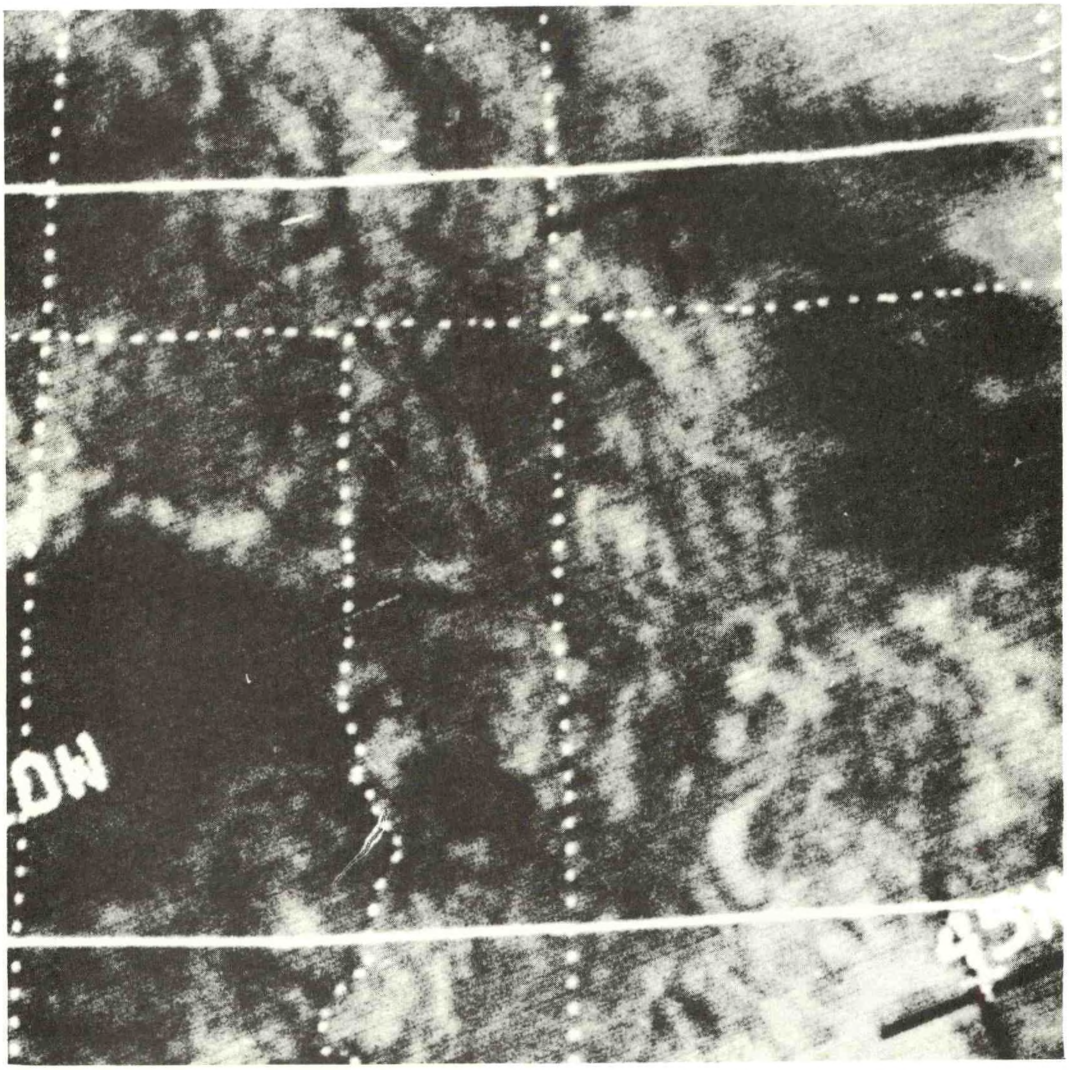


Figure A-15a ESSA-7 photograph of Upper Columbia Basin Region, 25 March 1969. Area for which snow extent mapped is outlined in Figure A-12a.

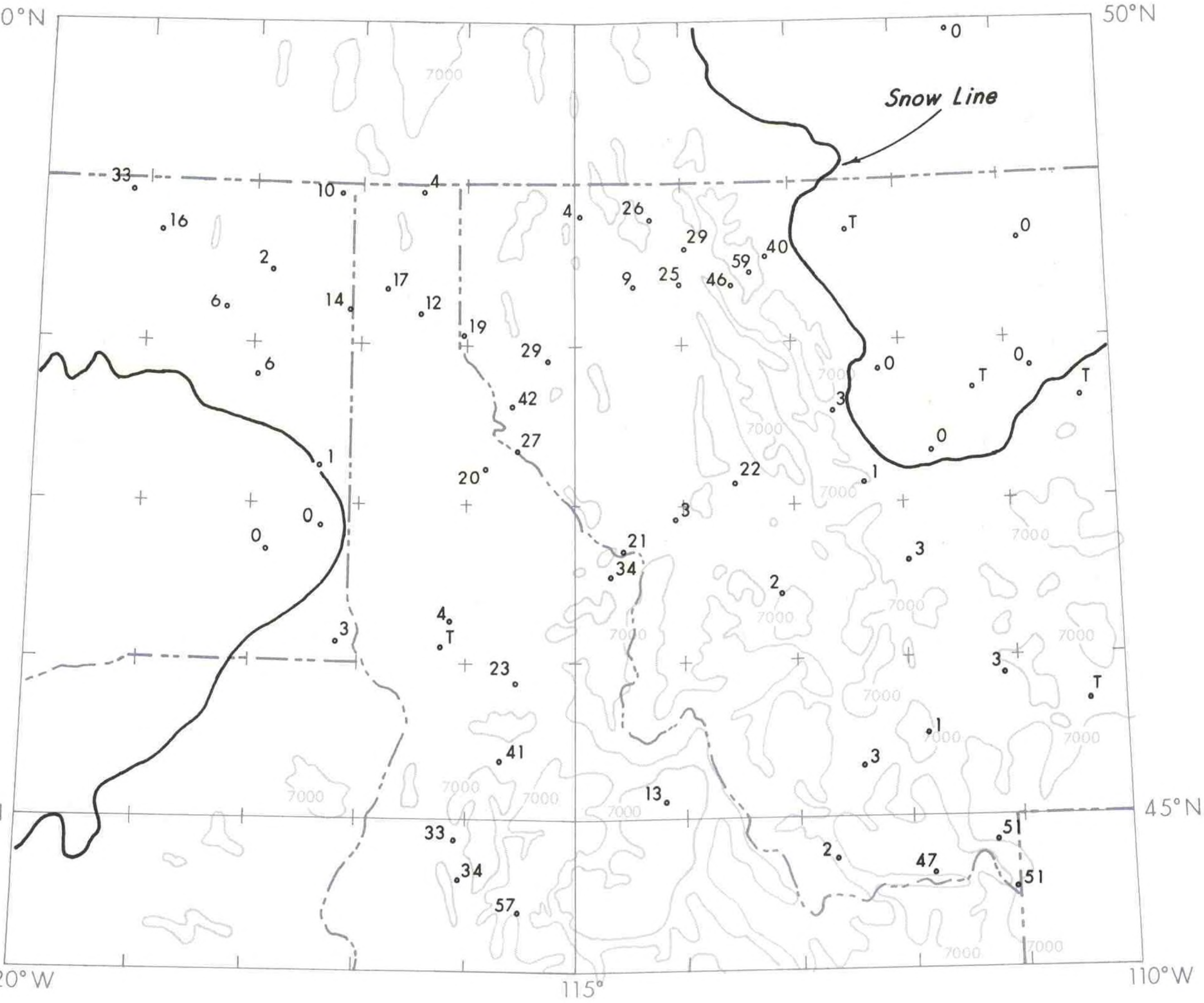


Figure A-15b Satellite snow extent mapped from Figure A-15a. Snow depths measured about 1 April are in inches.

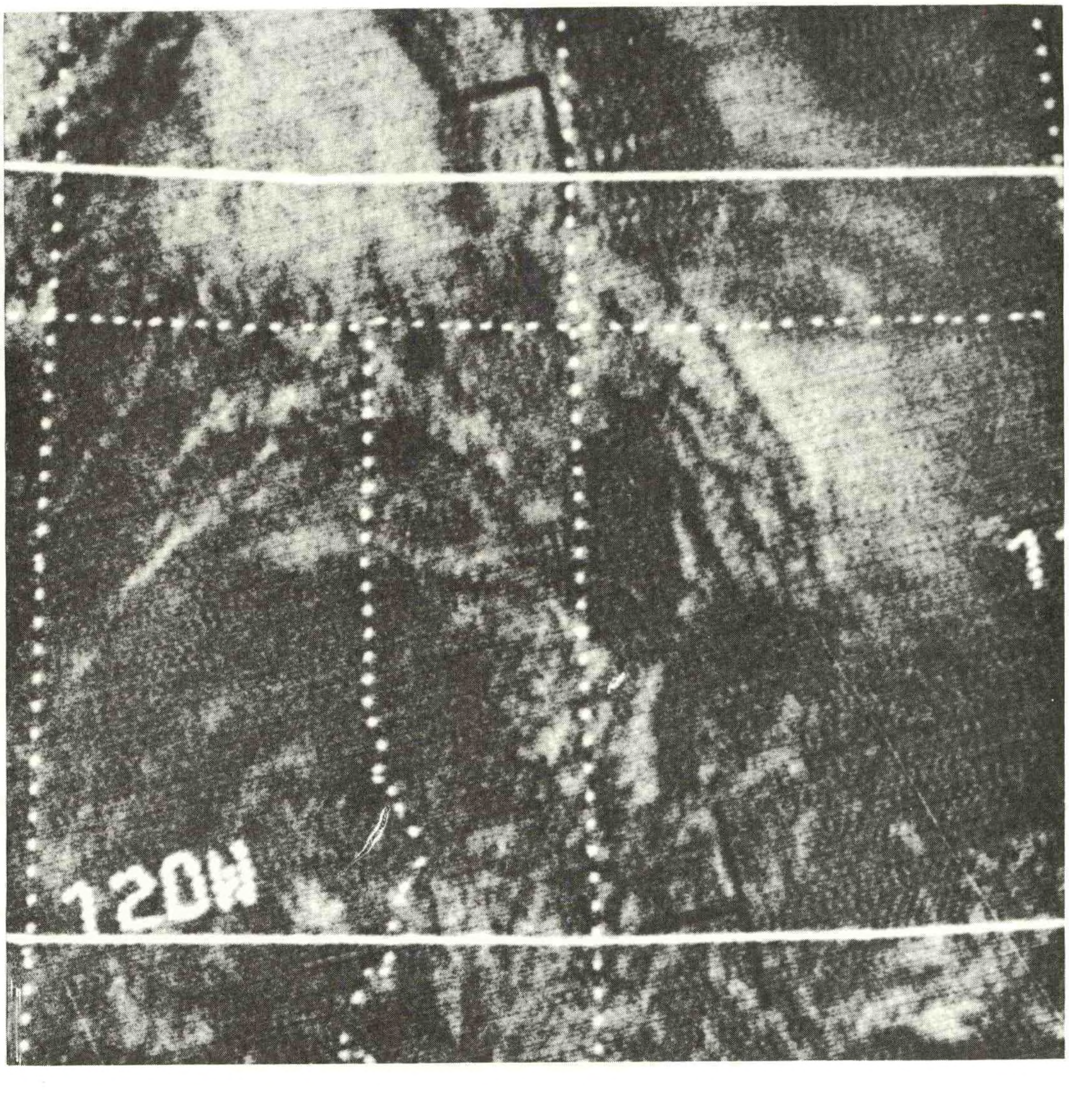


Figure A-16a ESSA-9 photograph of Upper Columbia Basin Region, 21 April 1969. Area for which snow extent mapped is outlined in Figure A-12a.

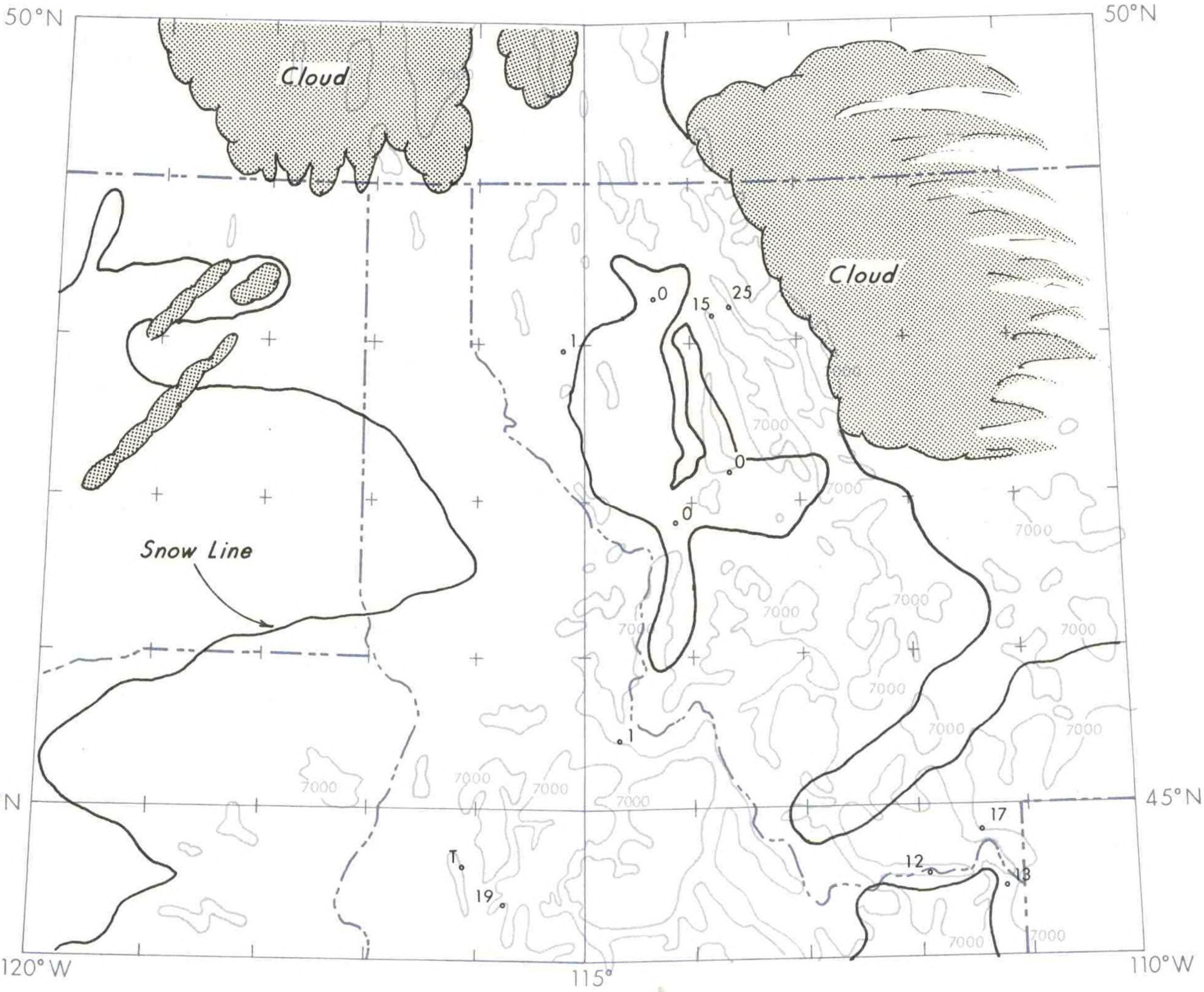


Figure A-16b Satellite snow extent mapped from Figure A-16a. Snow depths measured on 21 April are in inches.

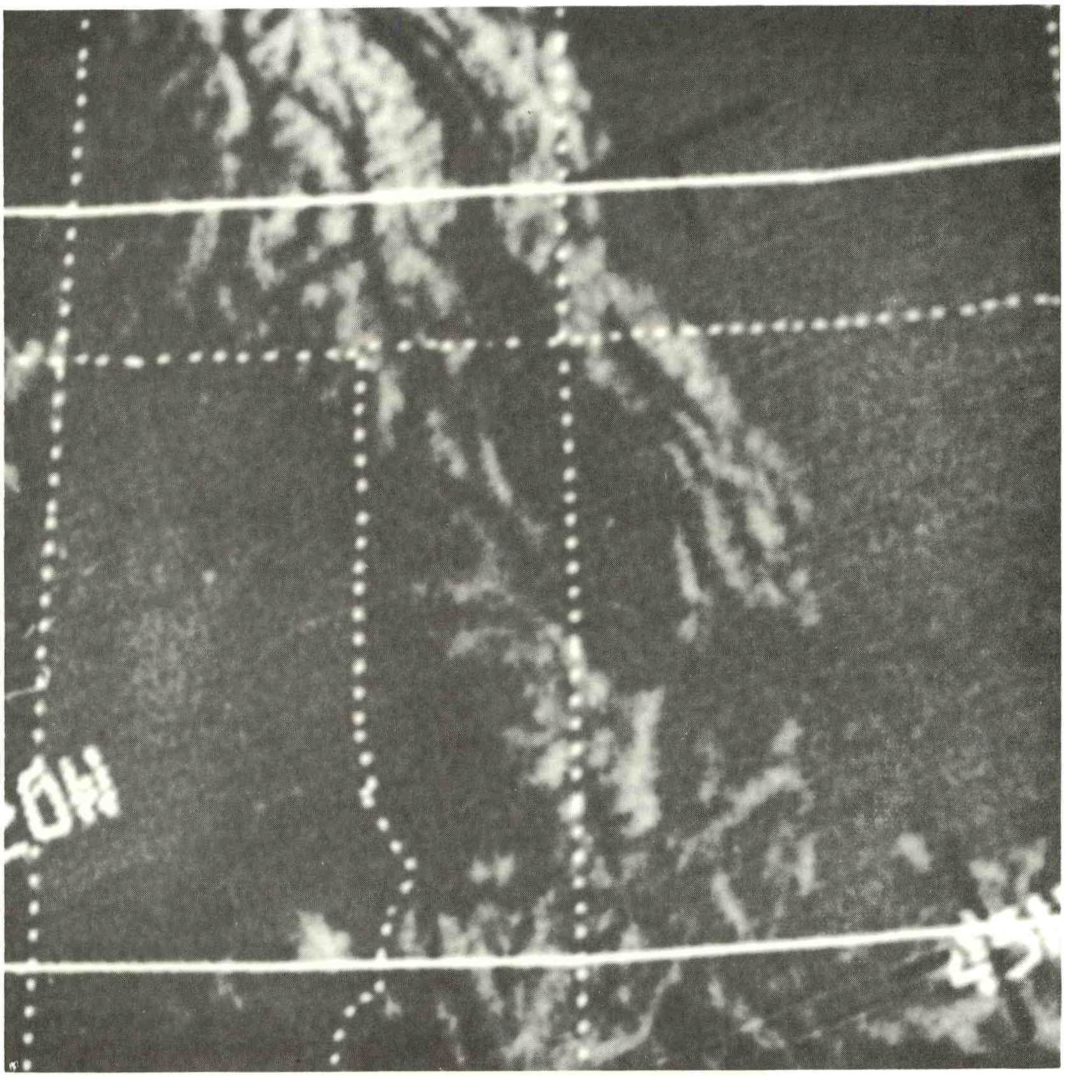


Figure A-17a ESSA-9 photograph of Upper Columbia Basin Region, 6 May 1969. Area for which snow extent mapped is outlined in Figure A-12a.

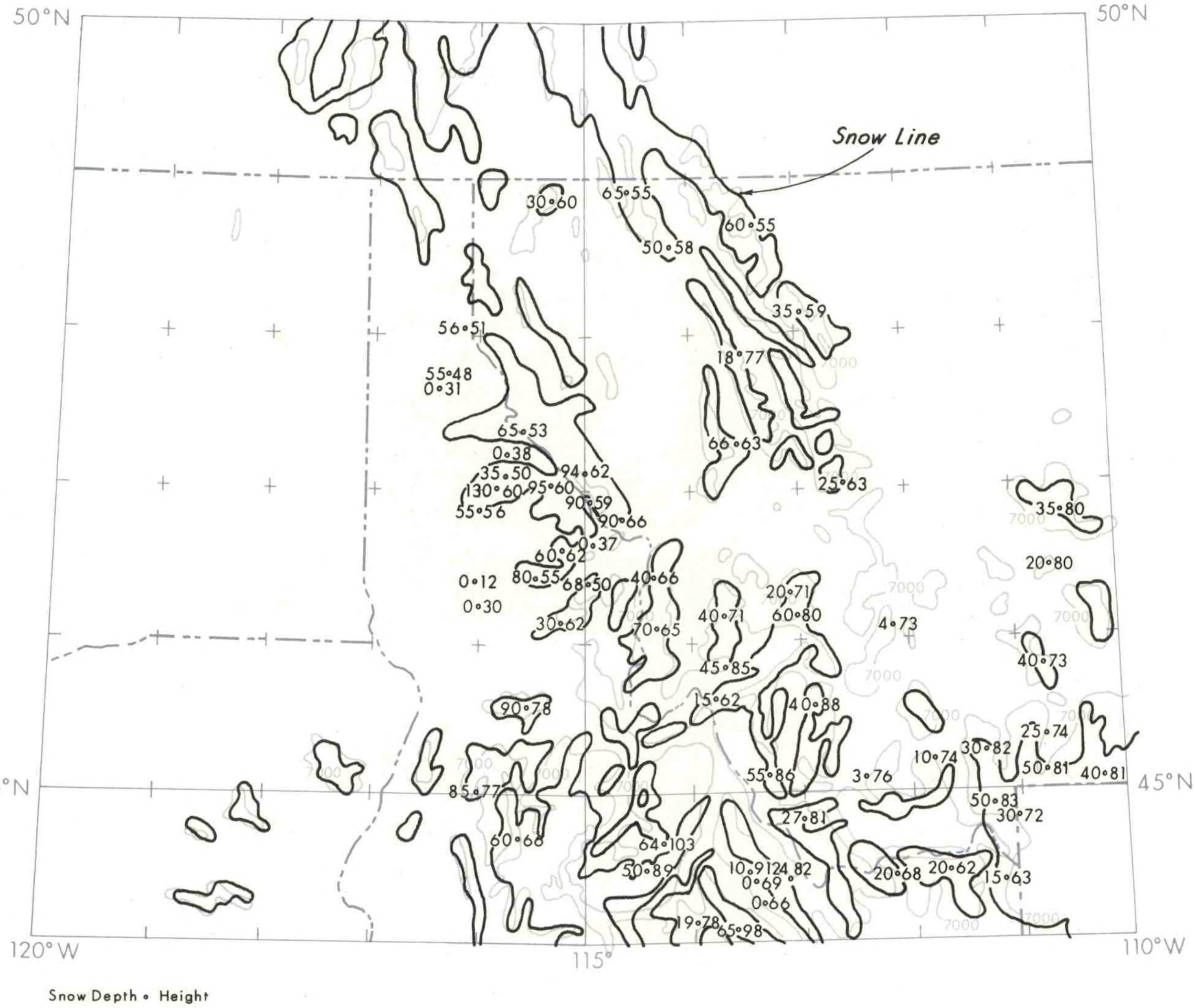


Figure A-17b Satellite snow extent mapped from Figure A-17a. Snow depths measured in early May are in inches; heights of stations are in hundreds of feet.

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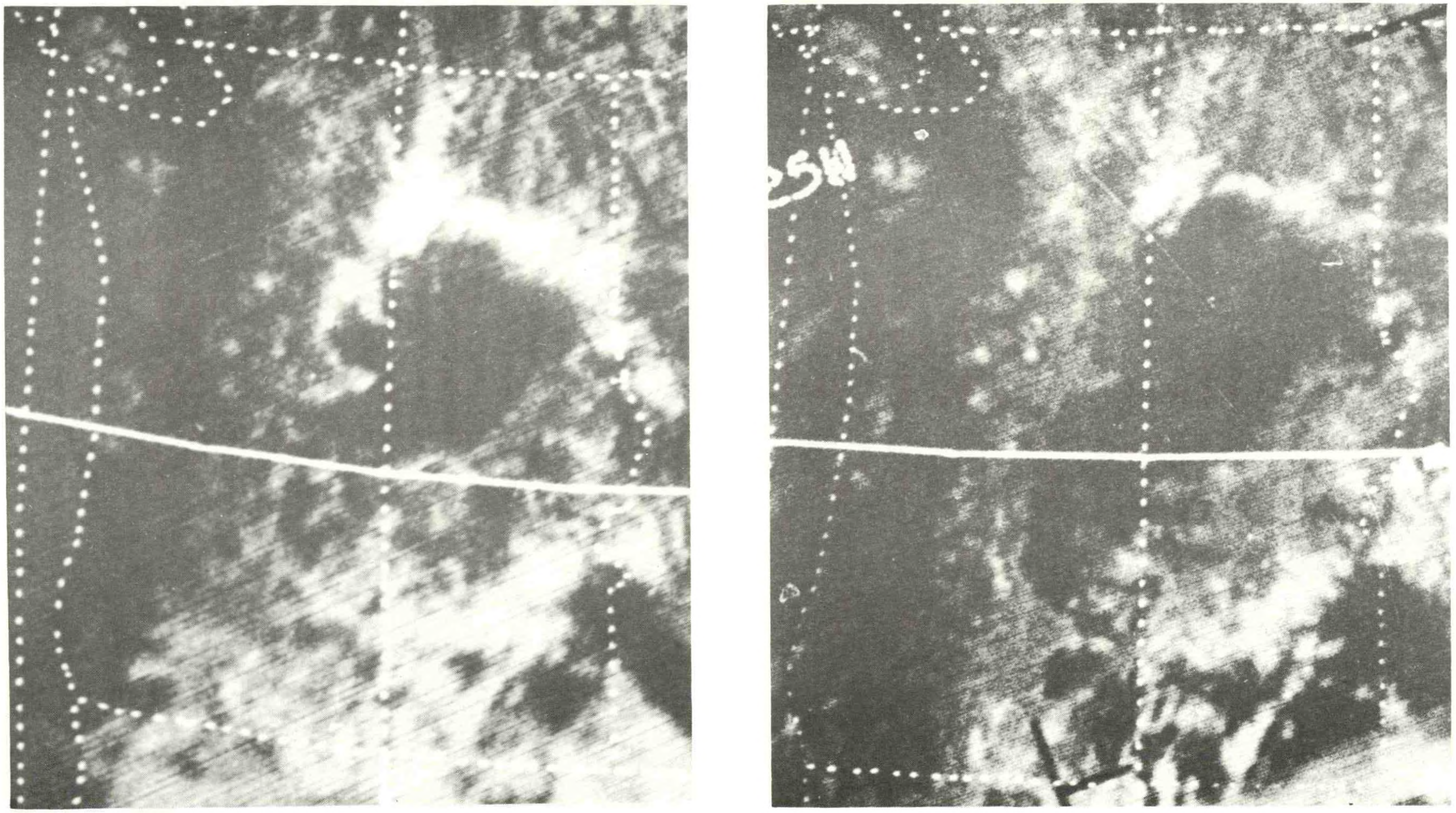
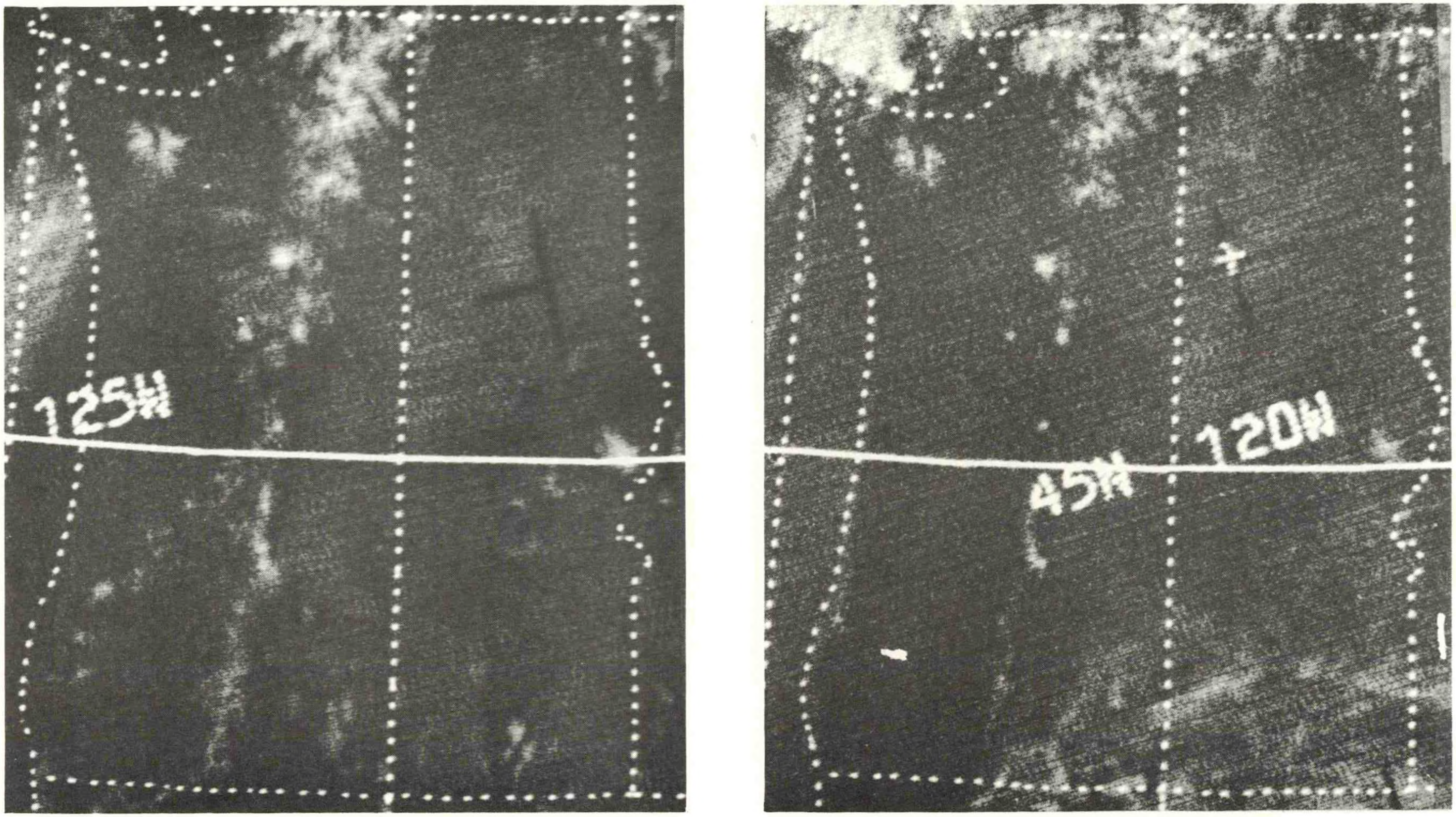


12 March 1969

21 March 1969

Figure A-18 ESSA-7 photographs of Lower Columbia Basin Region, 12 and 21 March 1969.



5 May 1969

1 June 1969

Figure A-19 ESSA-9 photographs of Lower Columbia Basin Region, 5 May and 1 June 1969.

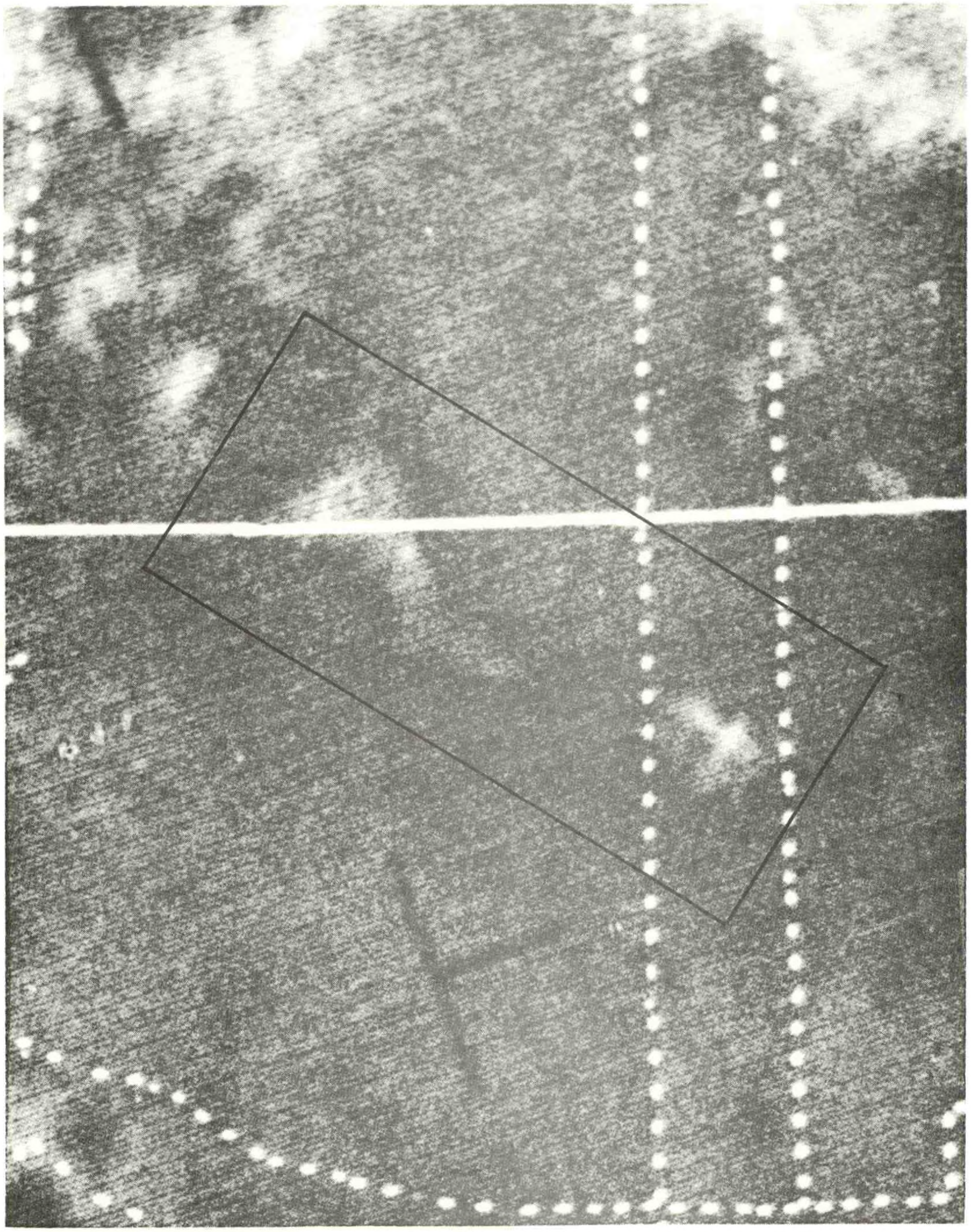
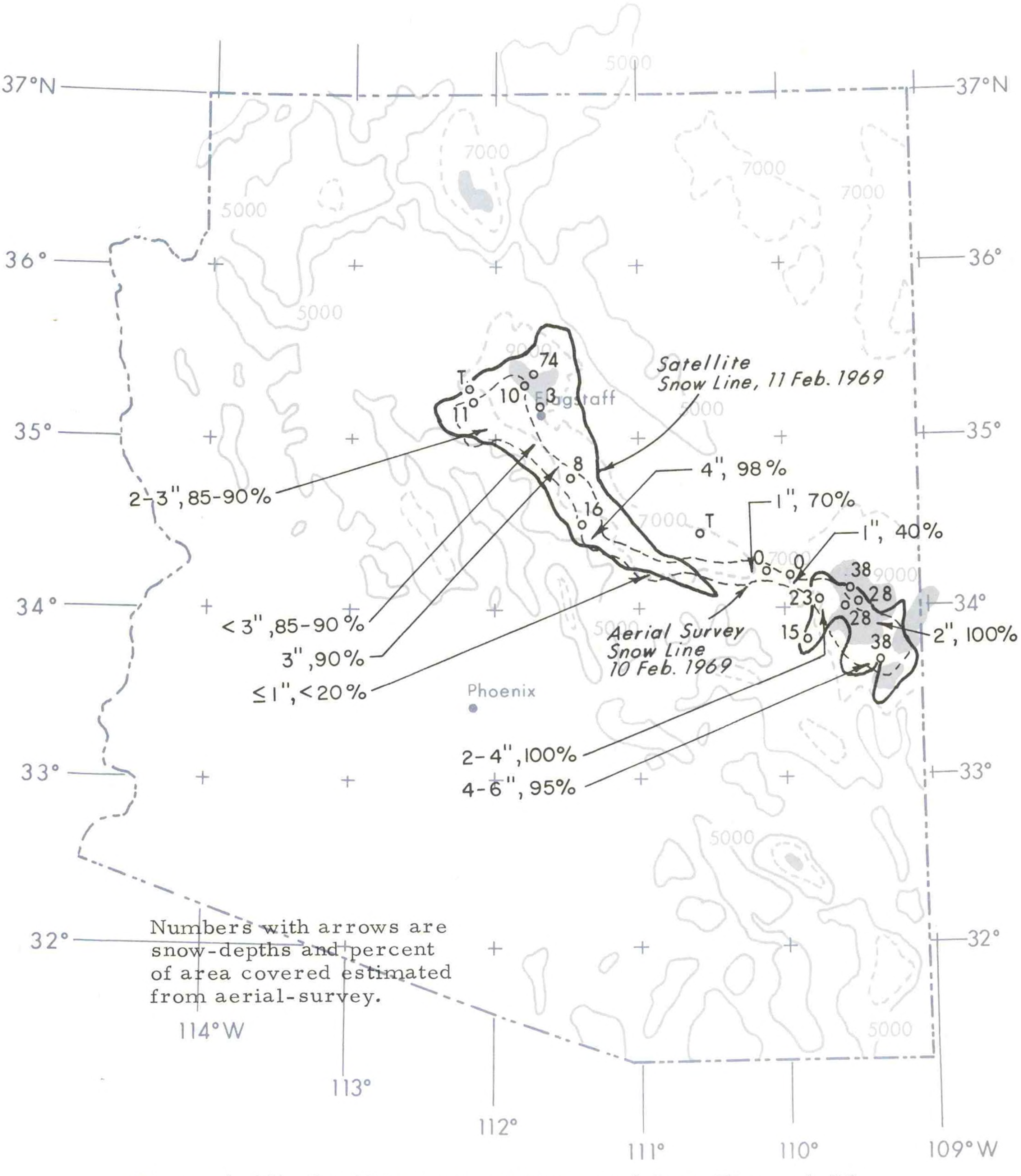


Figure A-20a ESSA-7 photograph of Arizona, 11 February 1969. Area for which snow extent mapped is outlined.



Numbers with arrows are snow-depths and percent of area covered estimated from aerial-survey.

Figure A-20b Satellite snow extent mapped from Figure A-20a and aerial-survey snow data for Salt River Project Area, 10 February 1969. Snow depths in inches for 11 February (from climatological reports) also given.

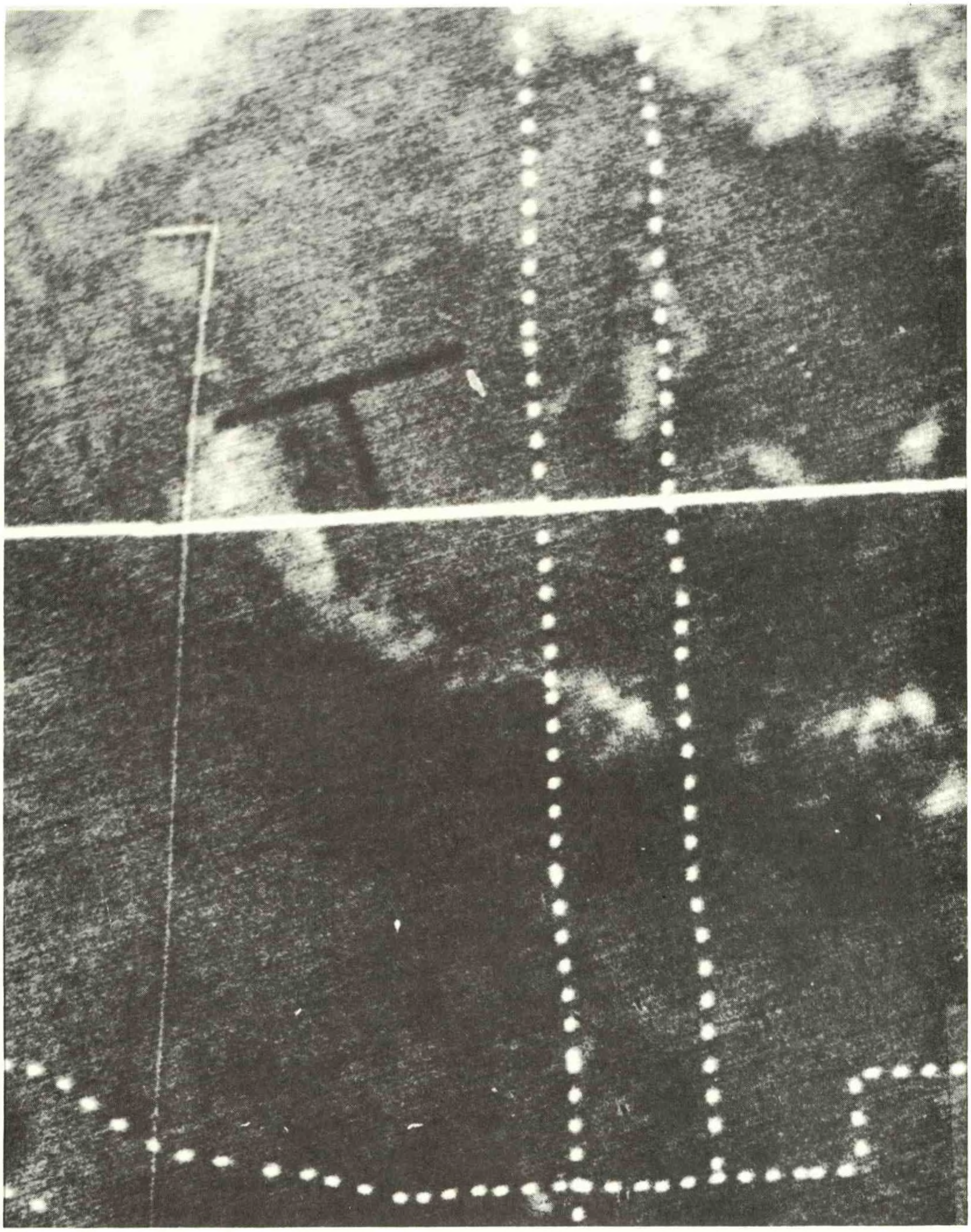
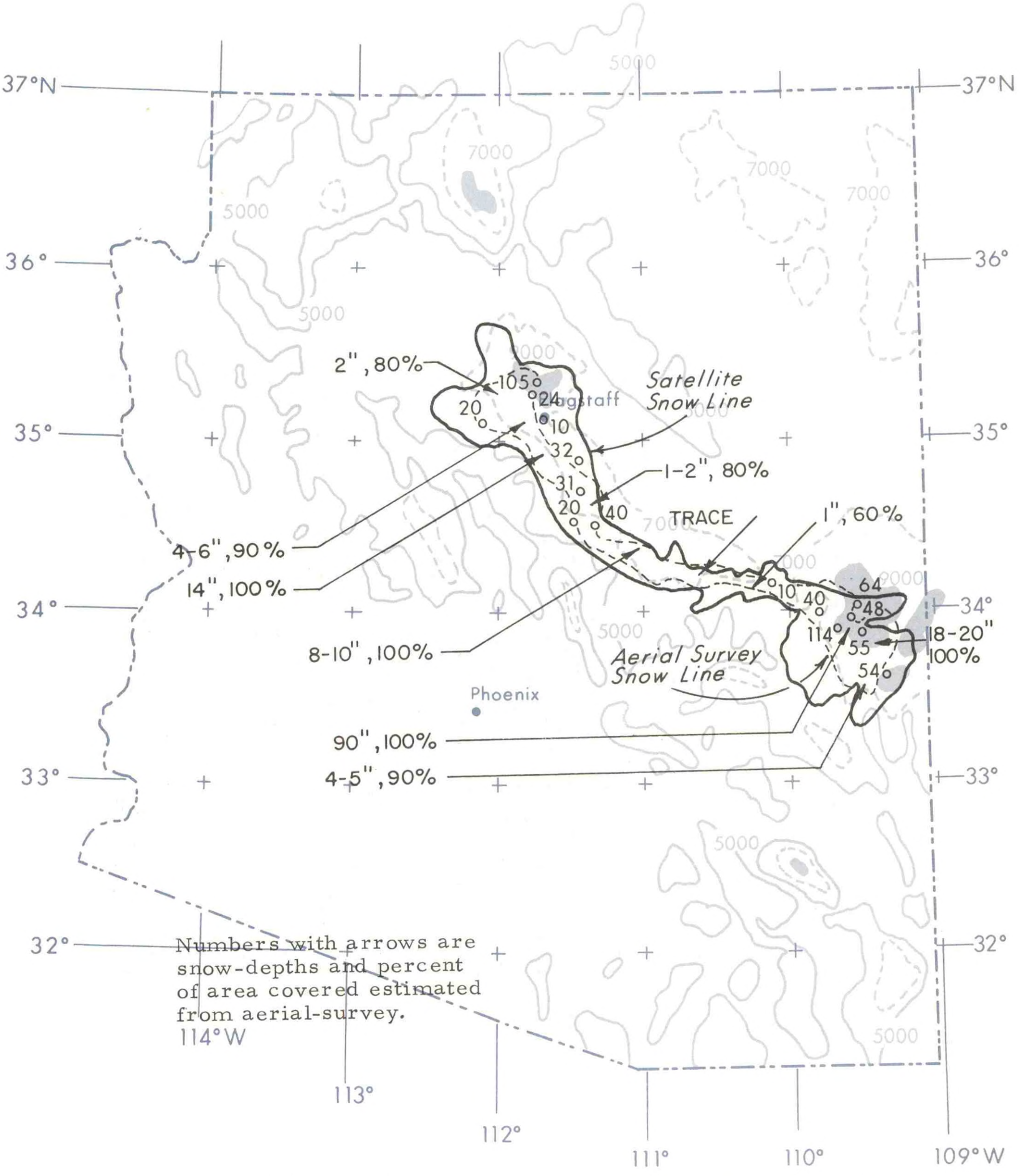


Figure A-21a ESSA-7 photograph of Arizona, 19 March 1969. Area for which snow extent mapped is outlined in Figure A-20a.



Numbers with arrows are snow-depths and percent of area covered estimated from aerial-survey.

Figure A-21b Satellite snow extent mapped from Figure A-21a and aerial-survey snow data for Salt River Project Area, 19 March 1969. Snow depths in inches for 19 March (from climatological reports) also given.

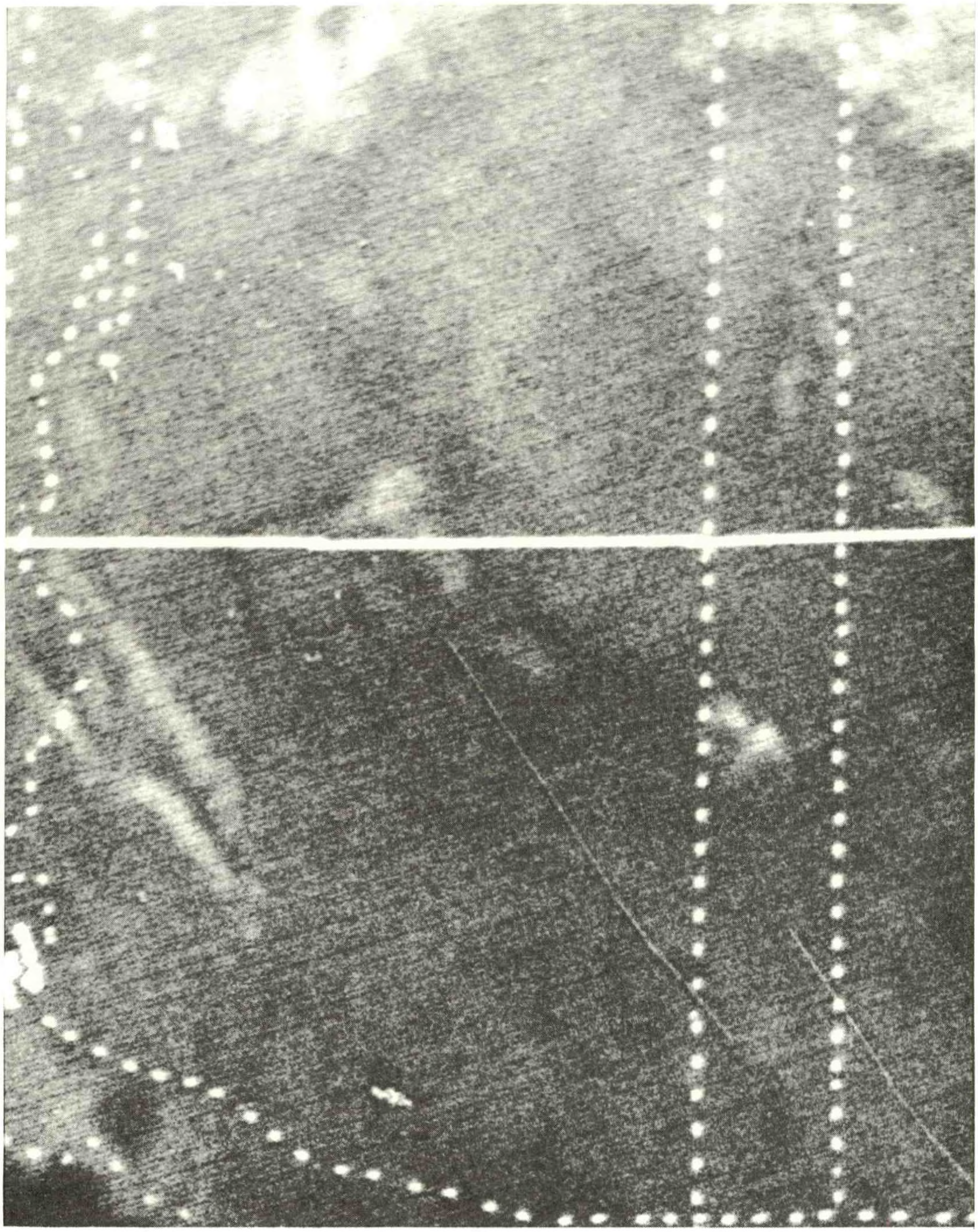
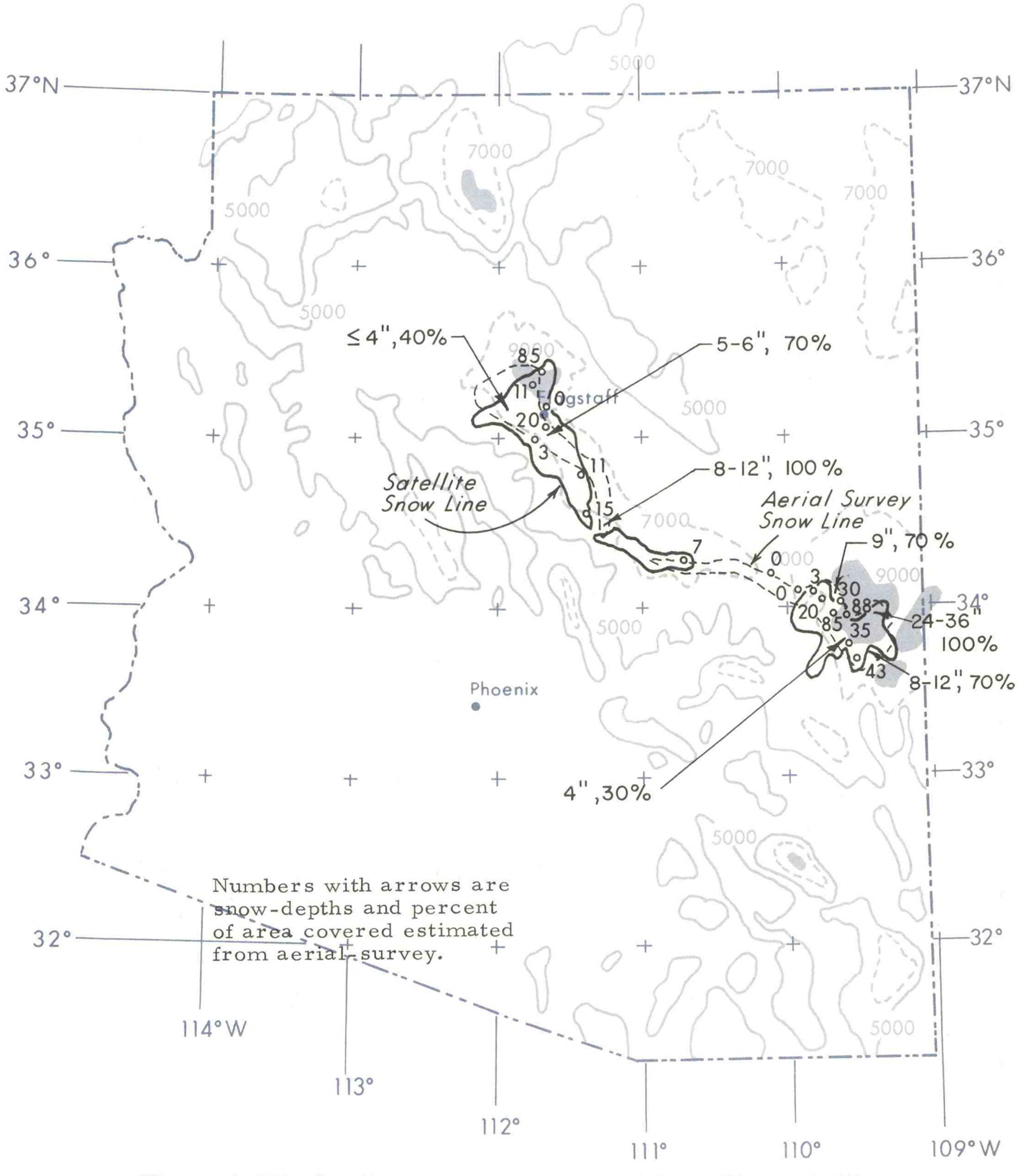


Figure A-22a ESSA-7 photograph of Arizona, 27 March 1969. Area for which snow extent mapped is outlined in Figure A-20a.



Numbers with arrows are snow-depths and percent of area covered estimated from aerial-survey.

Figure A-22b Satellite snow extent mapped from Figure A-22a and aerial-survey snow data for Salt River Project Area, 2 April 1969. Snow depths in inches for 27 March (from climatological reports) also given.

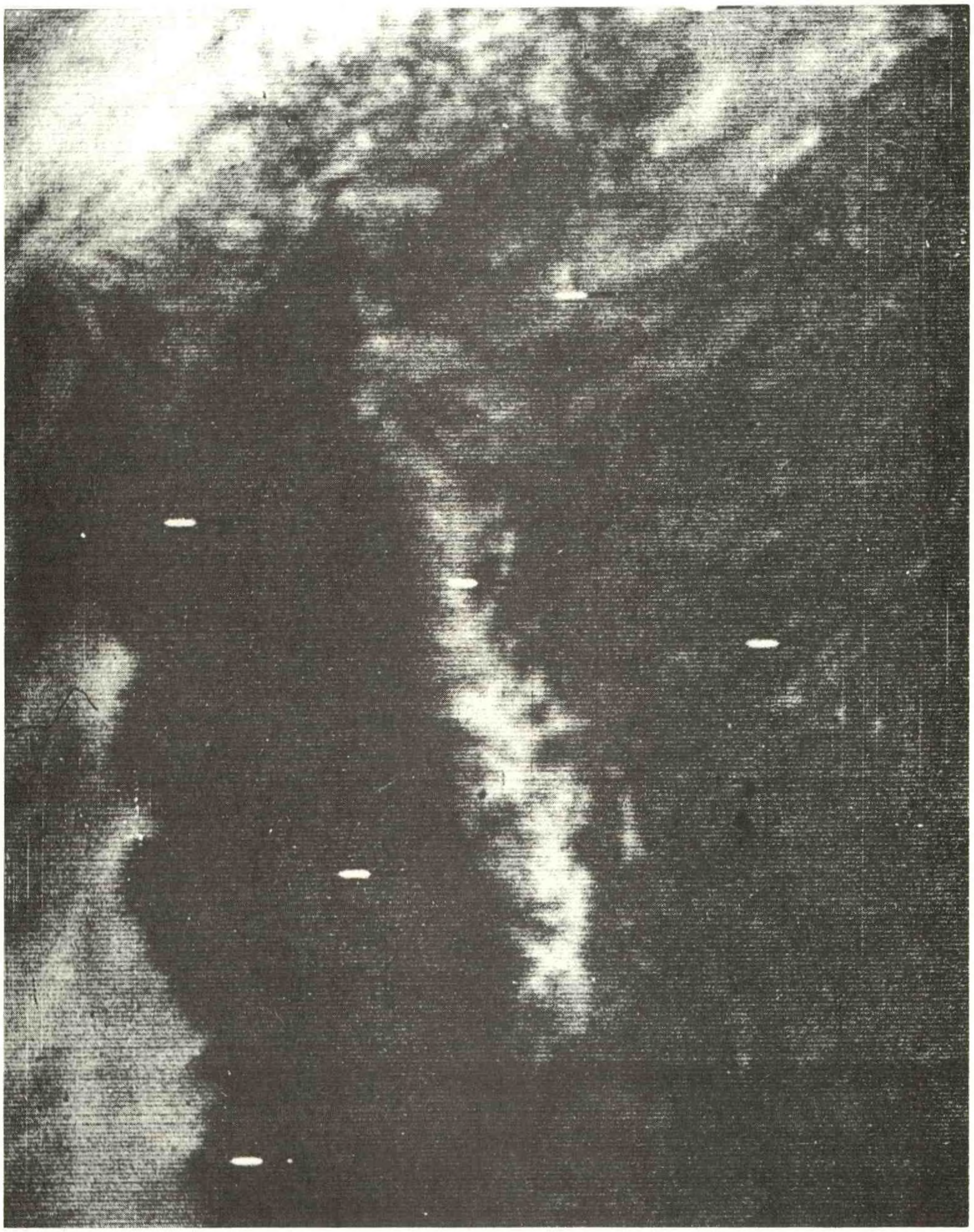


Figure A-23 Nimbus III IDCS photograph of Sierras, 28 April 1969.

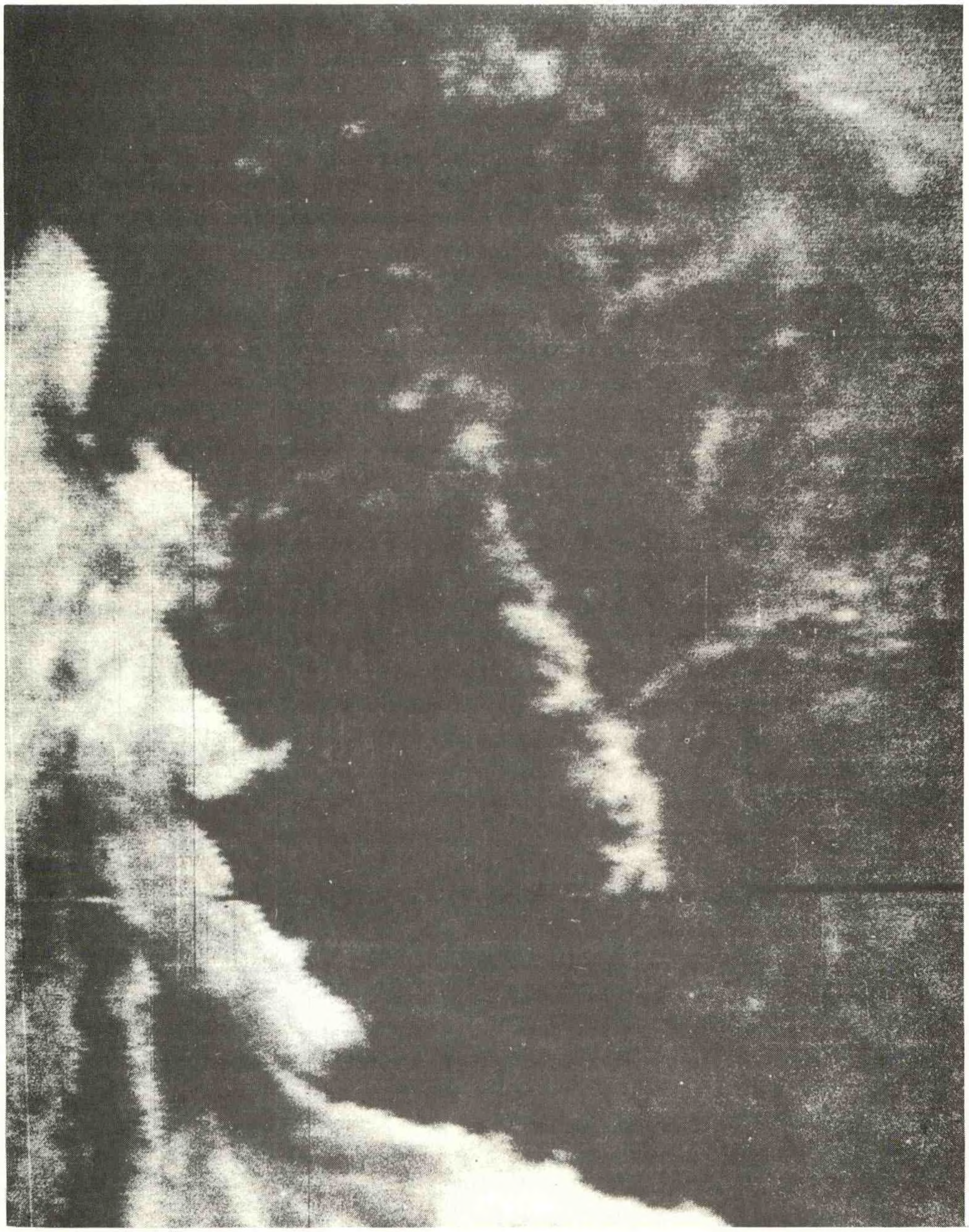


Figure A-24 Nimbus III IDCS photograph of Sierras, 1 June 1969.

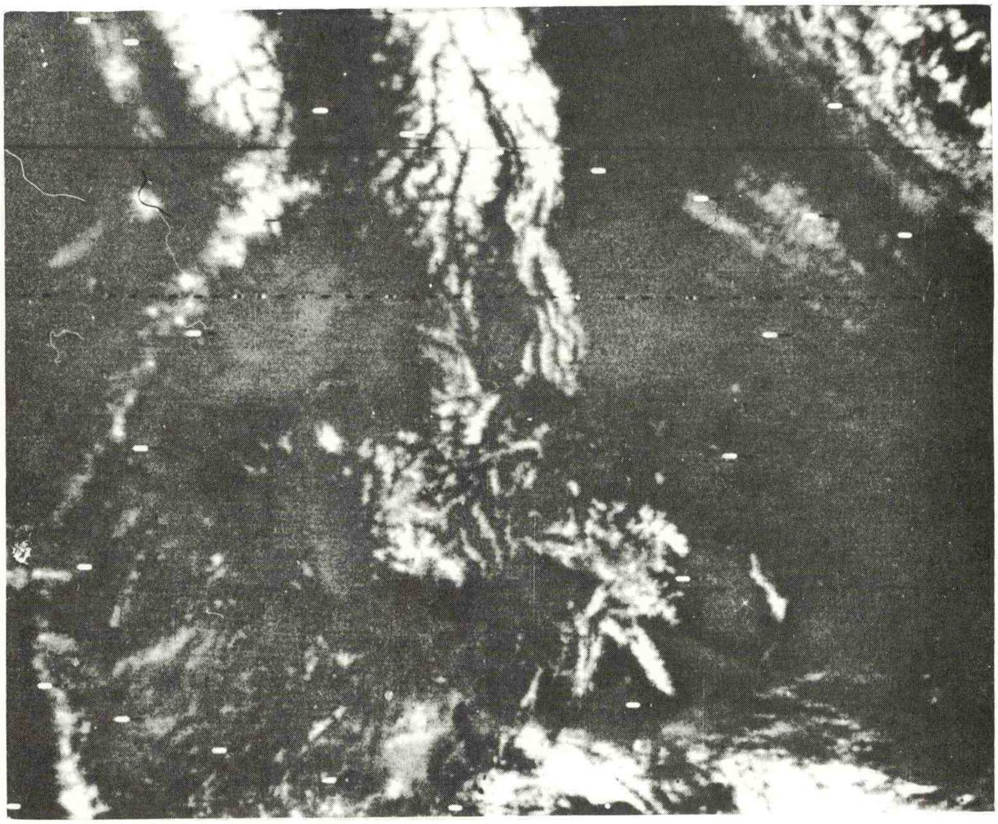


Figure A-25 Nimbus III IDCS photograph showing Upper and Lower Columbia Basin Regions, 6 May 1969.

Figure A-26 Nimbus III Daytime HRIR film strip showing the western United States, 30 April 1969.

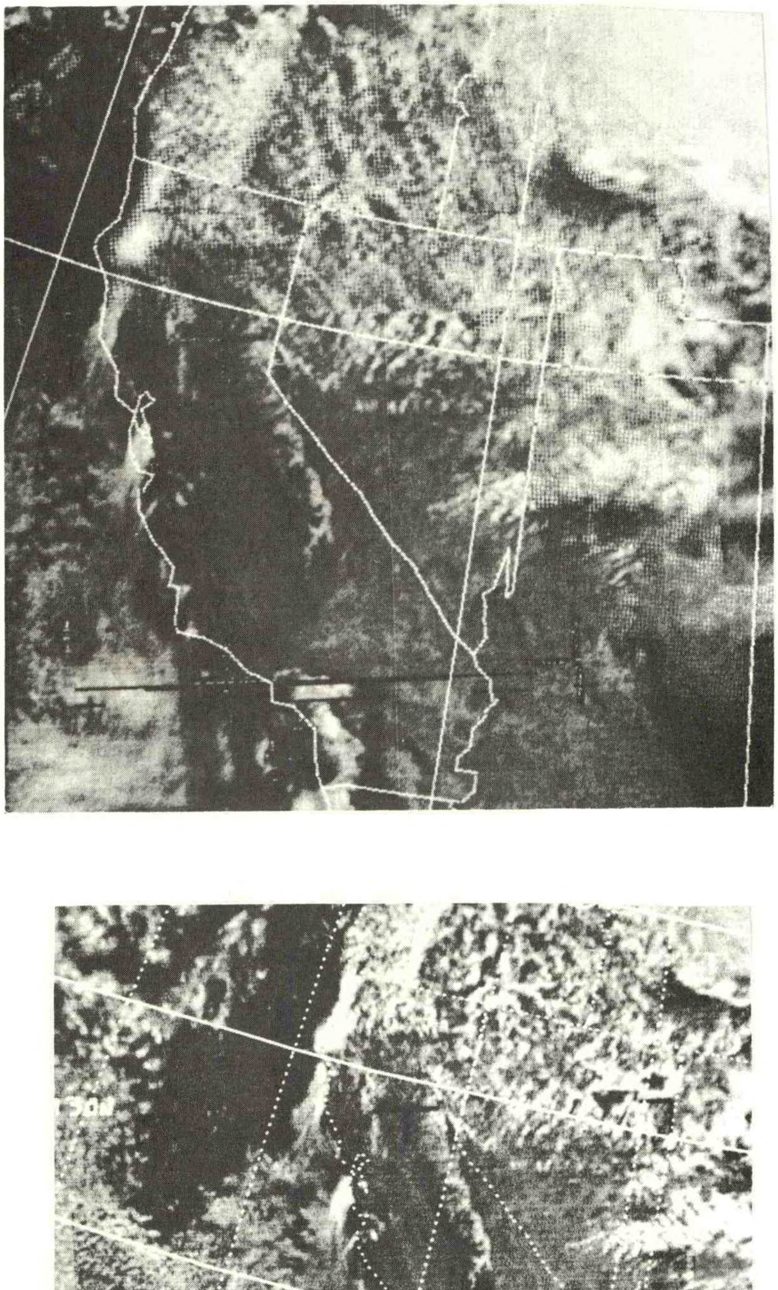


Figure A-27 ESSA-9 Augmented Resolution Chip (above) and original photograph (below) for 25 June 1969.

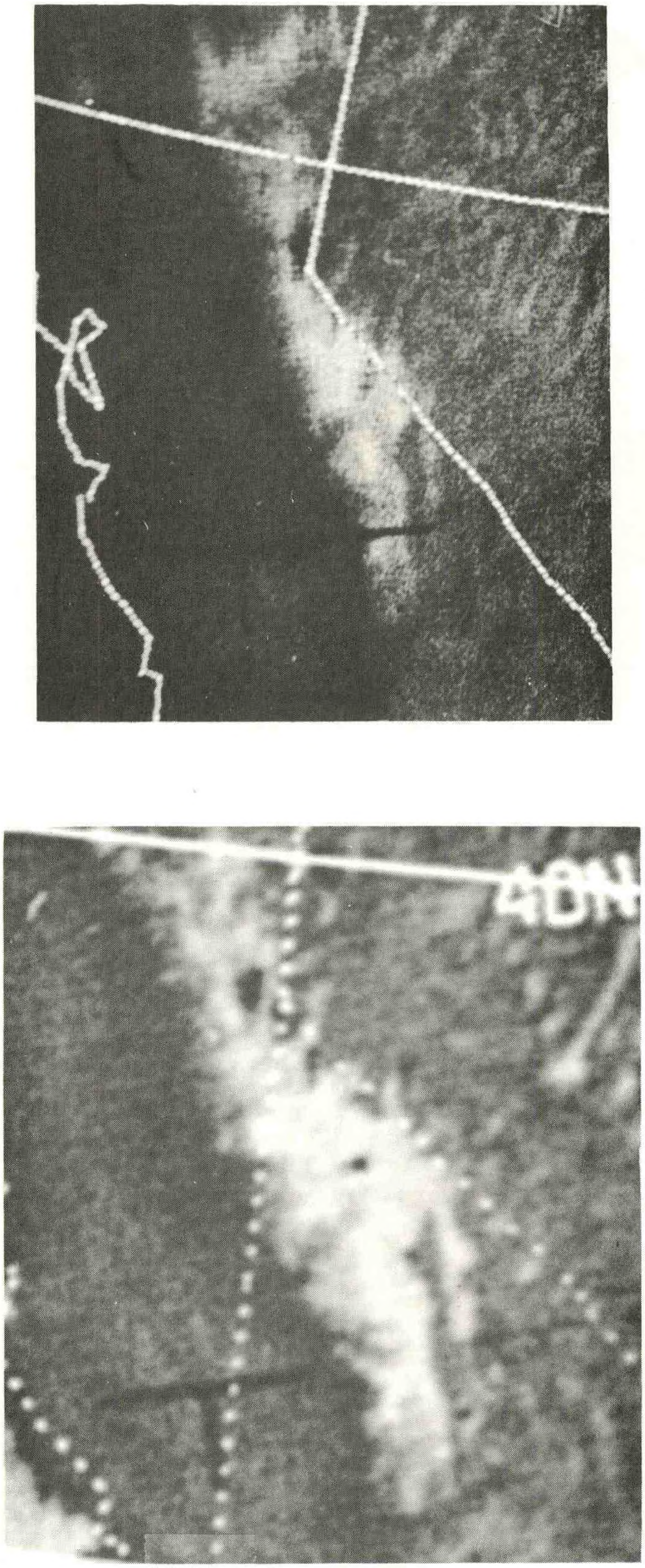


Figure A-28 Five-Day Composite Minimum Brightness Chart of Sierras, 26-30 March 1969 (above) and ESSA-7 photograph for 28 March 1969 (below).