SUSITNA HYDROELECTRIC PROJECT

GLACIER STUDIES

DECEMBER 1981

GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA

Prepared by:
R&M CONSULTANTS, INC.

Prepared for:
ACRES

ALASKA POWER AUTHORITY

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TASK 3 - HYDROLOGY
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SUSITNA HYDROELECTRIC PROJECT

GLACIER STUDIES - 1981

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I - INTRODUCTION

This is the report of the 1981 glacier studies for the proposed Susitna Project, undertaken by R.& M Consultants and University of Alaska. The objective of the glacier studies program, is to identify any problems peculiar to the existence of glaciers in the Susitna basin. This report goes beyond that objective and includes results from a regional glacier assessment program, sponsored by University of Alaska, that are relevant to the Susitna Project. The U of A project received logistical support from the Susitna Project, except for one high altitude snow survey conducted out of Fairbanks.

Although the effect of glaciers on hydroelectric power development is relatively well-studied in some parts of the world, notably in Norway and Switzerland, our experience in North America is still somewhat limited (Tangborn, 1980). Nevertheless, it is clear that the importance of glaciers within a given drainage basin is greater than one might expect by simply considering the proportion of the basin area which is glacierized, for several reasons (see Meier and Tangborn, 1961; Meier, 1969): (a) Precipitation is often extremely high on glaciers and the surrounding high mountain terrain.

(b) Glaciers act as reservoirs that may produce most of the water in a basin in times of drought. More generally, glaciers are subject to large changes in activity and volume that complicate the relationship between precipitation and runoff. Glaciers may undergo large changes in volume during the lifetime of a hydro project.

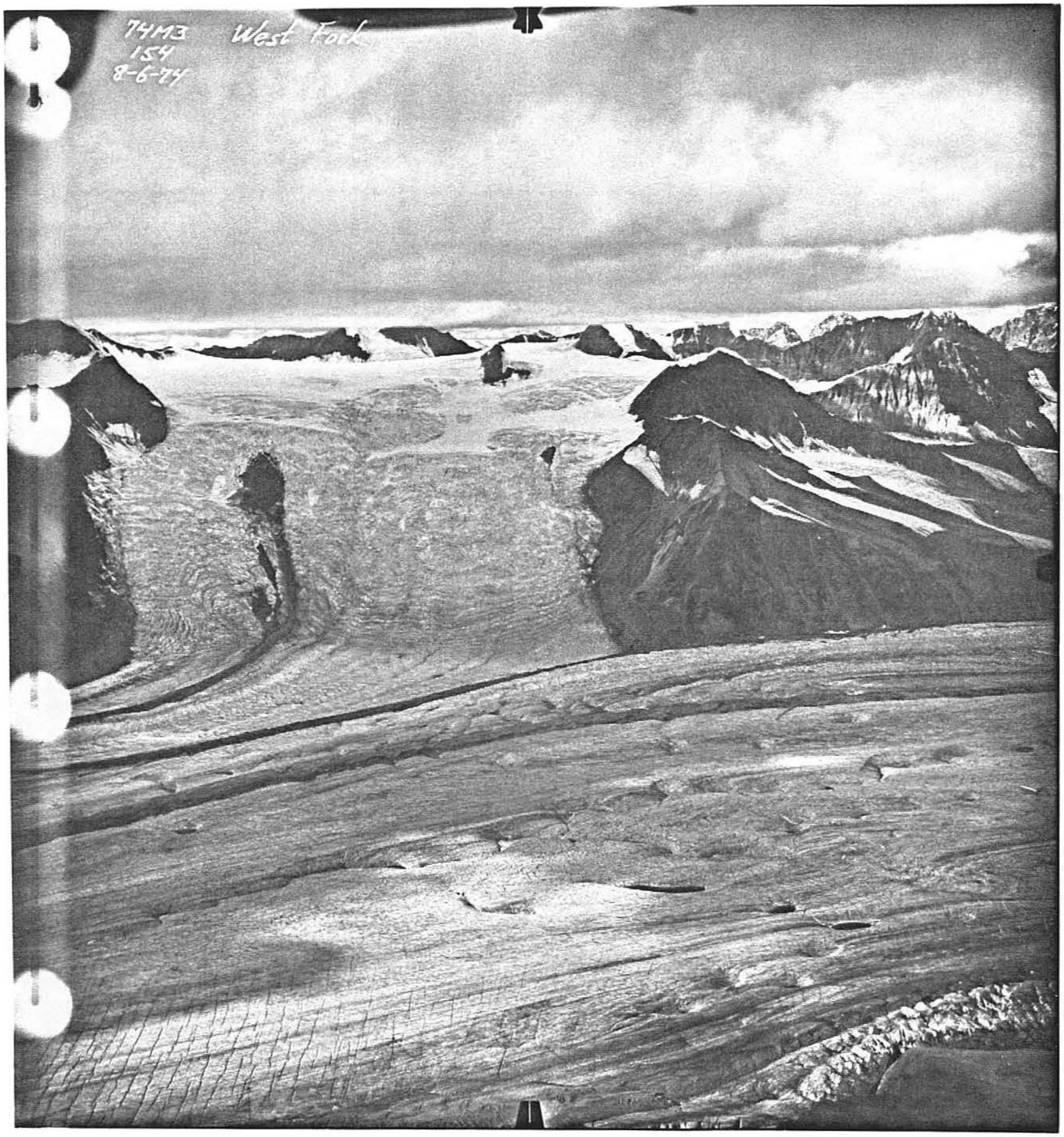
(c) Glaciers are prolific sources of sediment.

(d) Glaciers store or impound water that can be suddenly released, sometimes causing large floods.

(e) Many Alaskan glaciers are subject to periodic catastrophic advances or "surges" that are unrelated to climate and are probably accompanied by significant changes in their hydrologic and sedimentological regimes, and that sometimes these surges cause large floods.

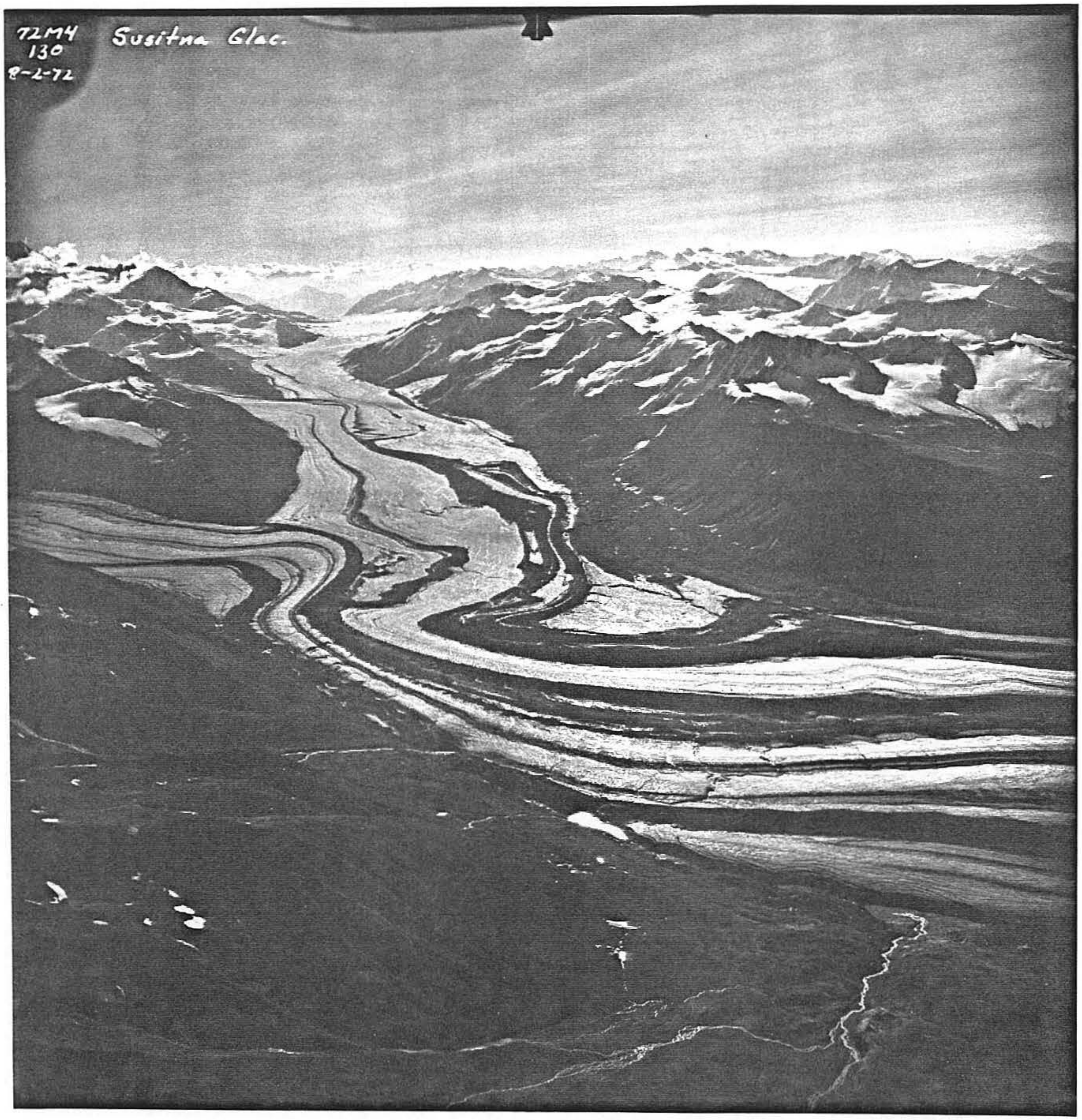
The Susitna basin glaciers, while only covering about 4% of the basin area, are huge by conterminous U.S. or European standards. The largest is West Fork Glacier, about 30 miles long and typically 2 miles wide. It alone probably has a considerably larger volume than the proposed Watana reservoir. Susitna Glacier is roughly the same size if its complicated system of tributaries is included. The terminal areas of the glaciers lie at altitudes which are typically about 3500 feet above sea level; the late summer snow line, defining the boundary between the areas of net accumulation and ablation, was at about 6000' in 1981. The glaciers have been wasting strongly in recent years, perhaps supplying 10 to 15% of the Gold Creek discharge from ice storage, as discussed later. Such a trend could change during the life of the Susitna project if it has not already. Most if not all of the major glaciers are unstable in their flow and are subject to surging. Why this should be is still a mystery. When the weather permits, oblique photography of the glaciers is obtained annually by the U.S. Geological Survey. The surging glacier problem has been defined this way. However, by European standards the glaciers have hardly been studied and to our knowledge no studies on the ground have been carried out in the Susitna basin prior to this project.

A selection of some of the U. S. Geological Survey oblique photographs taken by Larry Mayo is given in Figures 1.1 to 1.5. Locations are Figure 1.6.



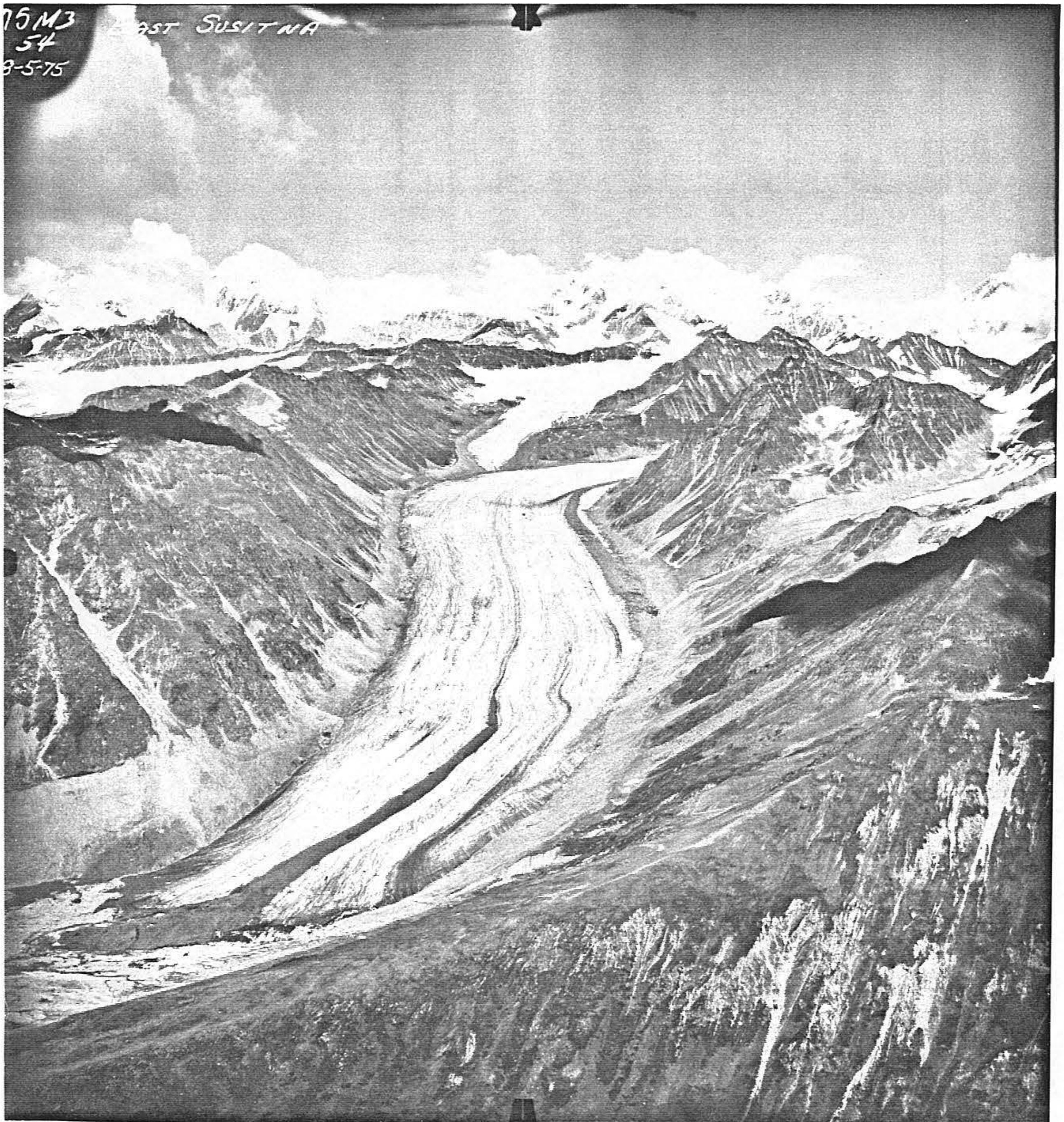
WEST FORK GLACIER

FIGURE 1.1



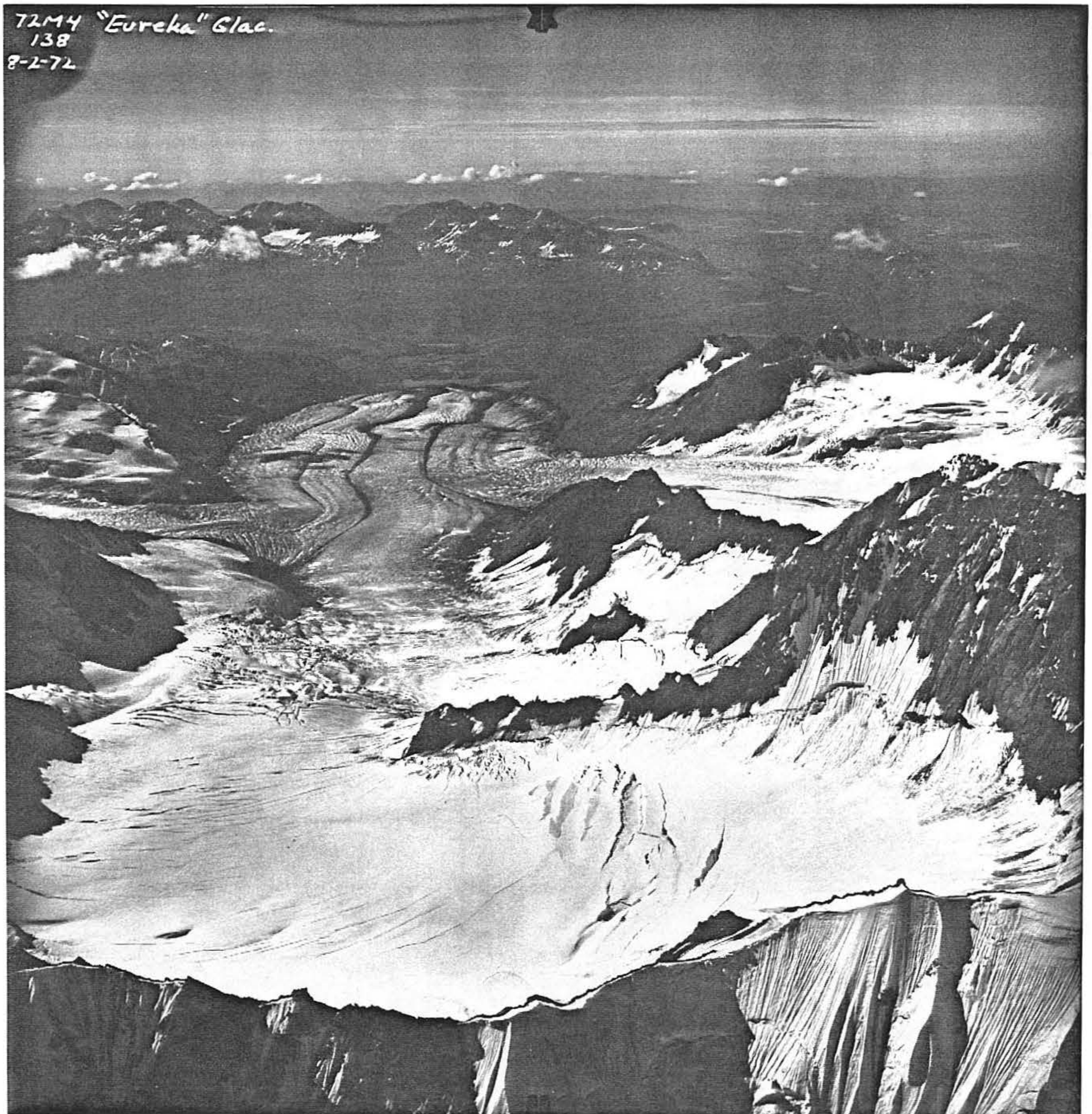
SUSITNA GLACIER

FIGURE 1.2



EAST FORK GLACIER

FIGURE 1.3

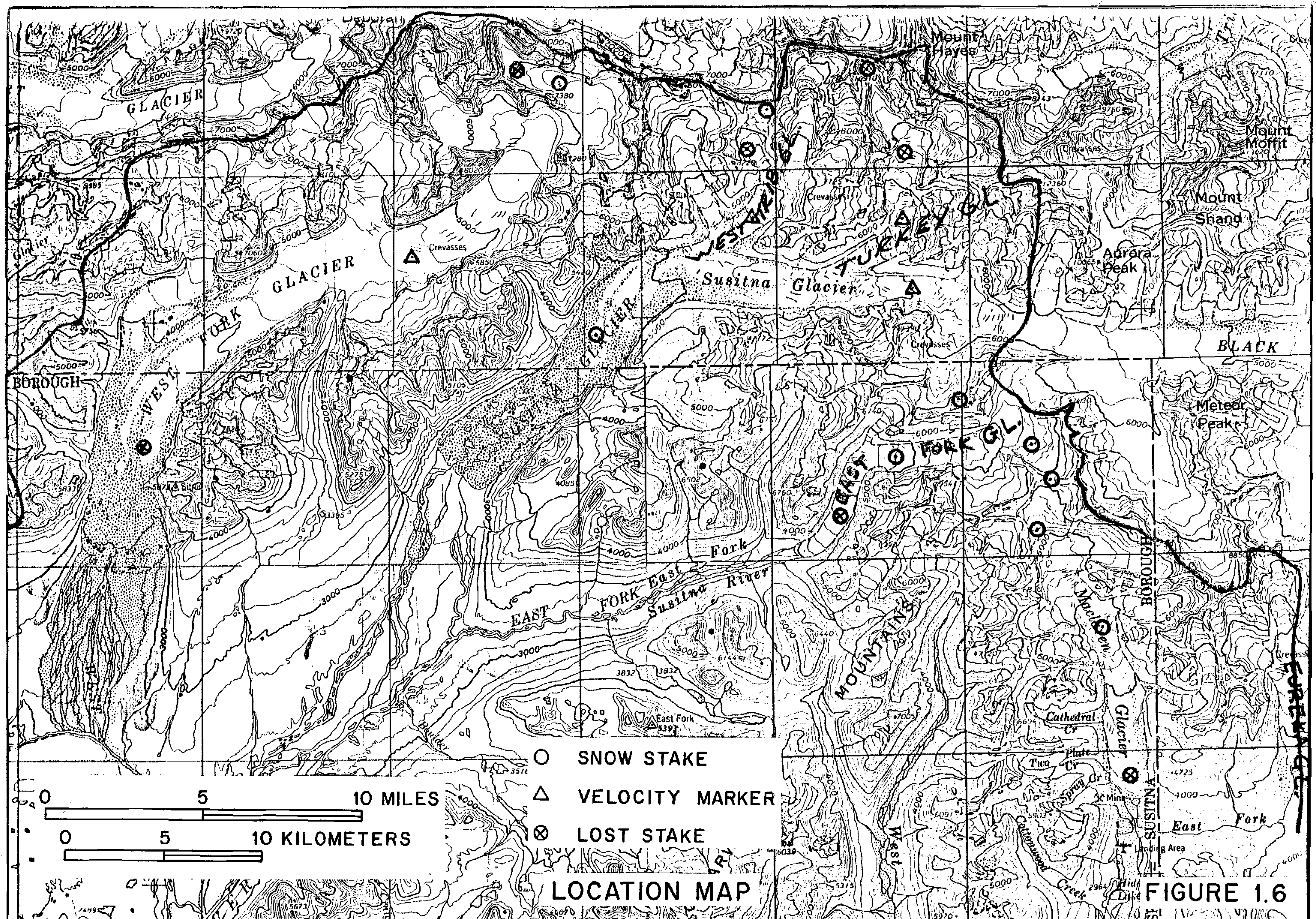


EUREKA GLACIER

FIGURE 1.4

MACLAREN GLACIER

FIGURE 1.5



LOCATION MAP

FIGURE 1.6

2 - HYDROLOGY

Although glaciers cover only 4% or so of the Susitna basin, together with the adjacent mountain terrain they seem to contribute a disproportionate fraction of the average annual streamflow. Roughly 38% of the streamflow at Gold Creek originates above the gaging stations on the Maclaren River near Paxson and on the Susitna River near Denali, although these represent only 20% of the basin area. It is in this context that the following topics on glacier hydrology should be viewed.

2.1 - Glacier Mass Balance Studies

Glacier balance measurements were made on all the major glaciers in the basin. (Glacier balance is the study of mass changes of a glacier, as distributed in space and time throughout a year.) Site location information is in Figure 1.6; the data are shown in Figure 2.1. Measurements were made at altitudes lying between about 3500' and 8100', and were tied in with R & M snow courses sites where possible (Field Data Index or/and Subtask 303 report - field data appendix January, 1982). Winter snowpack data were obtained by two mountaineers, usually travelling on skis, in May, 1981 (Figure 2.1). The results were obtained by measuring the snow depth above the 1980 late summer surface as identified by the stratigraphy in snow pits and by probing. Snow density was measured using samples from pit walls and from cores. The errors are probably dominated by the accuracy of density interpolation at unmeasured sites. The altitudes in Figure 2.1 were read from topographic maps and may be 200' or more too high due to wasting of the glaciers as discussed later. The spring of 1981 was unusually mild and some melting or "ablation" had already taken place before the high altitude snow survey was undertaken. The May data therefore do not quite represent the total winter snow accumulation or "winter balance". The difference is probably negligible at highest altitudes, and at lower altitudes can be estimated from the R & M data, which suggests that roughly 16" of water equivalent ablation had taken place at 4500' to 5050'. Probably several inches of this was not really ablated but went into the formation of superimposed ice (Larry Mayo, private communication). Therefore, the ablation at lower altitudes was probably more like 12" water equivalent before the snow survey. The snow had become isothermal at 0°C (32°F) by the time of the survey.

The 1981 late summer snowline, which defines the boundary between net ablation and net accumulation areas, was at roughly 6000' in 1981. Heavy snowfalls occurred in August and September at the higher altitudes, resulting in a net mass gain of 66" water equivalent at 7700' between the end of May and mid-September (Figure 2.1). At this altitude the net balance, the mass accumulated above the 1980 late summer surface, was 120" water equivalent. This is somewhat arbitrary since a 1981 late summer surface was not well defined. At 4600' the summer balance was about -110" water equivalent; the net balance for the year was about -85" water equivalent there. These quantities were not determined on the low parts of exposed glacer ice at roughly 3500', due to loss of the reference stakes. July data indicate a large ablation gradient with altitude. The net balance at 3500' was probably (and very roughly) on the order of -140" water equivalent. Ablation data are important since they give some idea of water availability in times of drought.

An important feature of Figure 2.1 is the comparison it gives of the balance-elevation data for the major Susitna basin glaciers. They are all rather similar, as is implicit in the foregoing discussion. However, there are significant differences. For example, winter balance is highest on Maclaren Glacier.

There is a good possibility that with sufficient data we can learn to estimate balance parameters on Susitna basin glaciers using similar data from long term U.S. Geological Survey studies on Gulkana Glacier. This is highly desirable, as it would minimize the field effort required to monitor the Susitna Glacier balances.

2.2 - Change in Glacier Volume

Over a period of decades, or even less, glaciers are subject to significant changes in volume. It is therefore of interest to investigate the volume changes in the Susitna glaciers over the last 30 or so years, the period over which stream flow has been measured at Gold Crrek.

A project to see if order of magnitude estimates could be obtained cheaply using existing uncontrolled aerial photos was carried out in cooperation with Anthony B. Follett of North Pacific Aerial Survey, Anchorage. East Fork glacier, draining into the East Fork of the Susitna River (Figures 1.3 and 1.6), was chosen as a convenient representative glacier because of its moderate size. Rapid retreat is suggested by the high trim lines in Figure 1.3. Longitudinal profiles of its center-line surface altitude were constructed from 1949 and 1980 photo sets.

An analysis of the altitude changes and of planimetric maps of the glacier in 1949 and 1980 indicates a surface altitude decrease of about 163' between 1949 and 1980, averaged over the glacier surface area of about 13.6 mi^2. Considering the maximum altitude difference error of 60' (Appendix), a statistical tendency for errors to cancel, and the limited data, the error in average altitude change could be 33% or more. It has two sources, the absence of any ground control other than that provided by existing topographic maps, and the lack of complete topographic mapping, only the profiles of altitude at the glacier center line being measured. The first problem is ameliorated somewhat because altitude changes, rather than absolute altitudes, are of primary interest. The second problem is complicated by the fact that limited elevation data were obtained in the high basins, although a center line elevation profile was also measured up the tributary basin (see Figure 1.6). In some places the elevation change exceeds 250'.

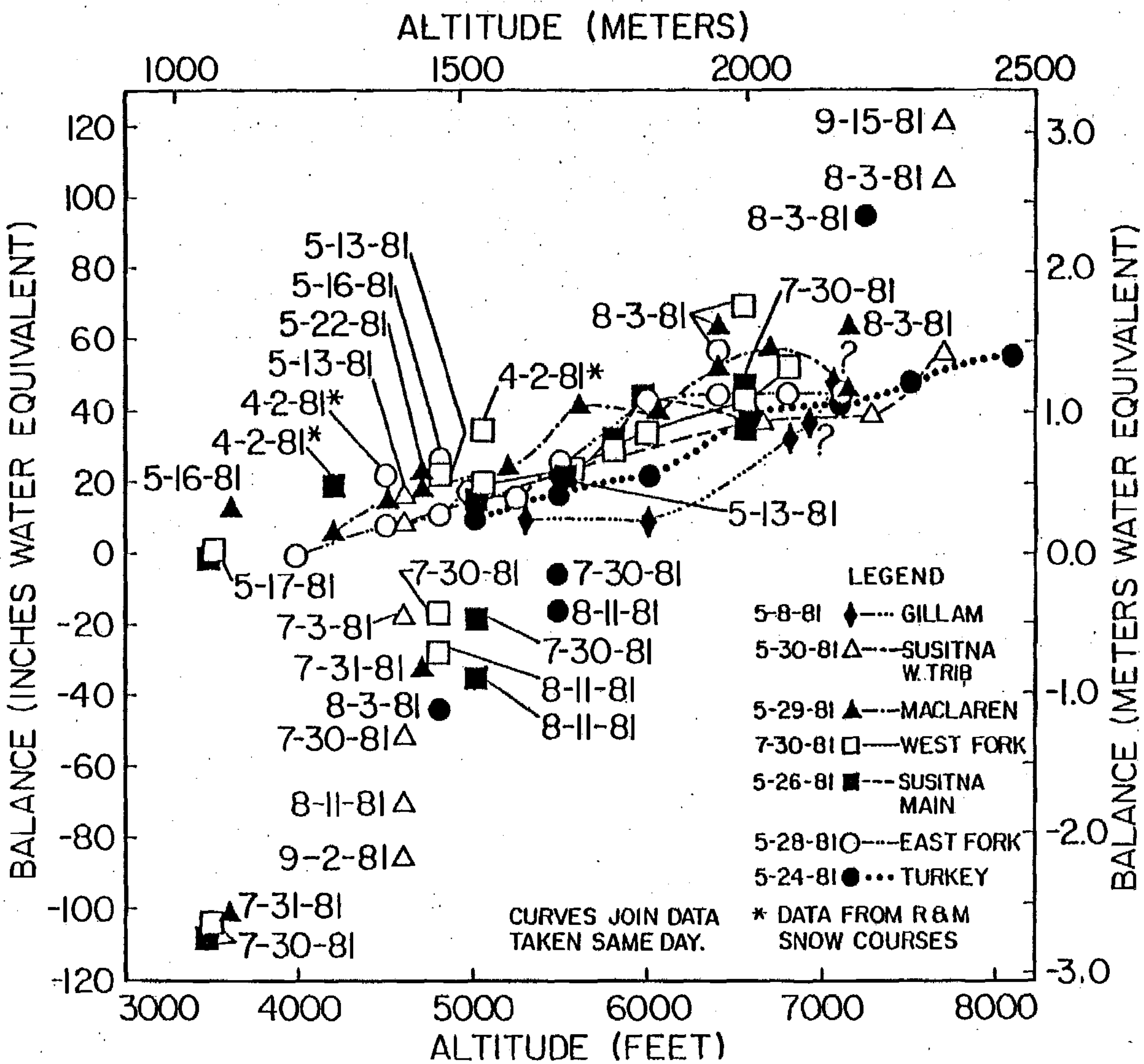
Over the period 1966-1977 Gulkana Glacier, situated 43 miles to the east of East Fork Glacier, lost an average ice thickness of only about 1.1' per year (Meier and others, 1980), while over the period 1949-1980 East Fork Glacier lost an average of 5.3' per year. This is perfectlyl possible, but it may also indicate that the error in the East Fork estimate is larger than anticipated. Care needs to be exercised in extrapolating the change of East Fork to the other glaciers of the Susitna basin, particularly since East Fork represents only 5% of the total glacier area. For example, the adjacent North and South Klawatti Glaciers in the Cascade Range of Washington behaved quite differently between 1947 and 1961, the former thinning by an average of 8.3 m (27') while the latter thickened 5.8 m (19') (Meier, 1966). Semi-empirical methods for taking account of differing characterisitics of different glaciers exist, but we have not applied them to the Susitna basin glaciers, Instead, we have estimated the contribution to runoff from glacier wasting, merely assuming that all of the glaciers have lost the same average thickness as East Fork, although, as noted, this is a dubious assumption. Then, for an ice specific gravity of 0.9, a total glacier area of 290 mi^2, a period of 31 years, and a thickness decrease of 163', the average runoff from ice wasting would be 1210 cfs. This is to be compared with total average flow at Gold Creeek over the same period of about 9,600 cfs. The result suggests that roughly 13% of total flow at Gold Creek has been coming out of ice storage, with the serious accuracy limitations discussed above.

The significance of this glacier wasting needs to be discussed. First of all, the change in glacier volume over the 31 year period, although large, is probably less than 10% of the total volume, so that glaciers are unlikely to be exhausted as water reservoirs in the immediate future. Still, as they retreat they will produce less water for given climatic conditions. Another plausible scenario is that a small change in climatic conditions, with constant precipitation, could balance the glaciers, if it has not done so already, and 13% less water would be available for hydro power production. (The average net balance for 1980-1981 could be estimated from the data of Figure 2.1 but this has not yet been done.) An extreme scenario is one in which the glaciers would begin storing the same amount of ice as they were losing previously, precipitation still being constant; then 25% less water would be available for power production.

The possible mistake of projecting future water supply from glacierized basins without taking account of glacier wasting apparently is not without precident, as indicated by informal discussions with staff of the Swiss Federal Technical University in Zürich. The case in point was the 190 MW (average) Grande Dixence project, the largest in Switzerland. It has been necessary to augment the water supply has been augmented by expansion of a system of collecting and pumping tunnels.

2.3 - Susitna Basin Boundary

Evidence for instability in the drainage of the basin occupied by Eureka Glacier, on the eastern boundary of the Susitna basin (Figures 1.4 and 1.6), was observed during an August 1981 glacier reconnaissance flight. At present the drainage is divided between the Susitna and Delta Rivers, with probably more than 50% going into the Susitna. It appears that most of this drainage could easily be captured by one river or the other, particularly since Eureka is a surging or pulsing glacier (Post, 1969; Mayo, 1978), and a pulse could rearrange the drainage. Inasmuch as this basin has an area of roughly 25 mi^2, and must be subject to very high precipitation because most of it is at high altitude, the potential loss or gain of water merits consideration.



BALANCE DATA

FIGURE 2.1

3 - SEDIMENT

The quantitative estimation of the amount of sediment transported by the Susitna basin rivers was not part of the glacier studies. Instead, in the glacier studies we have attempted to assess the basic approach to sediment transport estimation, and to try to determine whether there are any serious errors caused by the existence of glaciers. This seems worthwhile because much of the suspended sediment in the Susitna basin is produced by glaciers. The conventional approach is to relate spot measurements of suspended sediment transport to river discharge via a simple power law rating curve, which is then used to calculate suspended sediment transport from measured discharge. The potential for large errors in this approach is known, at least for small unglacierized basins (Walling, 1977), and it seems reasonable to ask if there are any peculiarities of glacierized basins which could lead to further complications. The question is not trivial because the processes which produce and transport sediment at glacier beds are poorly understood. For example, large fluctuations in suspended sediment concentration or water turbidity that show little if any correlation with discharge have been observed near the termini of Gornergletscher in Switzerland (Collins, 1979), Variegated Glacier near Yakutat, Alaska (Raymond and Malone, 1981) and elsewhere. It has often been emphasized in the literature that no simple relationship exists between suspended sediment transport and discharge in glacier streams exists, at least near glacier termini where the measurements have been made (Collins, 1979; Østrem, 1975; Zeigler and others, 1972; Østrem and others, 1967). Glacier surges may also present a problem as discussed later.

The authors who caution against the use of simple sediment transport-discharge relationship also note that there is some correlation between the two, so from an engineering point of view it seems that the question is to estimate the errors that might be involved in the use of an admittedly over-simplified relationship. To do so we have used two sets of data, taken at Gold Creek by the U.S. Geological Survey in 1952 and 1957, and at Engabreen, a glacier in northern Norway, by the Norwegian Water Resources and Electricity Board in 1979 (Kjeldsen and Østrem, 1980).

Gold Creek:

Daily measurements of suspended sediment transport and discharge were made from April to the end of September in 1952, and from June 1 to September 6, 1957. At least the first period covers most of the annual transport. A simple power law rating curve was fitted to the 1952 data; the R^2 of the fit was 0.87. This curve was then used to calculate the daily suspended sediment transport from the measured stream discharge. The calculated total over the measurement period was 5.4×10^6 tons, which is 85% of the measured value of 6.3×10^6 tons. Although the calculated daily values differ considerably from the measured values, the calculated total value is reasonable, which is expected since it is determined from a curve which represents the complete 1952 data set.

It is interesting how much the appropriate rating curve may vary from year to year. The 1952 rating curve was used to calculate the 1957 transport over the June 1 - September 6 daily measurement interval. In this case the result was only 44% of the actually measured value. Evidently the sediment transport regime, and therefore the appropriate rating curve, vary a great deal from year to year. This suggests that projected sediment production should be based on a curve in which equal weight is given to each year of data. This is not the case when all the data are used, becaue many more meaurements were made in the 1952 and 1957 years than have been made subsequently.

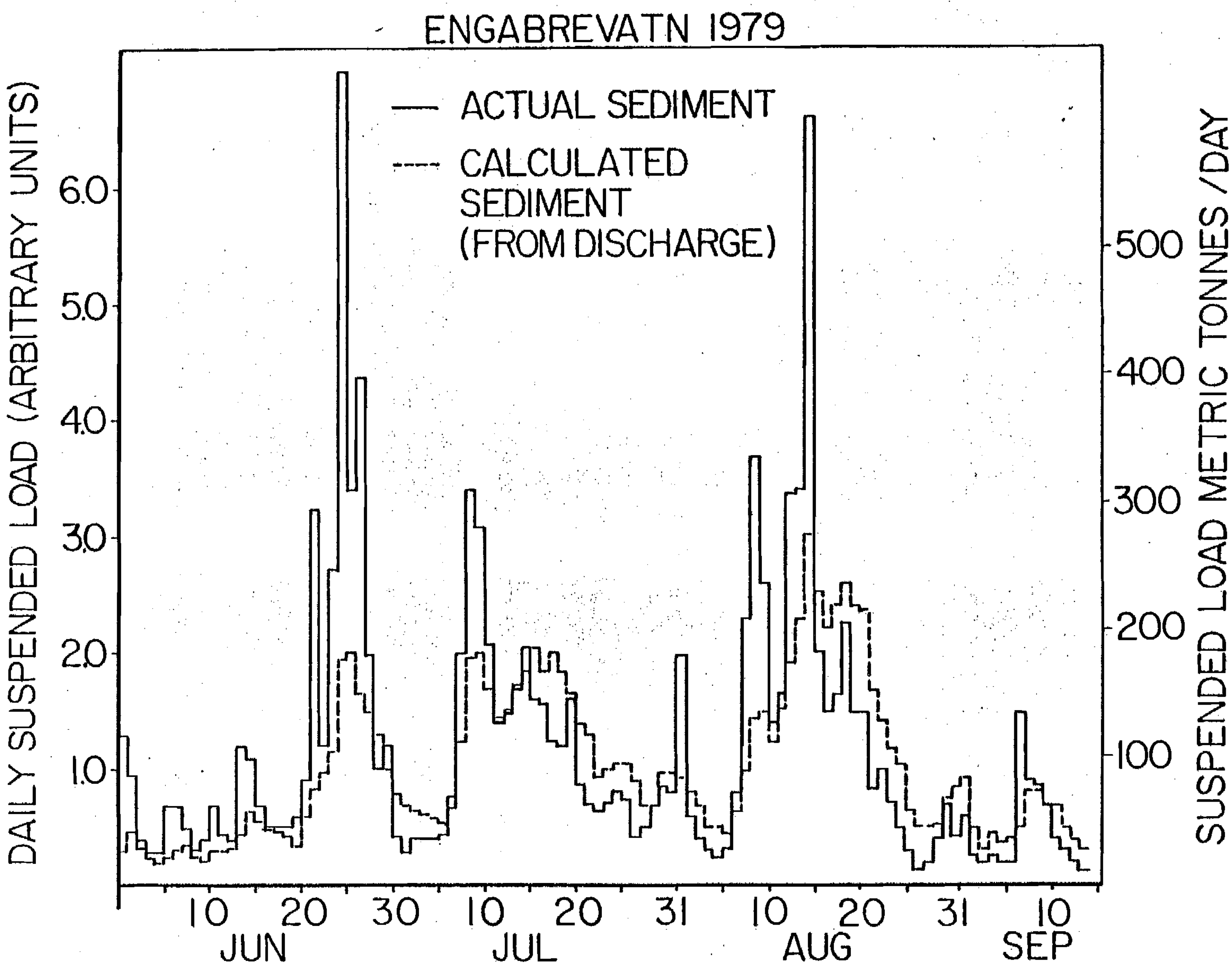
Engabreen:

Measurements of daily suspended sediment transport and discharge have been made in Engabrevatn, the stream at the terminus of Engabreen (glacier), since 1969. An analysis of all of these data would give a good idea of the long term variability in transport in a glacier stream, and of the realiability of a rating curve predictive approach. However, only the 1979 data have been analyzed. The R^2 of the power law fit was 0.59, which is significantly poorer than the 0.87 for the Gold Creek data, and which might perhaps be expected so near a glacier terminus, where there has not been time for any of the variations to be smeared out. The predicted and measured daily sediment transport are shown in Figure 3.1. When integrated over the measurement interval, the predicted value is about 85% of the measured. As in the case of Gold Creek this one year agreement is expected, but the rating curve probably varies a great deal from year to year.

This simple analysis of Gold Creek and Engabrevatn data lends some perspective to the problem of estimating suspended sediment, both downstream from glaciers and at their termini. One other factor deserves mention. There is probably a tendency for the rating curve approach to underestimate the total suspended sediment transport, especially when rather limited data are available. For example, Østrem and others (1967) note that more than 50% of the toal annual transport may occur on a single day. What is probably more relevant to the Susitna basin is that glacier surges may complicate the picture. For example, the impressive stream turbidity pulses produced by Variegated Glacier, a surge-type glacier in its "quiescent" phase of motion, are associated with short-lived pulses of ice motion, and not with stream discharge. It is not known how much sediment is released by a surge, but it may be very large (Uskov and Kvachev, 1979; Shcheglova and Chizhov, 1981).

No study of bed load processes peculiar to glacier streams has been carried out in connectin with the proposed Susitna Project. About 37% of the total sediment from Engabreen is transported as bed load.

To summarize, it is felt that an error in the projected suspended sediment transport of a factor of 2 or 3 would certainly not be surprising. The sediment is more likely to be underestimated than overestimated, but the time to fill in the proposed Watana reservoir would still be on the order of centuries. However, we cannot completely eliminate the possibility that larger errors could be associated with glacier surges, or possibly with glacier outburst floods.



CALCULATED AND MEASURED SEDIMENT

TRANSPORT FROM ENGABREEN

FIGURE 3.1

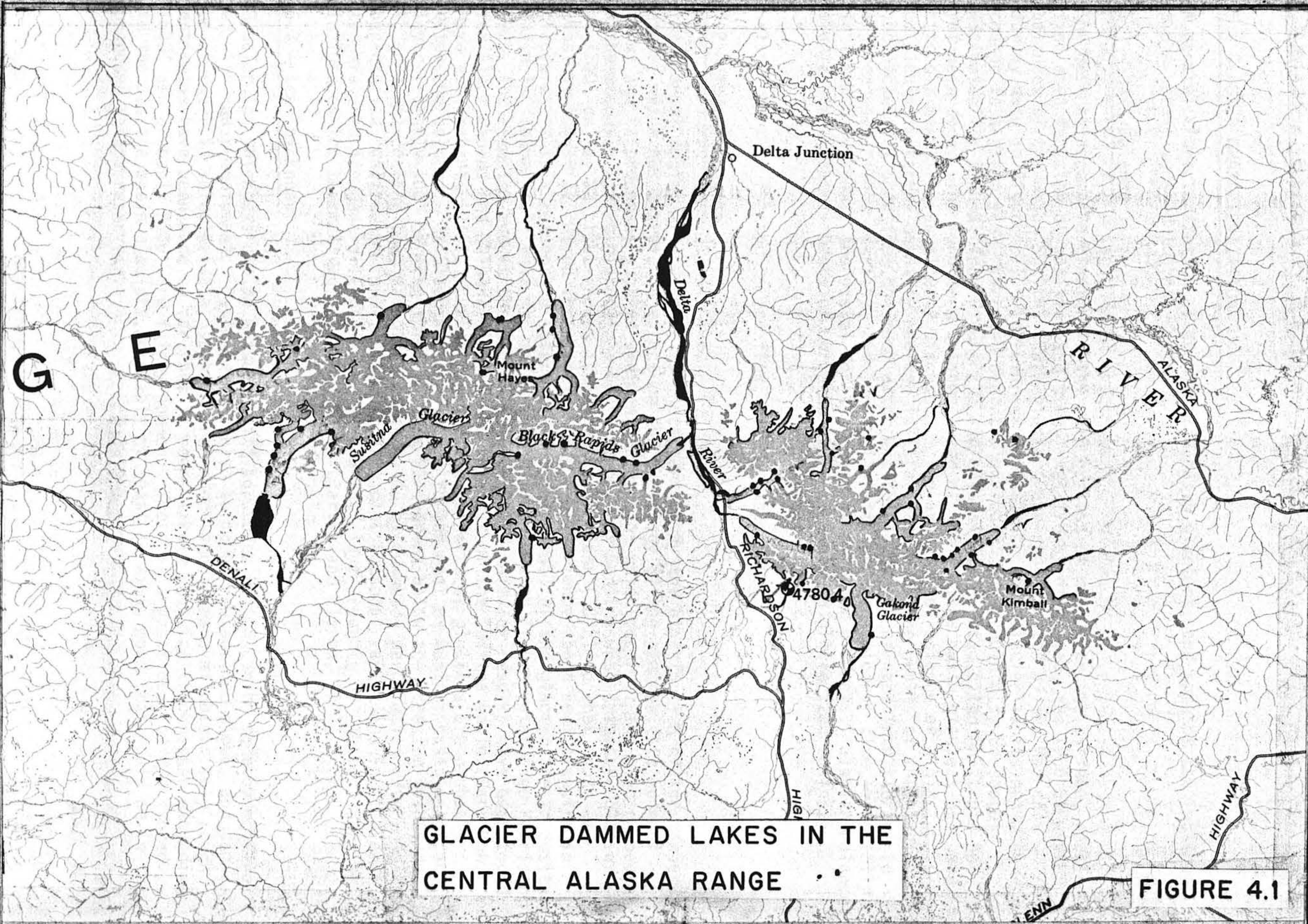
4 - GLACIER OUTBURST FLOODS

Outburst floods from glaciers are fairly common. These usually seem to fall into two categories: floods from glaciers on volcanoes, the water for which is stored sub- or englacially, and is not visible at the surface, and floods from glacier dammed lakes. The Icelandic name jökulhlaup is often used for the former. The latter are more common in Alaska, and have been mapped by Post and Mayo (1971), who also describe some of their characteristics. Glacier dammed lakes usually dump catastrophically, and may cause huge floods. For example, a 20' increase in the stage of the Copper River occurred during the construction of the Million Dollar railway bridge in 1909.

Outburst floods occur in different settings and by different triggering mechanisms. The peak discharges downstream may be an order of magnitude greater than those of non-outburst floods. Future outburst floods cannot be predicted reliably using standard statistical procedures, because small and unpredictable glaciological conditions may totally change lake formation and drainage. Since they involve filling of reservoirs, it is possible that there is a statistical tendency for outburst floods to be superimposed on non-outburst floods, but this has not been demonstrated.

In the Susitna basin several glacier dammed lakes have been mapped by Post and Mayo (1971) on West Fork and Maclaren Glaciers, and the downstream areas are mapped as flood courses (Figure 4.1). The lakes are comparatively small, the larger ones being characteristically 2,000' across. Volumes could be determined from field studies, and flood magnitudes by assuming the same release pattern as indicated by existing hydrographs below other glacier dammed lakes. This does not seem to be of high priority in view of the small size of the lakes and the large capacity of the proposed Watana spillways.

A broader question that needs attention is whether conditions could change in the foreseeable future, causing the formation of large lakes (see Dolgoushin and Osipova, 1975). The answer is probably yes. A surge or pulse of Maclaren Glacier could enlarge the lake on its east side. The same is true of West Fork Glacier, particularly with regard to the lake at its lowest tributary on its northwest side. Even without surges lake conditions could change considerably during the life of the Susitna project, and some surveillance will probably be necessary. This must be done carefully, as a lake may have recently dumped, or only partly refilled, when visited. The Maclaren lake was dry but showed evidence of recent dumping when we saw it on August 11, 1981. This lake, apparently nearly full, can be seen on the right side of the glacier in Figure 1.5. The strip of broken ice extending down glacier from it is probably due to previous dumping episodes (Larry Mayo, private communication)



GLACIER DAMMED LAKES IN THE CENTRAL ALASKA RANGE

FIGURE 4.1

5 - GLACIER CHARACTERIZATION

A general characterization of the Susitna basin glaciers, and some of the implications, are discussed in this section.

5.1 - Mass Balance

The mass balance of a glacier is the gain or loss of mass over its surface, specified as a function of position and time. As already discussed, the 1980-81 winter balances of the major Susitna basin glaciers are approximated by the May snow survey data in Figure 2.1. The average net balance of a glacier is its net mass change in a given year, averaged over the surface. This could also be roughly estimated for 1980-81 from Figure 2.1 and area-altitude data, although it has not yet been done. The long-term balance trend of the Susitna basin glaciers has been strongly negative, as already discussed. The average net balance of a glacier is a particularly useful quantity because it is a measure of the health of the glacier, and because it specifies how much water was released from or went into storage in a given year. This quantity, and its variability over a period of time, especially in times of drought, are useful for the planning of water projects. Glacier balance studies are integral parts of European hydro projects in glacierized basins.

Balance is also related to ice flow, as discussed later.

5.2 - Thermal Regime

The thermal regime of a glacier is characterized by the distribution of ice temperature, which has a profound effect on the hydrology of the glacier, its mode of flow, and in processes such as sediment production which occur at the glacier bed. A thermocouple string placed in a 66' deep hole on Susitna west tributary glacier at 7700' on May 22, 1981 showed isothermal conditions (32°F) to that depth at least by August 3. Given the existing body of experience about heat transfer in glaciers, it is a reasonable inference that almost all of the glacier ice in Susitna basin is "temperate"; that is, it is in equilibrium with liquid water (see Harrison, 1975, for example) and is therefore close to 32°F. Similar results have been found for Black Rapids and Gulkana Glaciers to the east of the Susitna basin (Harrison, Mayo and Trabant, 1975). Curiously, the lowest parts of glaciers are probably often the coldest. On Black Rapids Glacier to the east of Susitna basin a surface layer probably 100' or less thick is several degrees below the freezing point, due to seasonal cooling that cannot be compensated by downward percolating water, because ice, unlike snow or firn, is impermeable. Seasonal variations in glacier temperatures are generally confined to a surface layer roughly 50' thick. Surging influences the thermal regime of a glacier (Jarvis and Clarke, 1974).

5.3 - Ice Thickness

Glacier ice thickness can be measured with boreholes (which can be made by melting) or with radar equipment. Estimates can also be made from surface slope, and can be improved if velocity data, such as presented later, are available. Only rough estimates have been made so far, but it seems likely that ice thicknesses exceeding 1500' and probably 2000' are fairly common. There is a great deal of H_2O stored in the Susitna basin glaciers, probably at least 10 times more than would be in the proposed Watana reservoir.

5.4 - Glacier Dynamics

Instability of their ice flow regimes seems to be the rule for all the major Susitna basin glaciers. Probably all of them are "surge" type (Meier and Post, 1969); Post, 1969; Mayo, 1978), which means that they are subject to periodic episodes of rapid motion that bear no direct relation to climate. The definition of surges is not easy. At the one extreme a surge implies a catastrophic advance (during which the ice may move 300' or more per day); at the other extreme it implies a weaker and short lived "pulse" of motion. Susitna Glacier, which underwent a major surge in 1952 or 1953 (Post, 1960), is in the former category; Maclaren, probably Eureka and possibly East Fork would be in the later. The situation seems to suffer from lack of published information on past surge histories, and from the fact that major surges of large glaciers occur infrequently, perhaps every 50 years or so.

Sometimes surge behavior must be inferred from indirect evidence such as moraine patterns or "potholes" on the surface. West Fork Glacier is in this category (Figure 1.1). The famous moraine patterns on Susitna Glacier give information about its surge history. Figure 5.1 shows them before and after the 1952 (or 1953) surge as taken from Meier and Post (1969), and in 1980 as sketched from NASA photography. Assuming that the patterns always look about the same just before a surge, it is evident that no surge is imminent. Probably the next surge of Susitna Glacier is on the order of 30 years in the future. There is no doubt that major surges will occur during the lifetime of the Proposed Susitna Project.

The effects of surges on the Proposed Susitna Project cannot be predicted in detail, particularly since few accessible data exist on the sediment and water discharges associated with surges. Most of the effects of surges have been noted earlier:

(a) There is some evidence that sediment discharge during a surge may be large.

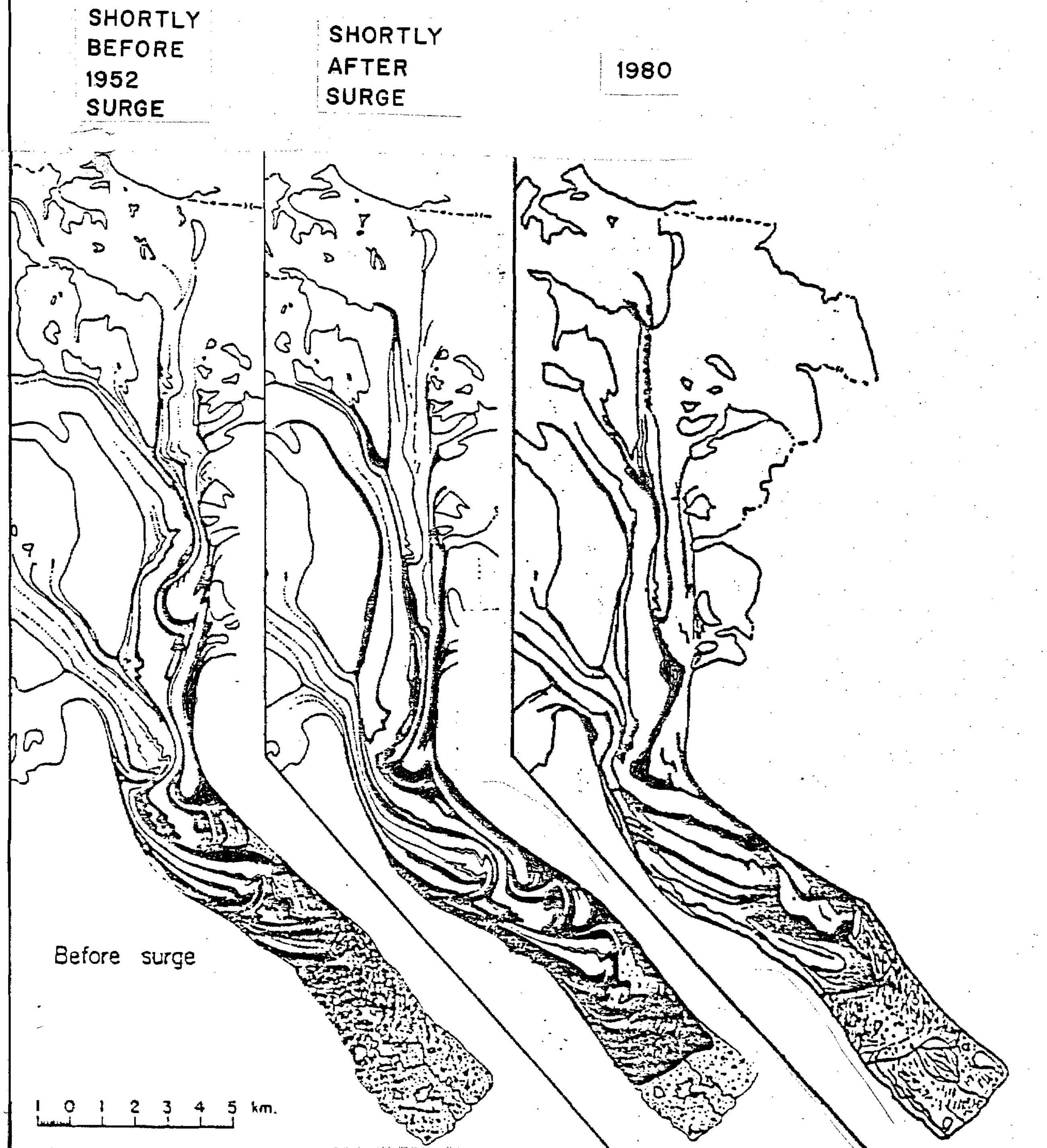
(b) Glacier dammed lakes much larger than those now existing might be formed, particularly by Maclaren and West Fork Glaciers.

(c) The water supply to the Susitna basin from Eureka Glacier might be affected.

(d) The area of ice at lower elevations exposed to high ablation would be increased, leading to a temporary increase in water production.

The causes of surges are not understood, but it is known that a key role is played by the hydrology of liquid water in glaciers, and that seasonal variation in ice velocity and its evolution with time can point to surge imminence (Variegated Glacier data reports, 1973 to 1979). A knowledge of velocity can also be used in the estimation of ice thinkness, and to estimate the ice discharge past the "equilibirum line, the imaginary line that divides the net accumulation and ablation areas of the glacier. This amounts to "glacier gaging", and comparison with the total net snow accumulation above the equilibirium line gives a measure of the equilibrium of the glacier. Glaciers can be out of equilibrium because of climatic change, or because of unstable flow. Surging behavior and possibly the strength of a surge can be identified this way.

Accordingly, surface velocity measurements on several of the major glaciers are underway. The results to date are in Table 5-1. The winter speeds, which are not yet measured, are of interest because they are probably considerably less than summer speeds for glaciers that have a tendency for water-induced instability. The behavior of the large West Fork Glacier will be of particular interest because it is an important glacier with an uncertain surge history.



EVOLUTION OF MORAINE PATTERNS OF SUSITNA GLACIER

FIGURE 5.1

TABLE 5.1 - 1981 VELOCITY DATA FOR SUSITNA BASIN GLAICERS.

Glacier	Measurement Interval	Velocity m/day	Velocity ft/day	Velocity azimuth grads	Velocity azimuth degrees
Susitna main branch	5/18-9/2	0.141	0.462	301.6	271.4
Susitna "turkey" tributary	5/18-7/3	0.786	2.58	221.5	199.4
	7/3-7/30	0.653	2.14	221.2	199.1
	7/30-9/2	0.529	1.73	222.0	199.8
Susitna west tributary	5/30-7/3	0.373	1.22	247.7	222.9
	7/3-9/2	0.306	1.00	247.4	222.7
West Fork	5/17-7/30	0.227	0.744	291.9	262.7

Locations of measurement sites are shown in Figure 1.6.

6 - SUMMARY

The glaciers and associated high mountain terrian of the Susitna basin have had, and will continue to have, a significant effect on the water supply for the Proposed Susitna Project. That this should be so is not surprising considering that about 40% of the stream flow at Gold Creek originates above the Denali and Maclaren gages. The following is a list of some of the points made in this report:

(a) An estimate made on the basis of a limited study suggets that roughly 10 to 15% of the water discharge at Gold Creek since gaging began may have been provided by the shrinking of the Susitna basin glaciers. A scenario in which the trend is reversed could lead to significantly less available water for power generation.*

(b) Glacier balance measurements were initiated in 1981. At 7700' the net snow accumulation betweeen Septembers of 1980 and 1981, exclusive of rain and snow that later melted, was about 120" water equivalent.

(c) There is probably at least ten times more H_2O in the Susitna basin glaciers than there would be in the proposed Watana reservoir.

(d) The drainage of Eureka Glacier is unstable.

(e) Most if not all of the glaciers in the basin are surge or pulse type; that is, their motion is subject to periodic instability, sometimes of catastrophic proportions.

(f) Major surges will occur during the life of the Proposed Project.

(g) There are many glacier-dammed lakes in the basin that are subject to catastrophic drainage. They seem to be too small to pose much of a threat now, although the situtation could change with changing glaciological conditions, such as a surge.

(h) Water supply would probably be temporarily and slightly increased by a surge of a major glacier.

(i) Almost all of the glaicer ice in the basin is temperate; that is, it is very close to 32°F.

(j) Much of the suspended sediment is supplied by glaciers, which makes it more difficult to predict. Errors of a factor of 2 or more in projected future supply would certainly not be surprising. Glacier surging is one example of a possible complicating factor that cannot be evaluated properly with present knowledge.

*A special note on the significance of Glacier Mass Balance to estimations of stream flow is appropriate here because of its significance to the planning and operation of hydroelectric projects.

As discussed in section 2.2, there has been an overall wasting of glaciers during the past three decades. Although a large amount of ice came out of storage during this time, it is probably less than 10% of the total volume. Therefore, the glaciers are unlikely to be exhausted as water reservoirs in the immediate future. However, their contribution to runoff in the Susitna Basin can be expected to vary. Several plausible scenarios exist among which are:

(1) If the glaciers continue to retreat they will produce less water for given climatic conditions.

(2) A small change in climatic conditions, with constant precipitation, could balance the glaciers and 13% less water would be available for hydroelectric power production. This trend towards a more positive annual balance may already be underway.

(3) A extreme scenario is one in which the glaciers would begin storing the same amount of ice that they were losing previously, precipitation still being constant, in this case 25% less water would be available for hydroelectric power production.

The possibility of error in projecting runoff from glacierized basins without taking account of changes in glacier mass balance has been appreciated in other countries (see p. 2-3).

It is recommended that monitoring of glacier mass balance in the hydrological basin should be an integral part of hydroelectric planning and operation. In doing this we would be following the examples of other countries where glaciers play an important role in hydrology - Norway, Switzerland, Iceland and (most recently) Greenland.

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NPAS

PHOTOGRAMMETRY
TOPOGRAPHIC MAPPING
AERIAL PHOTOGRAPHY

NORTH PACIFIC AERIAL SURVEYS, INC.
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October 23, 1981

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Fairbanks, Alaska 99701

Subject: East Fork Glacier

Dear Will:

The following is a report of our photogrammetric work in preparing planimetric maps and profiles from different dates of photography for the East Fork glacier.

A. PROCEDURES

1. Purpose
In May of 1980 we discussed the possibility of obtaining new black and white aerial photography at a scale of 1"=3000' and profiling approximately 25 models of some selected glacier in the upper Susitna Basin. The objective of the project was to determine changes in glacial volume over a span of several years by comparing new photography with existing coverage obtained in the late 1940's or early 1950's by the government. Then in May or June of 1981, we met to discuss the project and examine various options open to us to meet the stated objective. During our meeting we narrowed the glaciers under consideration to the Susitna, West Fort, McLaren, and East Fork glaciers.

2. Research Existing Photos
We decided to conduct research into the availability of existing aerial photography from various sources to determine if the profiles could be accomplished from existing aerial photography and ground control. The first step we took was to examine indexes of existing government coverage in the area. We determined that aerial photography was available from the U.S.G.S. which was taken in the late 1940's and early 1950's in the area of interest. We also found more recent high altitude coverage taken by NASA in 1979 and 1980. Based on our preliminary investigation, we ordered one set of black and white contact prints from the EROS Data Center in Souix Falls, South Dakota to cover the old photography, and one set of color infrared and black and white prints from the more recent NASA coverage. Enclosed please find copies of the Mt. Hayes and Healy 1:250,00 USGS quadrangle maps in the study area. On the Mt. Hayes quad, I have indicated the approximate photo centers for the old USGS photography which we received

from the EROS Data Center. I am also enclosing one set of black and white contact prints from this photography for your files.

3. Based on an analysis of the existing photo coverage, we determined that the East Fork glacier to be the most suitable for analysis at this time using only existing photography and ground control available.

4. The next step was to order duplicate film negatives from the EROS Data Center for exposures 103 through 107 of their photography acquired on August 29, 1949. We also ordered color infrared film diapositives for the July 1980 NASA coverage, exposure 6104 through 6107.

5. Once we had selected the photographs to use in our analysis, we then obtained a copy of the Mt. Hayes B-6 quadrangle map at a scale of 1"=1 mile. From this quad map, we selected photo-identifiable control points which we felt could be identified on the aerial photographs and utilized for horizontal and vertical control in the subsequent bridging operation. Enclosed please find a xerox copy of the Mt. Hayes B-6 quad showing the location of control points which were selected and for which coordinates were scaled in a state plane coordinate system and elevations extracted directly from the quad map. On this map, points 301 through 304 were selected as horizontal and vertical control points, and points 315 through 320 were selected as vertical control points only.

6. From the EROS Data Center duplicate negatives we prepared one set of black and white film diapositives which were then utilized to conduct the bridging operation for the 1949 photography. The color IR diapositives were used for the 1980 bridging. We selected and drilled nine pass points per exposure utilizing a Kern PMG2 Point Transfer instrument. The horizontal and vertical ground control points selected from the quad map were also drilled on the diapositive as near to their map location as could be determined visually on the photograph. We then used a Kern MK2 Monocomparator to measure the plate coordinates to the nearest one micron for all pass points and ground control points so marked on the diapositives. The arbitrary plate coordinates were then processed through a series of analytical aerotriangulation programs to arrive at ground conditions and elevations for all pass points and residuals on the horizontal and vertical control points selected and utilized.

7. Upon completion of the aerotriangulation, we prepared a planimetric map directly at a scale of 1"=500' from the 1949 photography. All mapping from this photography was accomplished using a Kern PG2 stereoplotter system. Once the planimetric map had been completed, then a profile line was selected and plotted directly on the planimetric map. Distances and elevations along this profile line were

then digitized and recorded directly on magnetic Floppy Discs for later plotting.

8. Because the NASA pahotography had a nominal focal length of 12" which was beyond the mechanical limitations of our PG2 stereoplotters, it was necessary for us to perform the plani-metric mapping and digitizing for the 1980 photography on a Kelsh stereoplotter. The planimetric mapping from the 1980 coverage was done directly at a scale of 1"=1000'. Since the Kelsh stereoplotter is not equipped with automatic digitizing equipment, it was necessary to manually scale distances and elevations on the Kelsh plotter and record them by hand for later plotting.

9. Upon completion of the planimetric mapping from the 1980 photography, we photograpically enlarged the plan map to a scale of 1"=500' and repenciled the enlarged map on mylar.

10. The final step in the photogrammetric project was to plot the profiles from the 1949 and 1980 photographs. Using the Kern PG2 stereoplotter system, we plotted the profiles from both dates directly at a scale of 1"=500' horizontally and 1"= 100' vertically.

B. ACCURACY

1. All control was scaled directly from USGS quadrangle maps at a scale of 1"=1 mile. Horizontal measurements were taken to the nearest 100th of an inch which would relate to the measuring precision of + or - 50' at the scale of the map. Vertically the elevations were used as published on the map. Since the map was not field checked, the accuracy of the elevations with respect to an absolute datum is unkown.

2. The 1949 photography has a nominal photo scale of 1"=4,000'. In the bridging of the 1949 photography, five horizontal control points were held with a root mean square misclosure in horizontal position of + or - 23 feet. Eleven vertical control points were held with a root mean square error in elevation of + or - .5 feet. What these results indicate is that the computer programs were able to fit polonomial equations through the given horizontal and vertical control points within the stated residuals. This should not be inferred as control points which are accurate within this amount.

3. The 1980 photography has a nominal photo scale of 1"=5,000' with a 12" focal length camera. For the 1980 photography, four horizontal control points were held with a root mean square with a + or - 17 feet. Ten vertical control points were used with a root mean square misclosure of + or - 5 feet.

4. For the 1949 photography mapped in our Kern PG2 stereoplotter, the least count or precision of horizontal and vertical measurements was + or - 0.7 feet. For each of the four stereomodels set, we were able to match the elevations computed in the aerotriangulation within + or - 30 feet. Common points on the profile lines between between adjacent stereomodels were used as index points so that the elevation from both stereomodels would be the same for a common point.

5. For the 1980 photography set in our Kelsh stereoplotter, the least count or precision of horizontal and vertical measurement was 10 feet. We encountered similar discrepancies between the computed elevations of pass points and control points, namely + or - 30 feet.

6. Therefore, overall, I estimate that the accuracy of the apparent difference between the 1949 and 1980 profile lines is + or - 60 feet. Based on the information we have there is no really good way to pin down the accuracy any better than that.

C. RECOMMENDATIONS

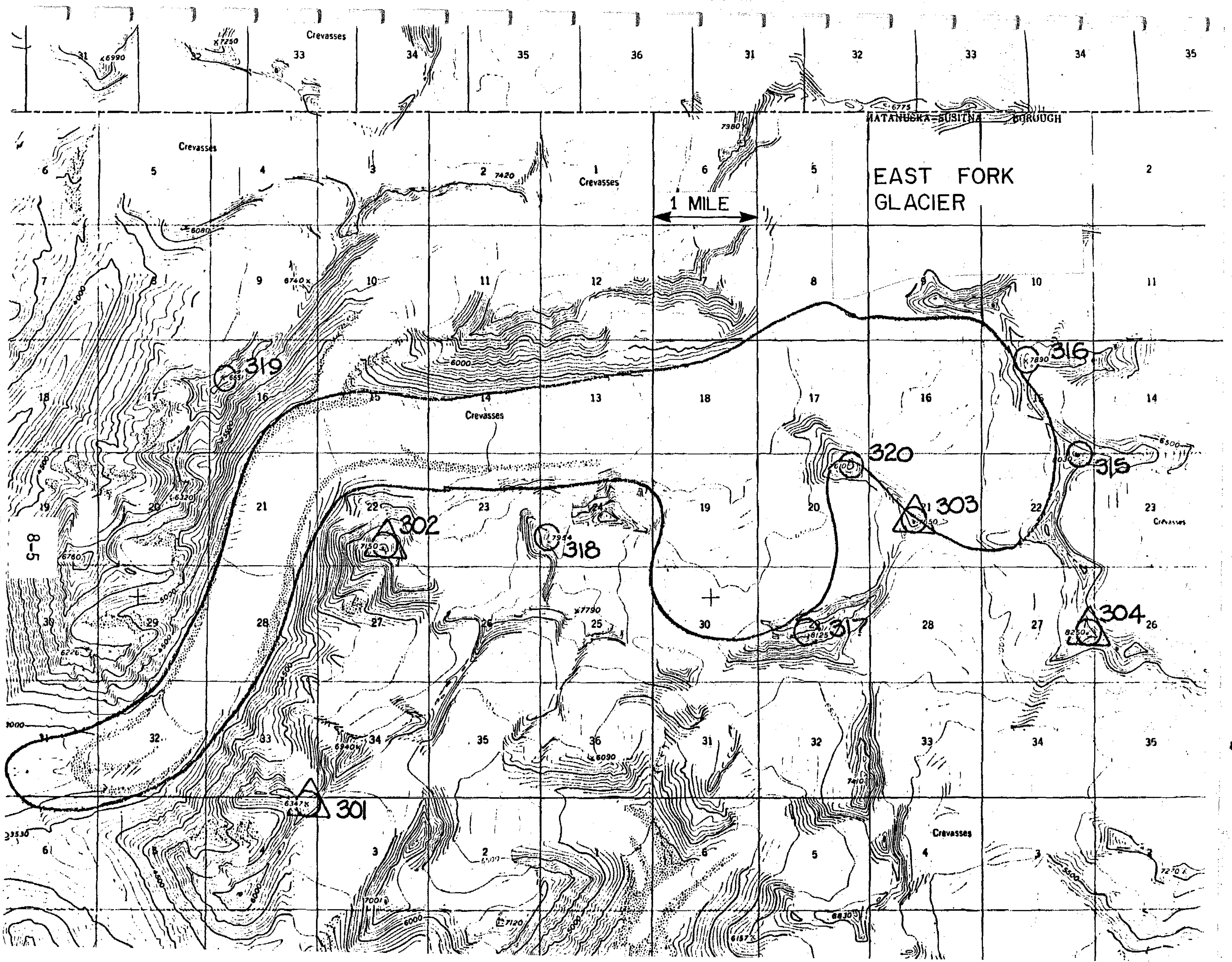
Using existing aerial photography and 1"=1 mile USGS quadrangle maps as control, I feel that the results we obtained on the East Fork glacier are the best we could hope for on any glacier in the Susitna drainage basin. We could probably improve somewhat on those accuracies by obtaining new aerial photography with a nominal 6" focal length camera. However, I do not feel that the increase in accuracy would warrant the additional cost which would be incurred in acquiring new photography. Of course, the optimum approach would be to establish horizontal and vertical control points, set premarks on those points, and obtain new photography. These surveyed control points could then be utilized in aerotriangulation of the new photography, and the same points could be stereoscopically transferred back to the 1949 photography. In this case, I feel that we could achieve accuracies on the order of + or - 10 feet.

After reviewing the foregoing procedures, accuracies, and recommendations, if you have any questions please give me a call. I enjoyed working on this project with you and look forward to future research projects involving aerial photography and photogrammetic techniques.

Sincerely,

NORTH PACIFIC AERIAL SURVEYS, INC.

Anthony B. Follett
Vice-President
Certified Photogrammetrist (ASP)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