# Application of Photogrammetry to the Study of Volcano-Glacier Interactions on Mount Wrangell, Alaska

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ABSTRACT: Mt. Wrangell is a huge, glacier covered, andesitic shield volcano in south central Alaska. Volcanic heat flux from its summit increased markedly following the Great Alaska Earthquake of 1964. Glaciological and volcanological research began at the summit in 1961 and, since 1965, has focused on interactions between the volcano and its glacier cover. Photogrammetry has played a key role. Aerial photographs from 1957, combined with annual aerial photography since 1972 and precision ground-control surveying, have enabled us to measure rates of ice loss from the summit by preparing detailed topographic maps and digital cross sections. Thus, melting of the glacier ice serves as a "giant calorimeter," enabling us to determine magnitude and variability of the volcanic heat flux. Controlled aerial photographs have also been used to prepare sets of orthophoto base maps which show variation in the termini of glaciers radiating from the summit. The procedures employed, equipment utilized, difficulties encountered, photogrammetric products generated, and application of the results are discussed.

## INTRODUCTION

THE MAGNIFICENT Wrangell Mountains in south central Alaska (Figures 1 and 2) are among many geographic features in Alaska named in honor of Baron Ferdinand Petrovich von Wrangell, the Governor of Russian America from 1830 to 1836. These high volcanic mountains are a northward extension of the rugged St. Elias Mountains which contain Canada's highest peak, Mt. Logan (6050 m). Some of the best-known peaks in the Wrangells are Mt. Blackburn (5000 m), Mt. Sanford (4950 m), Mt. Drum (3660 m), and Mt. Wrangell (4317 m) which is the northernmost active volcano (solfatara activity) on the Pacific Rim (62°N; 144°W). Heavy snowfall from the North Pacific produces a compact and continuous area of snow and ice cover in excess of 5000 km$^2$ in the Wrangell Mountains.

Mt. Wrangell itself is heavily glaciated, with an ice cap flowing outward in all directions, yet it retains the form of a very large shield volcano (Figure 3). Its summit consists of an ice-filled 4 by 6-km caldera with three craters perched on its rim (Figures 4 and 5). There are about 10 km$^3$ of ice at the summit of Mt. Wrangell plus another 150 ± 50 km$^3$ on the slopes. An eruption of this explosive, andesitic volcano, like that of Mt. St. Helens in Washington or Nevado del Ruiz in Columbia, could potentially mobilize many km$^3$ of ice and water. It has an area of about 34 km$^2$ above the 4000-m altitude; the more familiar Mt. Rainier in Washington has less than 1 km$^2$ above this altitude. If we compare volumes above the 2000-m altitude, Mt. Wrangell is eight times larger than Mt. Rainier. Mt. Wrangell is one of the largest andesitic piles in the world with a lava volume of about 900 km$^3$ (Nye, 1982). It is also the only site of current volcanic activity in the Wrangell Mountains. This activity has varied during the past two decades, with dramatic effects on the ice cover. After 1964 the heat flux at the summit increased by several orders of magnitude and began non-equilibrium (i.e., net loss) basal melting of glacier ice in the North Crater. Since 1965 we have measured the rate of loss of ice volume, by precision surveying and photogrammetry, as one means of estimating the volcanic heat flux (Motyka, 1983).

There is no melting at the 4000-m altitude of Mt. Wrangell's summit caldera except by volcanic heat. This fact simplifies analysis. In particular, it makes the interpretation of glacier response to changes in volcanic heat flux more straightforward at the summit than on the flanks of the volcano, especially near the glacier termini. The glaciers radiating from Mt. Wrangell have flow speeds on the order of 100 m yr$^{-1}$. The termini of these glaciers appear to be approximately in steady state except for some on the northeast flank which are *advancing* at rates of 15 to 30 m yr$^{-1}$. A major goal of the research on Mt.

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FIG. 1. A view looking east, across the Copper River near Copper Center, to the Wrangell Mountains. Mt. Sanford (4950 m) is on the left, Mt. Drum (3330 m) is in the center foreground, and the broad shield of Mt. Wrangell (4317 m) is on the right.

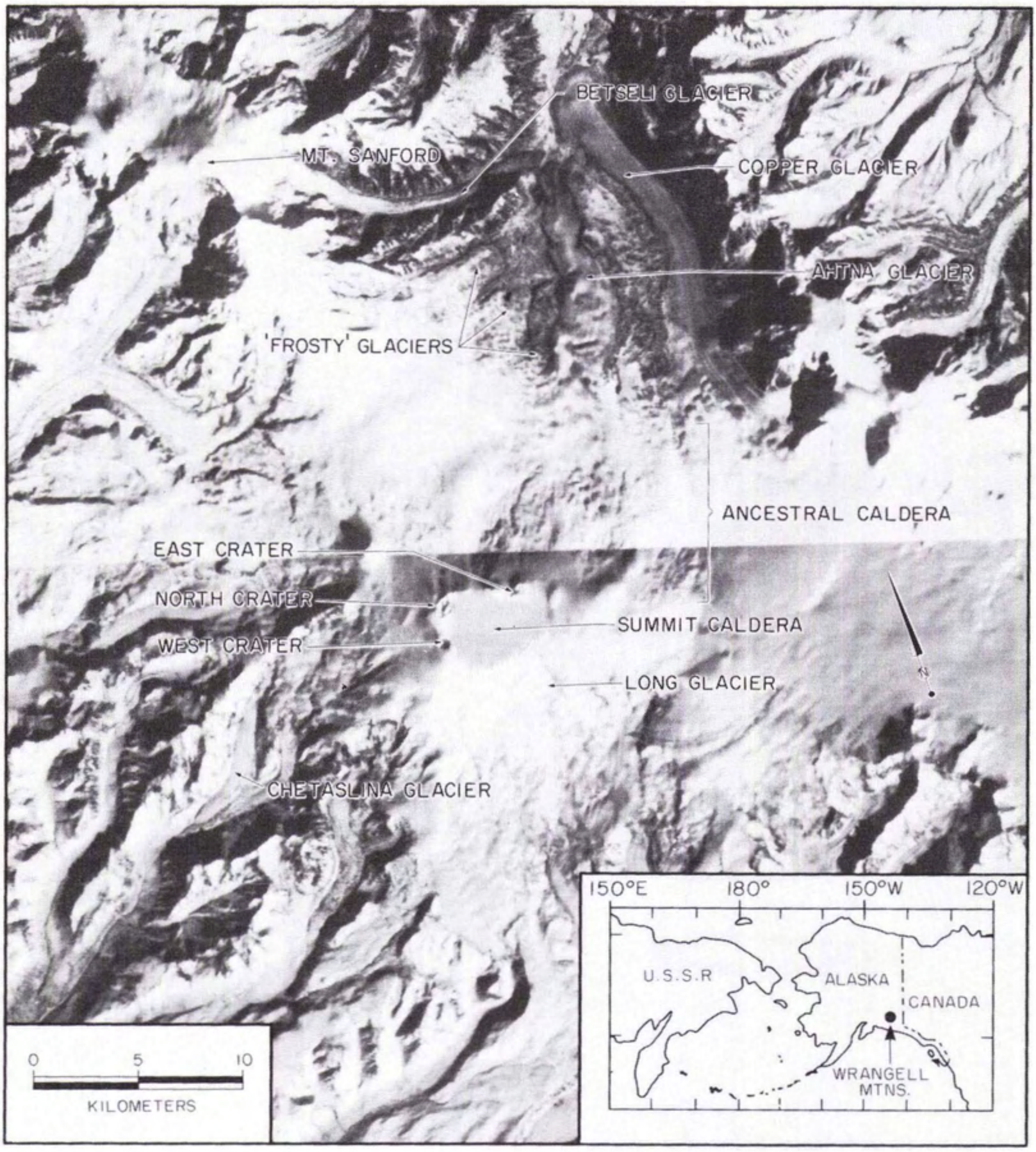


FIG. 2. Mt. Wrangell as seen from space on 24 March 1984. This Landsat satellite image (40251-20183-7) shows Mt. Wrangell's summit caldera and rim craters. The glaciers of the northeast flank ("Frosty," Ahtna, and Copper) and the Chetaslina Glacier are also discussed in this paper. Mt. Sanford is visible to the north of Mt. Wrangell (see Figures 1 and 3).

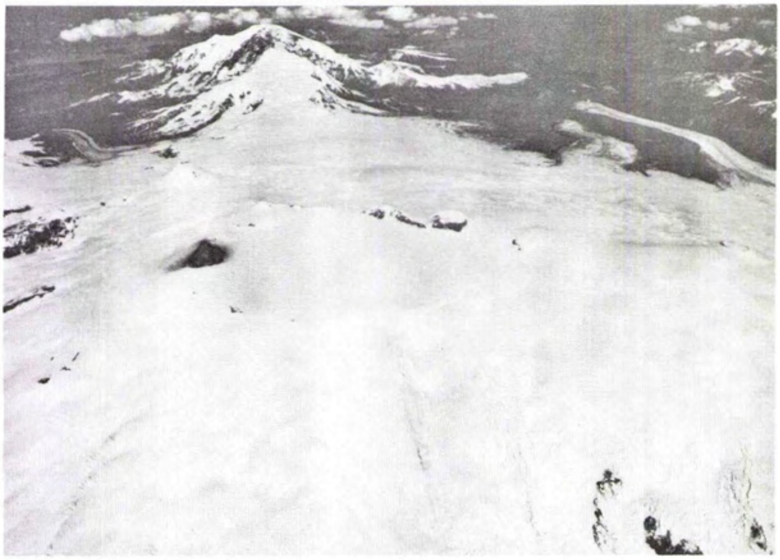


FIG. 3. A 1948 USGS Trimetrigon photo looking north across the summit of Mt. Wrangell with Mt. Sanford in the background. The north inner wall of the West Crater is snow-free, but only parts of the southern rim of the North Crater have bare ground exposed. Apparently, the summit looked like this in the early 1900's (Dunn, 1909). Marked changes have occurred since 1964 (see Figures 4, 6, and 7).

Wrangell's flank glaciers is to determine whether or not the anomalous advances are caused by the increased volcanic heat flux observed at the summit (Sturm, 1983).

Most Alaskan volcanoes are glacier covered and provide excellent opportunities to study interactions between glaciers and volcanoes. The phenomena involved are becoming more familiar as we gain experience in the more inaccessible parts of our planet. In Antarctica the best known example of a sub-glacial eruption occurred at Deception Island in 1967 and 1969 (Baker *et al.*, 1969; Brecker *et al.*, 1974). Glacier-volcano interactions in Iceland have been studied for many years by Thorarinsson and his colleagues, and the recent explanation of Jökulhlaups by Björnsson (1974, 1975) represents a fundamental advance to our knowledge. However, because Iceland is on a spreading ridge, its volcanism is basically different from the explosive volcanism in Alaska and Kamchatka which are both on converging margins. The glacier-volcano interactions in Kamchatka have been studied by Vinogradov for many years and continue to the present (Vinogradov, 1981; Kotlyakov *et al.*, 1985). The Alaskan glacier-volcano interactions, although not as well known, are probably very similar to those observed on Kamchatka (Benson *et al.*, 1985).

## HISTORY OF RESEARCH

Although the first photographs taken on the summit of Mt. Wrangell were published more than 75 years ago (Dunn, 1909), research there began in 1953 and 1954 with cosmic ray measurements and high altitude physiology experiments (Beiser, 1953). In 1961 glaciological research began at the summit. Initially it focused on the dry-snow facies of glaciers which only exist on Alaska's highest mountains (Benson, 1962; Benson, 1967). However, it included measurements of volcanic heat flux (Benson, 1963; Benson, 1968). Between 1961 and 1966, glaciological and volcanological studies continued (Bingham, 1967; Wharton, 1966; Bingham and Benson, 1968) and included construction of a volcanically heated hut on the southern rim of the North Crater in 1964. The volcanic heat flux increased markedly in and around the North Crater (Figure 6) following the 1964 Great Alaskan Earthquake in Prince William Sound. In 1968 and 1969 observations and oblique aerial photographs showed continuing loss of ice from the North Crater; this demonstrated that the high heat flux was persisting (Benson *et al.*, 1975).

Changes in ice cover at the summit were monitored by Landsat satellite imagery beginning in 1972 (Benson and Shapiro, 1974). Although the satellite images provide excellent regional coverage of the Wrangell Mountains and reveal activity at the summit of Mt. Wrangell (Figure 2), they do not have the resolution required for measuring ice volume losses within craters on the caldera rim. Therefore, we augmented the satellite observation program in two ways. We obtained vertical aerial photographs of the summit in 1972 (by NASA aircraft) and 1973 (by Navy aircraft). In August 1973, G. Weller and C. Benson of the Geophysical Institute made a field trip to the summit to measure the ice volume losses by surveying from the southern rim of the North Crater.

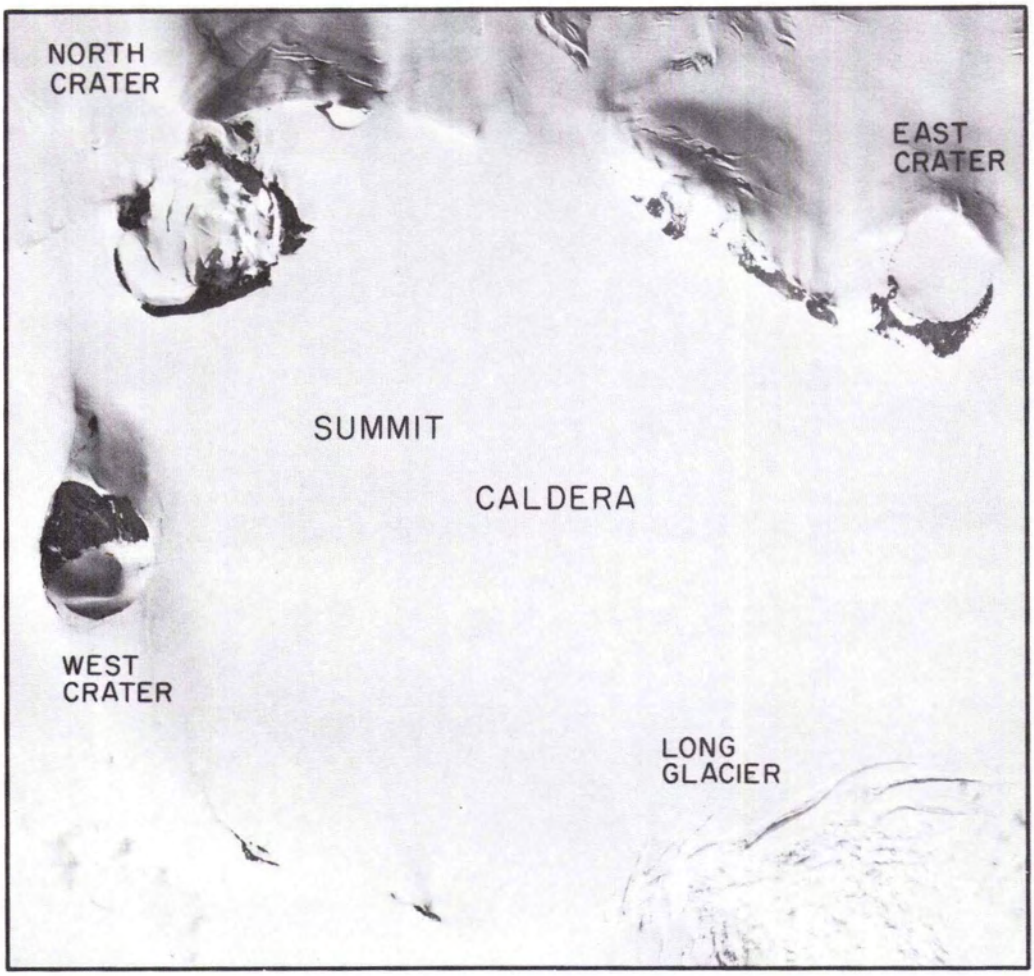


FIG. 4. A vertical aerial photograph (by NPAS) of Mt. Wrangell's summit on 22 August 1975. The scale is the same as that on the map of Figure 5.

On 4 September 1974, pilot Jack Wilson of Glennallen noticed a sudden blackening of the snow on Mt. Wrangell. On the following day, Benson and Shapiro of the Geophysical Institute flew with Wilson to observe the summit region. The North Crater rims had large areas of bare ground exposed, the snow surface was blackened by ash, and a lake was present in the bottom of the crater (Figure 7). We now know that this was a time of high volcanic heat flow and we may have been seeing the aftermath of phreatic eruptions.

The authors of the present paper began to collaborate at this point, and vertical aerial photographs have been obtained annually since 1974 by North Pacific Aerial Surveys (NPAS). Our basic assumption was that vertical aerial photogrammetry could enable us to measure the loss of ice volume caused by volcanic heating at the summit of Mt. Wrangell. This has proven to be a valid assumption (Motyka *et al.*, 1978; Motyka *et al.*, 1980). Photogrammetry was used extensively by Motyka (1983) in his Ph.D. research. Field work was concentrated at the summit of Mt. Wrangell until 1976 when the glaciers radiating from the summit were included in the field work and in the photogrammetry simultaneously. A study comparing glaciers of the northeast flank with the Chetaslina Glacier on the west flank was initiated by the late Peter MacKeith. It was completed as the M.S. thesis of Matthew Sturm (1983). In 1982 airborne radio echo sounding of ice thickness was done together with Garry Clarke, University of British Columbia and Philip Upton of the Arctic Institute of North America. Ice core was also obtained at the summit to a depth of 43 m in the caldera during 1982 (Figures 5 and 11).

## PHOTOGRAMMETRY

The U.S. Geological Survey (USGS) took Trimetrigon aerial photographs over the Wrangell Mountains in 1948 (Figure 3) and vertical ones in 1957. The USGS topographic maps, at scales of 1:63,360 with 100-foot contours and 1:250,000 with 200-foot

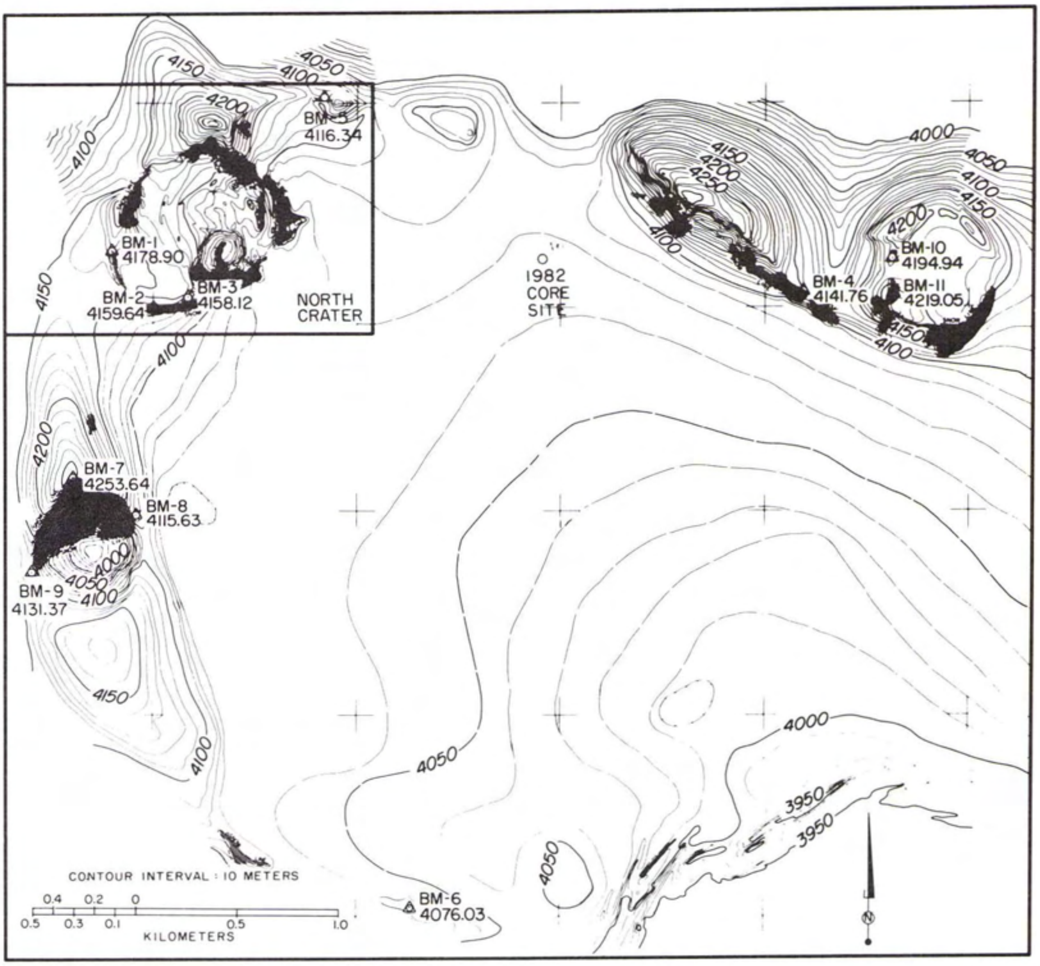


FIG. 5. A photogrammetric map of the summit of Mt. Wrangell based on ground control points 1 through 7 and aerial photographs taken on 22 August 1975 by NPAS. The boundary around the North Crater identifies the boundaries used in Figures 9 and 12; the original map scale was 1:10,000.

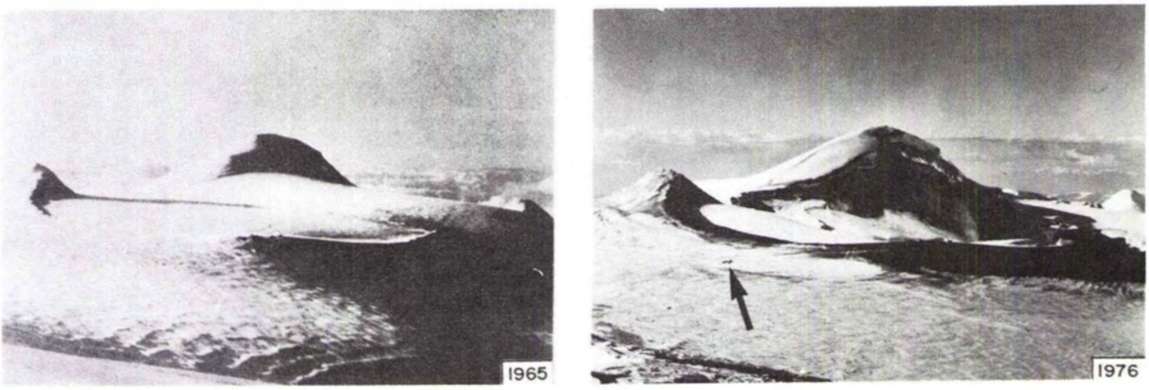


FIG. 6. The North Crater as seen from point 7 (see Figure 5) on the West Crater in 1965 on the left (photo by G. Wharton) and in 1976 on the right (photo by C. Benson). During these 11 years, volcanic heat melted more than 40 million cubic metres of ice in and around the North Crater (about 32 million within the crater; see text). The huts which served as research stations are visible on the southern rim and the tent camp of 1976 is visible outside the crater (arrow); volcanic fumes since 1976 have prevented us from living on the rim.

FIG. 7. Aerial photograph of the North Crater by L. Shapiro and C. Benson on 5 September 1974. The rate of ice loss was especially high in 1974 and it was accompanied by dirt being spread over the rapidly fracturing glacier surface. A lake was present in the deepest part of the crater, under the wispy fumarole plume just behind the southern rim.

FIG. 8. Carl Tobin surveying from bench mark 4 (Figure 5); the East Crater is outside of the picture to the left. The bare ground is kept snow-free by volcanic heat.

contours, were made from the 1957 photographs. Table 1 summarizes the vertical aerial photographs which have been taken over Mt. Wrangell.

### GROUND CONTROL

No premarked control points exist on the photos before 1975. However, we concluded that, by premarking control points on the 1975 and subsequent photographs, we could transfer this ground control to the pre-1975 aerial photographs and thereby use them photogrammetrically. Before selecting ground control points in 1975, we examined all available earlier photographs to aid in selecting points which had remained snow-free over the years. We were also able to base the ground control points on the network of survey points established for measuring glacier flow in the caldera and North Crater.

In 1961 the first control points were established at the summit of Mt. Wrangell by triangulation from the ends of a taped baseline with a Wild T-2 theodolite. The fixed points were located on ice-free places, and used to measure glacier flow by repeated triangulation to markers set in the snow surface (Figure 8).

In 1965 the network was refined, extended, and

TABLE 1. SUMMARY OF MOUNT WRANGELL VERTICAL AERIAL PHOTOGRAPHY

| | | Craters | | | Glaciers | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Photo Date | Film Type | North | West | East | Copper | Ahtna | Frosty | Cheta-Slina | Photo Source |
| | | | | Photo Scale Reciprocals | | | | | |
| 8-09-57 | BW | 25000 | 25000 | 25000 | | 25000 | 25000 | | USGS |
| 7-21-72 | C | 7600 | 7600 | 7600 | | | | | NASA |
| 7-22-72 | BW | 12000 | 12000 | 12000 | | | | | NASA |
| 7-24-73 | BW | 14000 | 14000 | 14000 | | | | | NAVY |
| 8-14-74 | BW | 12000 | 12000 | | | | | | NPAS |
| 8-22-75 | BW | 12000 | 12000 | 12000 | | | | 12000 | NPAS |
| 7-06-76 | C | 12000 | 12000 | | | | | | NPAS |
| 7-08-76 | BW | 12000 | 12000 | 12000 | | | | | NPAS |
| 6-19-77 | C | 50000 | 50000 | | | | | | NASA |
| 6-30-77 | BW | 8000 | | | | | | | ARMY |
| 7-28-77 | BW | 12000 | 12000 | 12000 | 30000 | 30000 | 30000 | 30000 | NPAS |
| 8-26-78 | C | 12000 | 12000 | 12000 | | | | | NPAS |
| 8-27-78 | C | 12000 | 12000 | 12000 | 30000 | 30000 | 30000 | 30000 | NPAS |
| 9-02-78 | BW | 12000 | | | 30000 | 30000 | | | NPAS |
| 8-18-79 | BW | 12000 | 12000 | 12000 | 30000 | 30000 | 30000 | 30000 | NPAS |
| 9-04-80 | BW | 12000 | 12000 | 12000 | | 18000 | 18000 | | NPAS |
| 4-16-81 | BW | 12000 | | | | | | | NPAS |
| 8-27-81 | BW | 12000 | 12000 | 12000 | 30000 | 30000 | 30000 | 30000 | NPAS |
| 8-12-82 | BW | 12000 | 12000 | 12000 | 30000 | 30000 | 30000 | 30000 | NPAS |
| 7-27-83 | BW | 12000 | 12000 | 12000 | | | 30000 | | NPAS |
| 8-14-84 | BW | 12000 | 12000 | 12000 | | | | | NPAS |
| 8-15-84 | BW | 12000 | 12000 | 12000 | | | 24000 | | NPAS |
| 7-06-85 | BW | | | | 30000 | 30000 | 30000 | 30000 | NPAS |
| 8-24-85 | BW | 12000 | 12000 | 12000 | | | 24000 | | NPAS |

resurveyed; it was used for extensive and detailed measurements of glacier flow in the North Crater and the caldera during 1965 and 1966 (Bingham, 1967).

In 1975 the summit network was extended to include points specifically located as photogrammetric ground-control points. These were marked by crosses of white fabric radiating from 3 to 4 m from the survey marker. Beginning in 1975, distances were measured electronically with an HP 3800; angles were measured with a Wild T-2 theodolite as before. Good agreement existed between coordinates of control points in the 1961, 1965, and 1975 surveys at the summit (Motyka, 1983). However, the 1975 network is considered to be the most reliable because it involved electronic distance measurement; it is the one used for all of the photogrammetric work.

In 1976 the network of pre-marked control points for aerial photogrammetry and glacier movement measurements was established on the northeast flank of Mt. Wrangell. In 1977 a similar network was established on the west flank for measurement of the Chetaslina Glacier. In 1978 the summit network was expanded by four more points, two on the West Crater and two on the East Crater.

Most of the survey control points consist of iron pipes, 1 1/2 to 2 inches in diameter, driven into the ground and secured by piling rocks around them. Labeled brass surveying caps identify the points (Figure 8). In some cases pieces of steel rebar were used with aluminum survey caps mounted on them.

A total of 11 points are on the summit (Figure 5), 20 on the northeast flank and seven on the west flank. Thus, three separate survey networks exist. Although we plan to connect them in the future, they serve adequately for photogrammetric and glacier flow measurements now.

## AERIAL PHOTOGRAPHY

In 1974 we acquired black-and-white vertical aerial photography of the North and West craters at a scale of 1:12,000 using a Zeiss RMK-A 15/23 mapping camera mounted in a Model 24 Lear Jet. In 1975, shortly after the pre-marking was completed, we again obtained black-and-white photography of all three summit craters at a nominal scale of 1:12,000 as well as the entire summit caldera at 1:36,000 using the same Zeiss camera and aircraft.

Since 1976 we have acquired aerial photography annually using black-and-white and/or color film in Zeiss cameras mounted in twin-engine Cessna 320D Skyknights. The areas of coverage have varied from just the summit craters to more than 800 km$^2$, including the flank glaciers. Table 1 presents a summary of the dates of photography, film type used, nominal scales, features photographed, and source. The 1957 and 1983 vertical photos of the North Crater have been selected as examples (Figure 9).

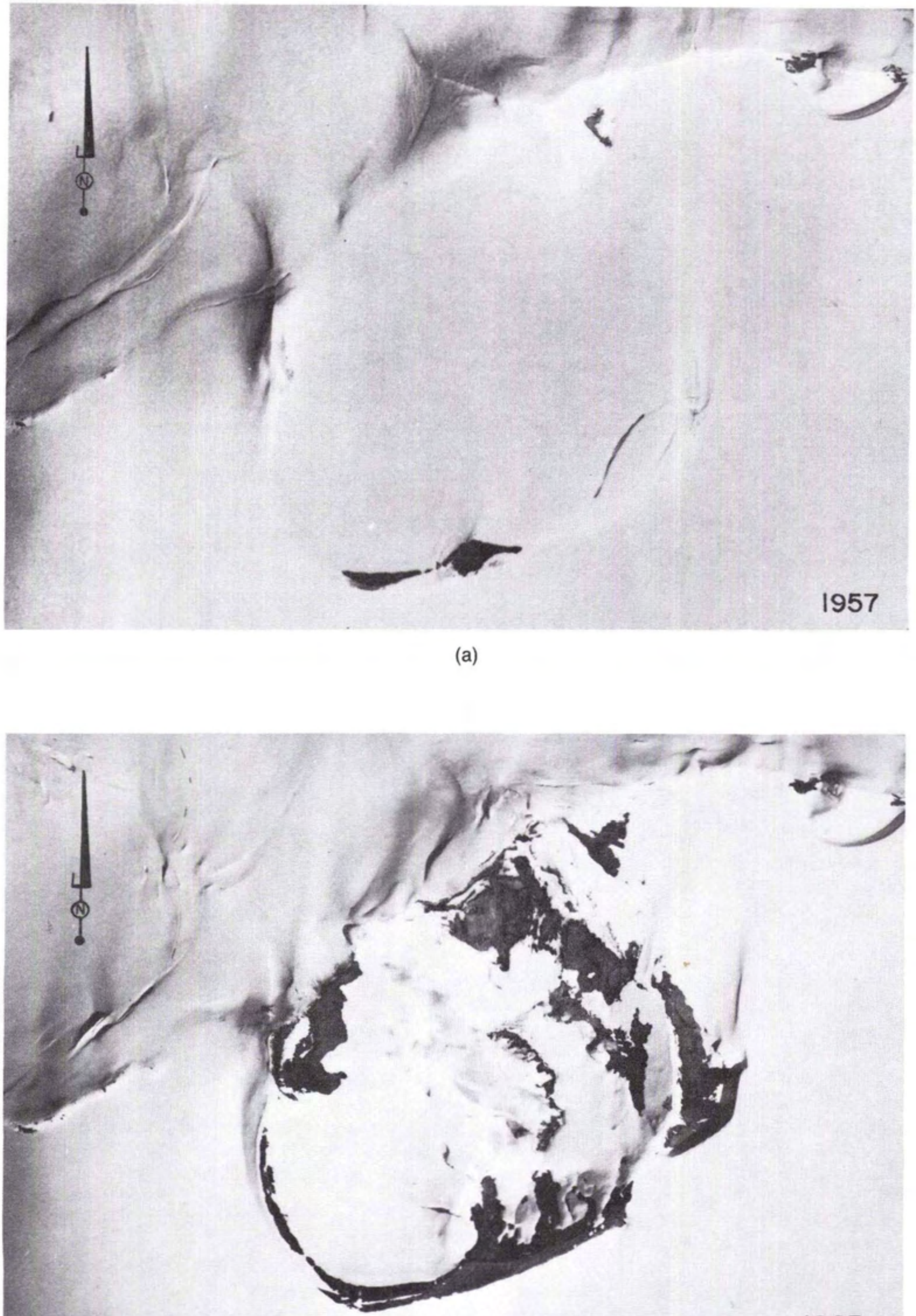
As in any photogrammetric project, acquisition of good quality aerial photographs is of utmost importance. Some of the factors to be considered on the Mt. Wrangell project are time of year, weather conditions, the presence of volcanic fumaroles which condense to form clouds in the North Crater, and the surface condition of the snow. First of all, the aerial photographs can only be taken in the latter part of the summer, usually after the middle of July and before the beginning of September. Ideally, the photographs should be taken on the same day each year to eliminate some of the other temporal variables in subsequent analyses of the results. Once the time of year has been selected, it is necessary to wait for acceptable weather. Because the terrain elevation is 4100 m, the aerial photographs of the summit craters must be taken at an altitude of 6100-m above mean sea level, which requires the use of oxygen on the photograph missions. Navigation is rather difficult because there is an absence of the usual landmarks one might follow on an aerial photography mission. The altitude of the project also makes it more difficult to find acceptable weather for taking the photographs. Either the skies must be clear or the clouds must be below the summit of the mountain (Figure 10). On days when clouds are present, we rely on people on the mountain to report conditions of the summit. When, as is often the case, no people are on the summit, weather reports for the summit are almost non-existent. This means that it is usually necessary to obtain the photographs on virtually cloud-free days.

The condition of the snow surface at the summit is also important. It must have good definition to permit a solid stereoscopic image in the stereoplotters. Generally to obtain the right conditions, the photography should be taken several days after the most recent snowfall, ideally while the snow surface is rippled from the wind or lightly covered with ash and debris from the exposed crater rim. The clouds produced by fumaroles in the North Crater interfere with photography (Figure 11). This problem can be minimized by taking pictures on a windy day, thereby allowing differing stereoscopic views through the cloud.

These requirements, consisting of a six-week acceptable flight period, clear weather, good surface definition, and minimal fumarole activity, severely limit the number of days on which acceptable photographs can be obtained.

## TOPOGRAPHIC MAPPING

The primary purpose for taking vertical aerial photographs of the summit craters annually has been to measure changes in the ice volume through photogrammetric techniques of mapping and digital analysis. Topographic maps have been prepared of the craters at scales of 1:2000 with 5-metre contours. These maps also show areas of bare ground, fissures in the snow, fumarole vents, standing water, and man-made structures which exist on the south rim of the North Crater. Table 2 summarizes the dates of photography and the photogrammetric products



(a)

(b)

FIG. 9. Vertical photos of the North Crater (see Figure 5 for photo boundaries). (a) is a 1957 photo by USGS and (b) is a 1983 photo by NPAS.

FIG. 10. Ski-equipped supercub on the northern rim of the North Crater in 1961; Jack Wilson is on the left and C. Benson is on the right (photo by Sam Scott). Often, when the summit region is clear, there is nearly solid cloud cover below, as shown here.

TABLE 2. SUMMARY OF 1:2000 TOPOGRAPHIC MAPS AND CROSS-SECTIONS PRODUCED

| Photo Date | North Crater | West Crater | East Crater |
|---|---|---|---|
| 8-09-57 | M,X | X | X |
| 7-21-72 | M,X | X | X |
| 7-24-73 | M,X | | |
| 8-14-74 | M,X | X | |
| 8-22-75* | M,X | | |
| 7-08-76 | M,X | X | |
| 7-28-77 | M,X | | |
| 8-27-78 | | M,X | M,X |
| 9-02-78 | M,X | | |
| 8-18-79 | M,X | M,X | |
| 9-04-80 | M,X | M,X | M,X |
| 4-16-81 | M,X | | |
| 8-27-81 | M,X | | |
| 8-12-82 | M,X | | |
| 7-27-83 | M,X | | |
| 8-15-84 | M,X | | |
| 8-24-85 | M,X | | |

M = Topographic map X = Cross-sections

*A topographic map of the summit caldera was also prepared at 1:10,000 with 10-metre contours.

produced for the three summit craters. The entire summit caldera was also mapped at a scale of 1:10,000 with 10-metre contours from the 22 August 1975 photographs.

The 1974 and 1975 maps were produced on a Kelsh projection stereoplotter. All other maps have been prepared using Kern PG2 stereoplotter systems consisting of the PG2 stereorestitution instrument, AT- and GP1-electronic plotting tables, and DC2 and MAPS200 digitizing and recording systems. The three-axis encoders provided a resolution of 0.05 m in *XYZ* coordinate positions. The 1957 and 1983 maps of the North Crater are presented as examples in Figure 12.

A potentially significant problem in preparing topographic maps and cross sections has been the operator's ability to see the snow surface stereoscopically, especially in areas unmarked by drifts, fissures, ash, or other features. To check the photogrammetric operator's ability to position the floating mark accurately on the snow surface, we have ground survey data to compare with some of the maps. In particular, the 1975 photography was fortuitously done on the same day that glacier flow markers were being surveyed in the North Crater. All of the points checked well within our ± 2-m accuracy estimate. In fact, most of them were within ± 1 m. In 1976 the photogrammetric points agreed with the ground survey points well within our accuracy estimate of ± 0.5 m. The primary reason for the increased accuracy in the 1976 data was because the aerial photographs were acquired under nearly optimum conditions, thereby providing excellent stereoscopic depth perception of the snow surface. To further check our accuracy, we established ten checkpoints at the North Crater in 1978. On 24 and 25 August 1978, the *XYZ* coordinates of stakes at these ten points were surveyed from the control points. On the following day, 26 August, the aerial photographs were acquired. The position of each of these ten checkpoints was plotted on the topographic map compiled at 1:2000, then the photogrammetrist digitized and recorded ten sets of elevations for each point. This data set (Table 3) provides an assessment of repeatability and accuracy for these checkpoints. Although we are still involved in error analysis, we are confident that our methods allow us to measure the lowering of the snow surface in the North Crater, which is generally about 5-m per year, and has been more than 50-m per year in places.

FIG. 11. Fumarole plumes coming out of the North Crater as viewed from the 1982 ice-core drilling site in the caldera (see Figure 5, Dan Solie at drill site, photo by C. Benson).

Photogrammetry also shows that the snow surface altitude decreased by 10 to 15 m in the caldera next to the southern and eastern rims of the North Crater between 1957 and 1975. Photogrammetric techniques were not applicable farther out in the caldera because of difficulties in seeing the featureless snow surface and because the distances from control points was excessive. However, survey data from 1965 and 1975 confirmed the 15-m drop in snow surface near the North Crater and showed that it decreased to less than 1 m within 1 km from the crater rim. In fact, most of the caldera surface has remained at the same altitude over the past decade, which indicates that the increased heat flux is highly focused on the region in and near the North Crater. As a check on the equilibrium status of most of the caldera, horizontal resection was made in 1978 of three points which had been surveyed in 1975. The results showed that the altitude of the snow surface in the center of the caldera had remained within ± 25 cm over the 3-year period.

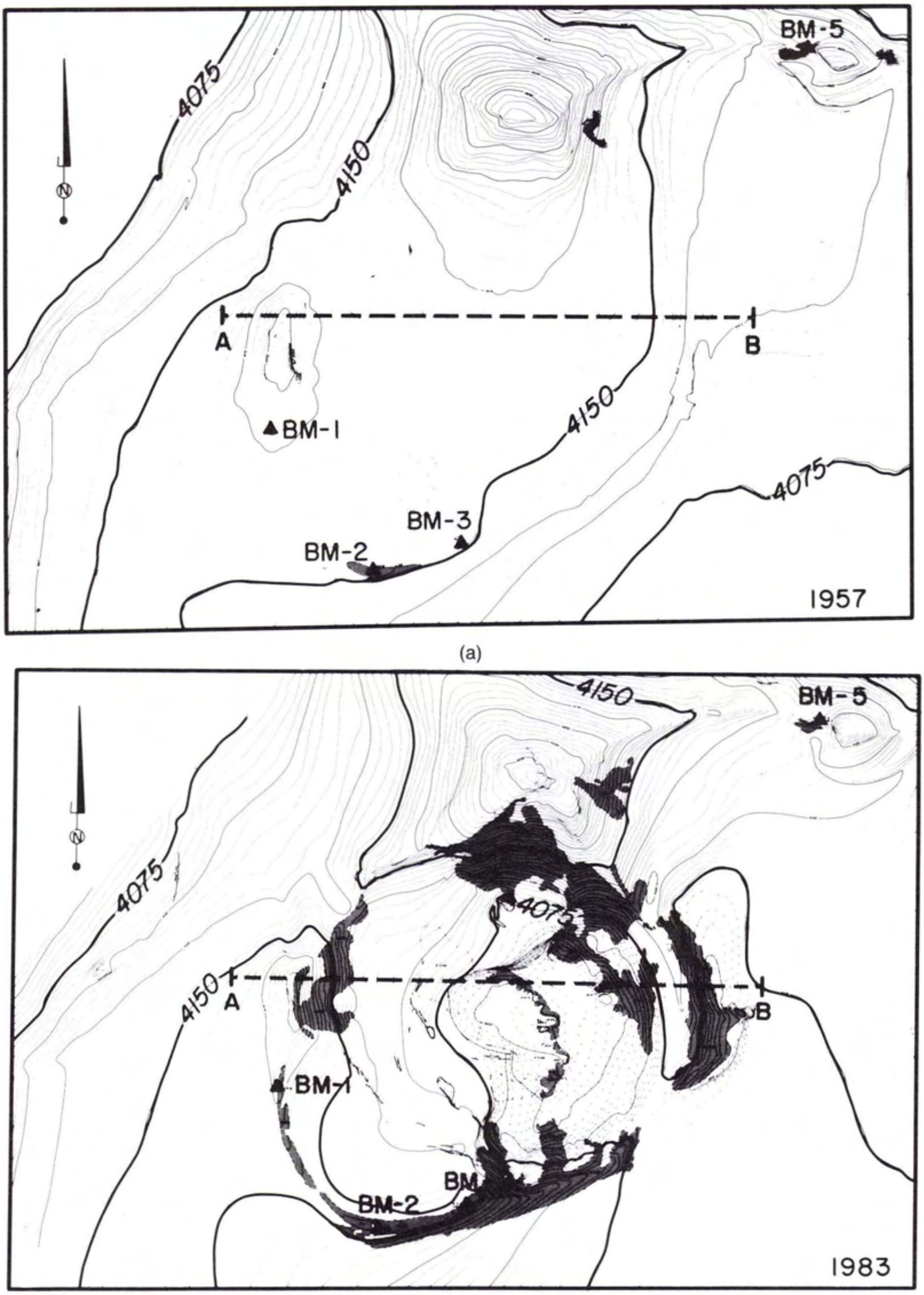


FIG. 12. Photogrammetric topographic maps of the North Crater in 1957 (a) and in 1983 (b). The 4075- and 4150-m contours are emphasized to aid comparison. See Figure 5 for map boundaries. The dashed lines A-B, along the *X* axis, show location of the cross sections in Figure 13a and b. The original map scale was 1:2000 with a 5-m contour interval.

TABLE 3. COMPARISON OF PHOTOGRAMMETRIC TO GROUND SURVEYED ELEVATIONS AT NORTH CRATER

| Stake | Qualitative Assessment of Surface Visibility on Photography | Mean, $Z_p$, and s. d. of Ten Photogrammetric Measurements 8-26-78 | Survey Measurement $Z_s$ 8-24 & 25-78 | Difference $Z_p - Z_s$ |
|---|---|---|---|---|
| | | Inside Crater Rim | | |
| 11(64) | Excellent | 4164.58 ± 0.20 | 4165.22 | −0.64 |
| 12(ON3) | Fair | 4141.15 ± 0.14 | 4141.31 | +0.16 |
| 13(NN3) | Fair | 4141.27 ± 0.15 | 4141.53 | +0.26 |
| 14(N7) | Excellent | 4139.62 ± 0.25 | 4139.68 | +0.06 |
| 15(N8) | Fair | 4151.25 ± 0.23 | 4151.57 | +0.32 |
| | | Outside Crater Rim | | |
| 16(NC23) | Poor | 4100.96 ± 0.87 | 4102.89 | +1.93 |
| 17(NC28) | Poor | 4093.73 ± 0.81 | 4098.02 | +4.29 |
| 18(NC29) | Excellent | 4081.84 ± 0.18 | 4082.13 | +0.29 |
| 19(NC34) | Fair | 4075.16 ± 0.22 | 4075.80 | +0.64 |
| 20(NS21) | Fair | 4097.18 ± 0.13 | 4097.49 | +0.31 |

## DIGITAL CROSS SECTIONS

Topographic maps of the summit craters show changes in ice volume in a unique and graphic manner that nothing else can equal. To quantify these changes, we made photogrammetric digital cross sections using the Kern PG2 stereoplotter system for the North, West, and East craters, as summarized in Table 2.

In the North Crater, parallel cross sections along the $X$ axis have been spaced 20-m apart along the $Y$ axis with distances and elevations for discrete points being digitized along each line at irregular spacing to portray the profile as accurately as possible. Distances are recorded to the nearest metre, with elevations to the nearest tenth. There are 104 parallel cross section lines in the North Crater with an average of 10,000 points being digitized each year.

The digital data are stored on magnetic tape, and computer programs have been written to draw comparative profiles (Figure 13) and to calculate ice volume changes between selected pairs of years.

As an example of the use of digitized data, we compare data from 1965 to 1976 (Figure 6). The area inside the North Crater rim is $5.164 \times 10^5$ m$^2$; the total volume change during the 11 years was $28.86 \times 10^6$ m$^3$. To this we add the average accumulation of 0.5-m water equivalent per year, and convert it to equivalent ice volume to get a total ice volume loss of $31.96 \times 10^6$ m$^3$. The heat required to raise this ice from −20°C (the mean annual temperature) to 0°C and melt it is $2.62 \times 10^{15}$ cal. If this is applied over the North Crater area for the 11-year period, we obtain an average volcanic heat flux of 62 watts m$^{-2}$, which is about 1400 times the Earth's average value. This is a minimum value because it does not account for heating or evaporating any of the water, nor does it allow for the fact that heat loss from ice-free areas is not measured by this simplified approach. These complications are discussed by Motyka (1983).

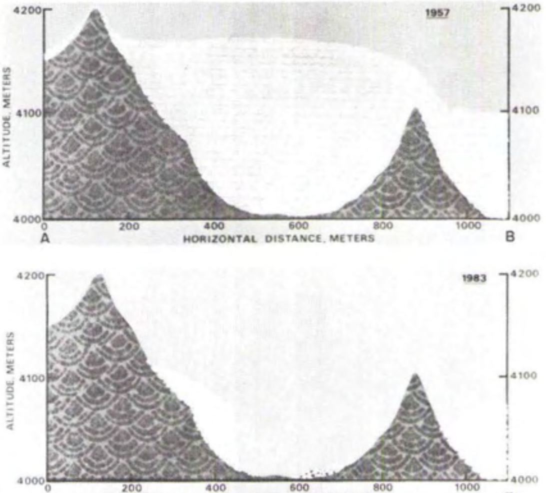


FIG. 13. Photogrammetrically determined digital cross sections of the North Crater in 1957 and 1983 along the section identified in Figures 12a and b.

By 1984 about 85 percent of the ice volume within the North Crater in 1965 had melted and drained or evaporated from the crater. The annual data on the loss of ice volume reveal significant variations in the volcanic heat flux. Maximum heat flux values occurred in 1968, 1974, and 1979. The first two maxima were followed by several years of reduced heat flux, but the high values begun in 1979 appear persistent (Motyka, 1983).

Digital cross sections of the West and East craters have not been as extensive as those of the North Crater. They were done along east-west and north-south orientations in the East Crater, and along the main symmetry axis of the West Crater (i.e., parallel to the caldera rim). The maps and cross sections show little change in ice volume of the East Crater.

In the West Crater they show a loss of ice in the mid-1960's followed by a gradual increase in its ice content. Some synchronism in the behavior of the North and West craters suggest that they are interconnected at depth. However, changes in the ice volume in the West Crater are an order of magnitude smaller than in the North Crater (Motyka, 1983).

### ORTHOPHOTOS

Research on the glaciers radiating from Mt. Wrangell began in 1976 on the Copper Glacier and other northeast flank glaciers, and in 1977 on the Chetaslina Glacier. During these studies pre-marked control points were set and surveyed in preparation for aerial photography and production of orthophoto maps; the same bench marks are used to measure glacier flow. It soon became clear that all of the glaciers on the north-northeast flank of Mt. Wrangell, except the copper glacier, had advanced on the order of 150 m since 1957. Partial 1965 aerial photo coverage of one of these termini indicates that much, if not all, of this advance occurred since 1965. In comparison with other glaciers in the region, these glaciers are marked by a conspicuous absence of any debris-covered stagnant terminal region. Numerous recent and ice-cored moraines in front of the present termini appear to record a fluctuating or pulsing advance and retreat of these glaciers (Sturm, 1983).

To compare the surface appearance of these glaciers and to measure the change in shape and position of their termini over the entire region for a period of about 20 years, we decided to produce orthophoto maps for the Ahtna, Frosty, and Chetaslina glaciers. All orthophoto maps were produced at scales of 1:25,000 for the years shown in Table 4.

TABLE 4. SUMMARY OF ORTHOPHOTO MAPS PRODUCED AT A SCALE OF 1:25,000

| Photo Date | Ahtna & Frosty Glaciers | Chetaslina Glacier |
|---|---|---|
| 8-09-57 | X | |
| 7-28-77 | X | X |
| 8-18-79 | X | |
| 8-27-81 | X | X |

In order to cover sufficient geographic area in the orthophoto maps, it was necessary to control several flight lines of aerial photography. Following preparation of glass diapositives, having a density range from 0.3 to 1.2, we performed fully analytical aerotriangulation using a Kern PMG2 point marking instrument, Kern MK2 monocomparator, E.D.S. Point 4 minicomputer, and Kenefick's Rapid Analytical Block Aerial Triangulation System (RABATS) software. These modularized programs provide for strip formation, transformation, and adjustment. The strips are formed by successive three-photo relative orientations so that primary passpoints are the result of three-ray intersections. Each strip is then scaled, leveled, and transformed into the ground coordinate system prior to adjustment. Planimetric and altimetric normal equations are then formed for the simultaneous solution of the polynomial coefficients which smooth the strips to better fit the control points and one another at the tie points. The residuals of the aerotriangulation adjustment are presented in Table 5. For the 1957 and 1979 flight lines, tie points and pre-marked control points were stereoscopically transferred to permit processing all three flight lines from both dates as a single block.

Following completion of the aerotriangulation, double-model orthophoto negatives were produced from the glass diapositives using a Gestalt Orthophoto Mapper system. From these negatives final orthophoto maps were photographically reproduced at a scale of 1:25,000 without contours or coordinate grid lines (Figure 14).

In studying these orthophoto maps produced from aerial photography taken over a period of 24 years in conjunction with ground observations, the advancing fronts of the "Frosty" and Ahtna glaciers are easily discerned (Figure 15). It is especially significant to note that the Betseli Glacier, which comes from Mt. Sanford, is receding while the Ahtna and Frosty glaciers from Mt. Wrangell are advancing. This argues against a simple climatic cause. Maps of the Chetaslina Glacier on Mt. Wrangell's west flank show that it has not advanced. The detailed flow behavior of glaciers on the west and northeast flanks of Mt. Wrangell was studied by Sturm (1983). He concluded that the advance of glaciers on Mt. Wrangell's northeast is probably a result of subglacial water being provided year-round by the increased volcanic heat flux at the summit of Mt. Wrangell.

TABLE 5. RESIDUALS OF ANALYTICAL AEROTRIANGULATION FOR ORTHOPHOTO MAPPING

| Photo Date | No. Flight Lines | No. Control Points | R.M.S. Values (Metres) | | | Maximum Values (Metres) | | | Glaciers Covered |
|---|---|---|---|---|---|---|---|---|---|
| | | | X | Y | Z | X | Y | Z | |
| 8-09-57 | 1 | | | | | | | | |
| 8-18-79 | 2 | 7 | 1.24 | 0.82 | 0.40 | 1.89 | 1.65 | 0.76 | Ahtna & Frosty |
| 7-28-77 | 1 | 5 | 0.41 | 0.70 | 0.61 | 0.57 | 0.90 | 0.98 | Ahtna & Frosty |
| 8-27-81 | 2 | 7 | 0.21 | 0.29 | 0.41 | 0.37 | 0.71 | 0.68 | Ahtna & Frosty |
| 8-27-81 | 1 | 4 | 0.31 | 0.25 | 0.35 | 0.46 | 0.42 | 0.44 | Chetaslina |

## DISCUSSION

During the course of this on-going project at Mt. Wrangell, several difficulties were encountered that are rare in conventional photogrammetric mapping projects. Some of these problems and our methods to minimize or overcome them are briefly outlined here.

The summit of Mt. Wrangell, at an altitude of over 4000 m, has winter conditions 12 months a year. It can and does get new snow at any time. During a brief period in the summer, higher sun angles coupled with volcanic heating permit evaporation and melting of some of the snow accumulation, most notably near rock exposures and on the crater rims. Ideally, the aerial photographs should be taken following at least a week of clear weather since the last snowfall, thereby improving the surface condition for stereoscopic viewing and increasing the probability that the pre-marks will be visible. This has been an annual problem with no obvious solution.

Depth perception of the snow surface is primarily a function of length of time since the last snowfall. As that time period increases, the snow surface begins to take on a texture more easily seen on the photography. This textured look is caused by natural factors such as high winds creating small drifts which cast shadows, solar and volcanic heating which expose more bare rock areas, and dusting of the snow surface from ash and volcanic debris spread by the wind. The key to good stereoscopic definition of the surface is an adequate period of time since the last snowfall. But one is always aware of the risk involved in delaying an aerial photo flight when weather is clear.

Pre-mark visibility is primarily affected by snow coverage. For the North Crater, the white pre-marks have excellent contrast with the dark volcanic material and are easily seen on the aerial photographs when not covered by snow. Due to severe weather and volcanic gases, the pre-marks have to be maintained and periodically replaced. Not all of the pre-marks have been visible each year, so additional photogrammetric identifiable control points have been established to supplement the primary pre-marked control. These identifiable points include rock outcrops and remains of the huts.

The presence of clouds within the North Crater, generated by condensing steam from fumaroles, has presented increasingly difficult problems to overcome. As the ice volume has diminished within the crater, more fumaroles have appeared. Generally the higher the wind at the time of photography, the more quickly the fumarole plumes are dissipated. We have found that, by acquiring multiple stereoscopic pairs of photographs of the North Crater over a period of an hour or so, we can minimize the problem. By setting each of these models in the stereoplotter, we are afforded slightly different views of the area obscured by the fumarole plumes, and in so doing have been able to map and cross section at least 90 percent of the North Crater each year. The obstructed portion of each map is compared with the map from the preceding year to assist in interpolation of the missing contours.

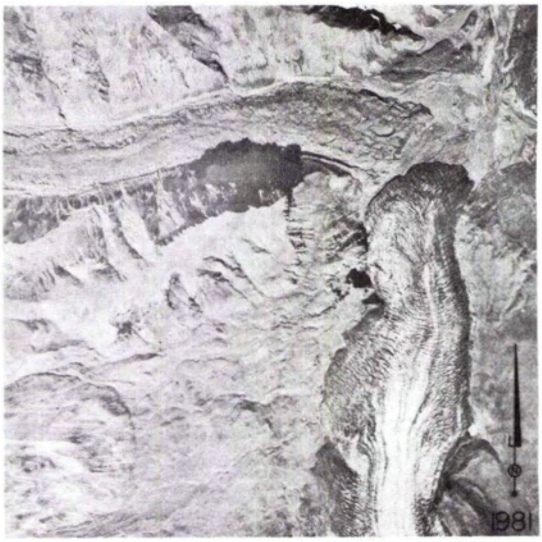


FIG. 14. Orthophoto map of part of the northeast flank of Mt. Wrangell, made from 1981 vertical aerial photographs. These maps have allowed us to determine changes in the glaciers on a regional scale.

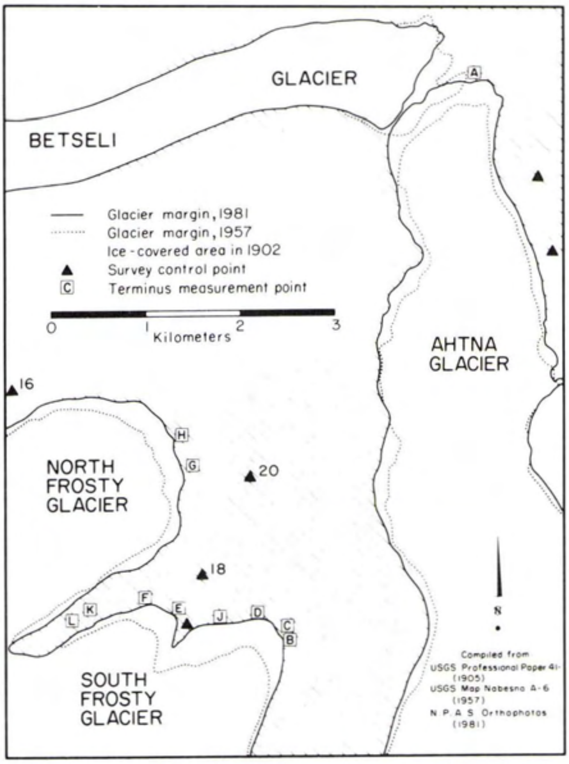


FIG. 15. Maps of glacier termini in 1957 and 1981 prepared from orthophoto maps (Figure 14). These are the only glaciers from Mt. Wrangell which are known to be advancing; they contrast with the Betseli Glacier, from Mt. Sanford, which is shrinking.

The presence of shadows can be both a help and a hindrance to the mapping effort. For most of the crater areas the slight shadows cast by the wind-caused ripple effect on the snow surface are a great help in depth perception. However, within the crater, as the ice surface has lowered, the shadows cast by the crater walls and by fumarole clouds present some difficulty, especially when the shadows fall on exposed rock areas. The adverse effect of these shadows can be minimized by proper exposure of aerial film, careful processing of the film for optimum density, and by varying the exposure on the diapositives for mapping. For the bright undisturbed snow surfaces, the exposure time is increased on the diapositives. When shadows are a problem, a duplicate set of diapositives are also produced, having lesser exposure and therefore better detail in the areas of harsh shadows. By using both sets of diapositives, the effect of the shadows are reduced.

We do not know what caused the recently increased heat flux at the summit of Mt. Wrangell. However, it is interesting to speculate that it may have been triggered by the 1964 Prince William Sound earthquake. Mt. Wrangell was observed to react to the 1899 earthquakes in Yakutat Bay (Powell and Rice, 1900), and the present increase in heat flux followed the 1964 quake. Both earthquakes exceeded magnitude 8 and were about the same distance (200 to 350 km) from Mt. Wrangell. They may have opened convective paths in the volcano which had been partially plugged by deposits of sulphur salts. It is important to continue monitoring changes in volcanic activity at the summit with special attention to its response to the next major earthquake, which is expected to occur in the Yakataga seismic gap.

When the remoteness of Mt. Wrangell is considered, the amount of available data is exceptional. In particular, Mt. Wrangell is one of the few volcanoes to have such long-term and detailed photogrammetric coverage. When we consider that this coverage spans 28 years and precedes a major increase in heat flux, and then monitors the changes in ice cover produced by the increased heat flow, we can start to think of the volcano as a large-scale laboratory.

Because of the multitude of basic scientific problems in the Wrangell Mountains, the potential for geologic hazards, the potential for useful geothermal energy, the interplay between volcanoes and glaciers, and the role played by these volcanoes in their active tectonic setting on the Pacific Rim, the Wrangell Mountains should be a focus of scientific attention for many years.

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