Mapping Glacier Flow on the Juneau Icefield, Alaska-Canada

by

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A RESEARCH PAPER

submitted to

THE DEPARTMENT OF GEOSCIENCES, OREGON STATE UNIVERSITY

in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

GEOGRAPHY PROGRAM

May, 2000

Directed by
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Mapping Glacier Flow on the Juneau Icefield, Alaska-Canada

ABSTRACT: Field data collection techniques in combination with remote sensing techniques were used to interpret and map the complex flow pattern of the numerous glaciers comprising the Juneau Icefield, spanning the Alaska-Canada boundary range. The extensive nature of the icefield mandated the use of a variety of methods for surveying and mapping purposes. Temporal and logistical constraints allowed only one-quarter of the icefield to be surveyed using GPS hardware, while the more remote and inaccessible areas were examined using satellite imagery, RADAR images, and existing topographic maps and digital elevation models. The final cartographic products were created using a combination of the terrain analysis program MicroDEM and the graphic software program Photoshop. Digital Elevation Models were used extensively for data analysis and as base layers for map images. The final mapping products illustrate fine-scale flow patterns and interactions between the ice streams. Each large-scale map shows 15 minutes of longitude by 15 minutes of latitude of the Juneau Icefield.

KEYWORDS: Cartography, Glaciology, Remote Sensing, Geomorphology, GPS, Field Survey, Digital Elevation Models

Introduction

The power of glacier ice as a sculpting agent is preserved in many of the Earth’s most recognized natural landmarks. Mountain peaks such as the Matterhorn in the Swiss Alps and Mount Everest in the Himalayas can attribute their current visage to the actions of glaciers. The deep U-shaped valleys of Yosemite National Park and the flooded fjords of Norway and Alaska also owe their existence to the work of moving ice. However, as early as 200 years ago, the very existence of glaciers - to say nothing of their dynamics - was a matter of great dispute (Bailey, 1982).
The roots of glaciology are imbedded in the work of scientists attempting to explain the many peculiar boulders that littered the landscape of Europe. Evidence of glacier flow was recognized by pioneering glaciologists such as Scheuzer, Gruner, de Saussure, and Agassiz in the early 1800's and proposed as a method for transporting the large erratics (Agassiz, 1967). Theories postulated by many leading scholars of the time, however, suggested that the great Biblical Flood had emplaced these erratic boulders dismissing the notions of glacial theory (Banning, 1995). Later work by Venetz, de Charpentier, and Agassiz eventually converted most scholars to glacial theory by 1850 (Bailey, 1982).

The first attempt at measuring the movement of a glacier was performed by Josef Hugi in 1827 on the Unteraargletscher, Switzerland. Using fixed geographical references, he measured the progressive displacement of a boulder positioned on the glaciers surface. Later techniques executed by Louis Agassiz in 1840 utilized stake networks drilled into the ice perpendicular to the glaciers assumed direction of movement (Clarke, 1987). Measurements of the stakes were first made using rudimentary means, but later methods implemented the use of theodolites greatly increasing accuracies.

The processes used to scrutinize glacier movement did not change greatly for the next 130 years. Advances in technology eventually introduced the use of satellites for monitoring purposes. Global Positioning Systems ultimately have replaced the use of theodolites and total stations for obtaining locational information while satellite imagery is now being used to monitor fluctuations.
attributed to glacial dynamics. Interferometric Spaceborne Synthetic Aperture RADAR is also being exploited to acquire ice velocities and movement vectors but is still in the developmental stage and has not been found applicable to all areas.

Traditional approaches to monitoring glaciers all have one inherent problem; they are subject to geographical constraints placed on them by the immensity of most glacier systems. Surveys performed using ground crews encounter temporal and logistical limitations due to short field seasons in glaciated terrain and the expensive nature of the research. Usually only small areas of a region can be covered during one project leading to generalized conclusions for the system as a whole. Important and useful information is gathered on specific ice streams, but the interactions of the structure in its entirety are often overlooked. Modern tactics have overcome this obstacle only for specific cases such as those in Antarctica but have yet to be found practical for all glaciated regions.

The Juneau Icefield is an ideal example of modern technology put to use for the purposes of monitoring ice flow. However, only generalized flow maps of the icefield currently exist revealing movement patterns for the main trunk glaciers such as the Taku, Llewellyn, Mathes, Demorest, and Mendenhall systems. These glaciers are subject to yearly analysis by the Juneau Icefield Research Program's (JIRP) survey crews (excluding the Mendenhall) and their movement profiles have been documented exhaustively. A large percentage of
the icefield, however, remains unchecked and detailed mapping of ice flow relationships for the system as a whole have not been performed.

The dynamics of flow on the icefield are complex, mainly governed by the underlying topography (Benn and Evans, 1998). Numerous divides exist on the icefield controlling the direction of ice movement and complicating the derivation of patterns. Since much of the icefield is perennially covered by firn, flow relationships are often indistinguishable at higher elevations. Lower elevation outlet glaciers, however, provide abundant physical clues to their travel orientation where they exist below the neve line.

The intent of this project is to analyze and interpret fine-scale flow patterns for the entirety of the Juneau Icefield. Movement vectors were not given consideration in the project due to the lack of data existing for remote sections of the icefield. Instead, only general flow regimes were derived from a variety of data sources covering the Juneau Icefield. Data for this purpose was collected in the field from July 10th, 1999 through August 22nd, 1999 while the author was a member of the expeditionary Juneau Icefield Research Program. Additional data was also gathered and examined from outside resources including satellite imagery and digital elevation models (DEM's).

The final product of the research consists of 23 large-scale flow maps, each encompassing an area of 15 minutes of latitude by 15 minutes of longitude, six mid-scale location maps of varying sizes, and one small-scale map of the Juneau Icefield region. Of major importance in the construction of the maps was
the use of digital elevation models (DEM) in conjunction with the terrain analysis software program, MicroDEM. The program allows for the manipulation of DEM's providing contour maps, topographic profiles, and oblique and perspective three-dimensional views of the terrain (Guth, 1996).

Study Area

Lying at the northern end of the Alaska-Canada Coast Range, the Juneau Icefield encompasses more than 1,500 square miles of rugged terrain (Miller, 1964). Thirty-eight named and numerous un-named glaciers comprise the extent of the region that stretches from Skagway, Alaska to the Taku Inlet south of Juneau, Alaska and from Juneau to Atlin Lake in northern British Columbia, Canada. The geographical boundaries of the icefield range from 59 degrees 30 minutes north to 58 degrees 15 minutes north, and 135 degrees 15 minutes west to 133 degrees 30 minutes west. Elevations on the Juneau Icefield extend from sea level at the terminus of the Taku Glacier to 8,584 feet at the summit of Devil's Paw. The uppermost snowfields crest at 6,300 to 6,500 feet serving as the accumulation areas for the numerous outlet glaciers that flow to the lower elevations (Miller, 1964).

Methods

Numerous techniques were utilized in creating the flow maps. Surveys performed in the field were integrated with data collected out of the field so that a
comprehensive composite of the region could be completed. Since temperate glacier systems are dynamic features and change over time, the use of different data sets allowed for crosschecks to be made to ensure accuracy in the final mapping products.

Field Techniques

Crevasse Measurements-

Crevasse measurements found on the surface of glaciers serve as extremely useful indicators for the direction of ice flow. While on the Juneau Icefield, a number of measurements were made concerning crevasse orientation and absolute positions. A Brunton Pocket Transit was used to attain crevasse orientations while a Garmin 40 8-channel GPS unit provided locational data. Measurements were made during trips between camps on the icefield and while stationed at the camps themselves.

The magnetic declination varied from 28 to 31 degrees east of north while traveling across the icefield. Magnetic declination was checked via 1:25,000 scale USGS topographic maps located at each camp and adjustments to the Brunton were made accordingly. The Garmin GPS unit was capable of achieving 50-meter accuracy in the horizontal plane which was sufficient for this project. Since the DEM's used to plot the data harbor only a 30 meter resolution, GPS data was left uncorrected.
Crevasse morphology also needed to be identified while measurements were made. Three types of crevasses were used on the Juneau Icefield for determining flow directions:

- **Chevron crevasses** are linear fractures aligned obliquely up valley from the glacier margins at approximately 45 degrees towards the centerline forming in response to the drag introduced by the valley walls.

- **Transverse crevasses** form due to extending flow and open up at right angles to the centerline curving downstream where the stress pattern is strongly influenced by the drag of the valley walls.

- **Splaying crevasses** form where the glacier is subject to compressive flow which causes the glacier to expand laterally, modifying the stress pattern. In this case the crevasses are curved, and are roughly parallel to the flow direction towards the center and bend outwards to meet the margins at angles of less than 45 degrees (Benn and Evans, 1998 p 212).

By identifying the type of crevasse present and noting its orientation and position, flow directions could easily be inferred.

Once data were recorded and catalogued, it was later plotted on 1:250,000 scale DEM's of the region using the terrain analysis program, MicroDEM. Survey points were located in the program by using the zoom
function to pinpoint the UTM coordinates. Since uncorrected GPS data are inherently inaccurate in the vertical dimension, elevations for the crevasse locations were also extracted in MicroDEM at a much higher resolution than the Garmin could attain.

This method covered only a small portion of the icefield due to time and travel constraints but did provide valuable first-hand and temporally sensitive information. Ice divides could be more readily identified using this method when compared with other techniques that were later employed.

GPS Survey Measurements-

Members of JIRP make measurements of main trunk glacial flow velocities and strain rates on an annual basis. Typically, transverse profiles are made at designated sites on pre-determined glaciers. During the 1999 field season, longitudinal surveys were made of these glaciers providing valuable information on flow directions. Surveys were conducted using real-time GPS with the Leica System 500, a unit capable of achieving 1 cm accuracy in the horizontal and 5 cm accuracy in the vertical.

Points of survey were first established in Arc/Info by Scott McGee, head of the survey crew for the 1999 JIRP season, and were later navigated to using the Leica system. Navigation procedures were performed by establishing a base station receiver on a known control point proximate to the survey locale. The base station transmits the signal it receives from the overhead satellites to the roving GPS unit on the glacier surface. The roving unit combines its satellite
signals with those from the reference unit to compute the x, y, and z position of
the roving unit allowing researchers to precisely navigate to the pre-determined
coordinates on the ice (McGee, 1999). Stake networks that were initially set
were re-surveyed approximately one week later using the same real-time system.

Data from the GPS surveys were also analyzed using MicroDEM.
Coordinates first had to be converted to standard UTM since JIRP survey crews
utilize a coordinate system developed specifically for use on the Juneau Icefield
(McGee, 1999). The system is metric based, however, and conversions to UTM
are easily accomplished. Although flow directions for the regions where GPS
surveys were executed are well known, they still proved valuable for verification
of data derived from older topographic maps (discussed in later section). Data
tables from the surveys will not be included in this report due to their extensive
nature but can be viewed at http://crevassezone.org/Data/reports_frameset.htm.

Morphological Observations-

Between July 7th and August 3rd, all areas traveled to were located on the
windward side of the icefield and were covered by firn allowing only for crevasse
reconnaissance and GPS surveys. Between August 3rd and August 22nd,
however, many opportunities were present to observe and record morphological
characteristics on the lee side of the icefield that were unavailable earlier in the
season. Features such as lateral and medial moraines were clearly evident in
areas such as the Gilkey Trench, the Tulsequah Glacier region, and the Atlin
sector of the icefield providing beneficial information pertaining to flow directions
in these areas. General sketches of the terrain were made and flow directions were noted from the field observations. GPS locations were acquired at several observation sites in the Gilkey Trench and the Atlin sector and were later used to mark these localities in MicroDEM.

Remote Sensing Techniques

Analysis of Topographic Maps-

Topographic maps proved to be a very valuable resource for determining movement directions of the ice. For areas of the icefield located in the United States, 1:63,360 scale maps were used. Areas located in Canada were evaluated using small-scale 1:250,000 scale maps. Large-scale quadrangles published by the United States Geological Survey do not cover areas in Canada necessitating the use of the smaller-scale maps for that region. Canadian techniques for mapping glaciers do not include contour intervals on the ice surface making them inadequate for use in this project. Instead, the smaller-scale maps were relied on for analysis and were combined with other sets of data for derivation of movement profiles in Canada.

The USGS quadrangles were primarily used to delineate "drainage basins" on the icefield. The process was analogous to the identification of drainage basins in non-glaciated landscapes. Ridgelines were identified and outlined, as were topographic highs near the heads of ice streams. This manner also proved useful for distinguishing flow divides on the high plateaus of the icefield. Examinations of topographic profiles allowed for the establishment of
preliminary flow markers on the maps that were later compared with other data
sets.

One downfall in this method was that the maps were quite dated. Most of
the aerial photography that the maps are based on was obtained in the 1950's
and the 1960's. Through various studies it has been established that every
glacier on the Juneau Icefield is currently in a recessional mode excluding the
Taku Glacier which is slowly advancing (Miller, 1964 and personal
communication 1999). Since the icefield is constrained by the local topography,
changes in relative positions of glacier termini were not considered a major
hindrance when determining flow directions. The main concern was the possible
changes in ice elevations across the icefield resulting from ablation over the past
40 to 50 years. Modifications of this nature surely have an impact on ice divide
locations leading to only generalized conclusions for these sites.

Satellite Imagery-

The major component used to for updating glacier terminal positions and
current ice coverage was a Landsat image acquired on June 27, 1992. The
image was obtained using the green, red, and near infrared bands of the Landsat
satellite. The image acquisition date was early in the ablation season prohibiting
examinations of crevasse or moraine morphologies which were shrouded by
snow. For this reason, no attempt was made to obtain flow data and the image
was instead used for delineating glacial boundaries. The image was converted
from a hard-copy format to a bitmap file using a computer scanner permitting the image to be carefully scrutinized.

A large-scale digital Landsat TM image focused on the Gilkey Trench was used for determining flow directions in this region. Dark bands of moraine material in the trench were easily distinguishable clearly showing the movement trends of the ice. Ogives and larger crevasses were also present solidifying the evidence. Regions in the image surrounding the Gilkey Trench including the Echo Glacier, West Branch of the Taku Glacier, the Mathes Glacier, and many subsidiary ice streams were also analyzed for flow direction.

Two side-looking RADAR images of the icefield located at Camp 18 were also examined but used sparingly due to poor image resolution. They did provide some useful insight into flow regimes on the Canadian side of the icefield. Larger crevasse patterns and icefall locales on the Llewellyn Glacier system revealed flow patterns which were very useful considering the lack of data existing for this area.

Digital Elevation Models-

USGS 1:250,000 scale DEM's were heavily utilized for determining slope profiles for glacier surfaces. No larger-scale DEM's currently exist for Alaska. Analysis was performed using MicroDEM where topographic profiles, oblique views, and perspective views could be studied. Flow directions were determined using the basic assumption that glacier ice flows downhill.
DEM's provided by the USGS are gridded using the World Geodetic System 1972 or World Geodetic System 1984 and are based on contour intervals from 1:250,000 scale maps. Features are updated and digitized into the database using the most current aerial photography available for the region (DEM Users Guide, 1990). No specific date could be found for the origin of the data for the Alaska DEM's, but comparisons using the terminus of the Taku Glacier as an index with current satellite imagery concluded that they were less than 15 years old.

Map Production

The use of many different data sets ensured a high degree of accuracy for determining flow patterns for the Juneau Icefield. It also guaranteed that all regions of the icefield would be covered by at least one of the previously described methods. Most areas were subject to overlap in the data sets excluding regions located in the northern and southeastern portions of the icefield.

Maps were created using a combination of two computer software programs. MicroDEM was designed and created by Peter L. Guth of the United States Naval Academy and is downloadable from the World Wide Web at http://www.usna.edu/Users/oceano/pguth/website/microdemdown.htm. DEM data was downloaded from the United States Geological Survey website at http://edc.usgs.gov/doc/edchome/ndcdb/ndcdb.html and served as a base for all mapping products. MicroDEM functioned as the primary utility for viewing and
manipulating the USGS DEM data. Three separate 1:250,000 scale DEM's were needed to obtain complete coverage of the Juneau Icefield. These were later merged together in MicroDEM to create the small-scale map of the icefield. Larger-scale DEM's spanning 15 minutes of latitude by 15 minutes of longitude were then produced by generating subsets of the smaller-scale map.

After creating the needed subsets, the DEM's were converted to bitmap files and opened in the image manipulation/enhancement program, Adobe Photoshop. Using bicubic interpolation, the larger scale maps were then resampled to provide higher resolution of the images. Photoshop was primarily used for adding colors to the original grayscale images. Outlines for glaciers were produced using satellite imagery and topographic maps as reference tools. This was accomplished by tracing the glaciers and using the fill tool to add color. Images were increased as much as 300% in total size to ensure the accuracy of boundary placements.

After analyzing all of the available data, preliminary arrows were drawn on hardcopies and then transferred to the digital images in Photoshop. Each arrow was carefully placed and individually rotated to best represent the movement profile for that specific area. Images containing geo-sensitive data obtained by GPS were draped over their corresponding DEM's in MicroDEM so that the specific coordinates of the arrows could be found. Each arrow located on the maps is approximately one-third of a mile long and one-tenth of a mile wide.

Scales for the maps were determined using MicroDEM which automatically computes scale bars for the original DEM's. The version of
MicroDEM used for this project did not support the creation of scale bars for subset images and these were subsequently figured manually. This procedure was accomplished in Photoshop using the measure tool which calculates distances to three decimal places. By measuring the width of each large-scale image, a simple conversion could be performed based on the known dimensions of the small-scale image. Scale bars were then created and added to each medium and large-scale map.

**Problems and Continued Work**

Many of the Problems that were encountered concerning methodological procedures have already been mentioned and discussed. Most of these difficulties were overcome simply due to the amount of data that was available. Areas of the Juneau Icefield contained within the United States were covered by many different data sets allowing different methodologies to be compared and contrasted and the best representation of flow extracted. Data covering Canadian areas, however, were quite sparse leading to some generalizations in the flow regimes. The lack of good topographic maps for this area proved to be a major hindrance when attempting to delineate flow basins.

A major concern that still exists is the absolute location of flow divides on the icefield. Since most of the topographic maps that were used were outdated, these divides could only be approximated. RADAR imagery proved useful for distinguishing divides in a few scattered regions on the Atlin Sector of the icefield where firn was not present. Topographic divides were differentiated mainly using
DEM's and then later compared with those found on the topographic maps. This method, however, presumes that divides are stagnant features. The actual movement of ice was not taken into consideration since this type of information could not be derived from the available data. Studies have found that the actual ice flow from a divide does not always correspond to the location of the physical topographic divide itself (Forester, Rignot, Isacks and Jezek, 1999). Divides also tend to move as a glacier develops and decays and the flow patterns adjust to these changes (Benn and Evans, 1998). Since the Juneau Icefield has been in a state of decay following the production of the topographic maps, elevations gathered from these sources is presumed to be inaccurate. The analysis of DEM's helped to place elevations more accurately, but precision of the data could be off by as much as 30 meters. All of these factors contribute to the generalization of the placement of flow divides on the maps.

One method that could be used to possibly create higher accuracy for delineating flow patterns would be the use of Interferometric Spaceborne Synthetic Aperture Radar (InSAR). This technique has been successfully applied on many glaciers throughout the world to measure flow velocities and to distinguish movement profiles. InSAR has mostly been performed on polar glaciers, but areas such as the Bagley Icefield proximate to the Juneau Icefield have demonstrated the usefulness of the method on temperate systems as well (Fatland, 1995).
Conclusions

The use of established field techniques and remote sensing technologies has helped in the delineation of flow patterns for the entire Juneau Icefield. The utilization of digital elevation models aided in the interpretation of flow patterns and further enhanced the results derived from other methodologies. By combining the information gained from crevasse measurements, GPS surveys, field observations, satellite imagery, topographic maps, and DEM’s, a comprehensive view of glacier dynamics for the icefield was achieved.

To fully comprehend the dynamic nature of glacier systems, careful documentation and monitoring must be performed. The understanding of flow patterns on an icefield or ice sheet can help researchers predict the impact of climate change on these systems in the future plus aid in other important research goals. Areas deficient in this type of data can benefit from the methodology used in this project. Resources are often unavailable for defining flow regimes for an entire region. By merging various types of data, a practical and economical solution can be found.
References


Map References

All Maps Produced by the United States Geological Survey, Reston, Virginia

1:250,000 Scale Maps


1:63,360 Scale Maps

Juneau B-1. 1952.
Juneau C-1. 1960.
Juneau C-3. 1952.
Skagway A-1. 1951.
Map Arrangement

An index map of the Juneau Icefield has been produced to help easily locate the specific larger-scale maps that have been constructed. Each map contains a reference number which corresponds with the numbers given on the index map. Red numbers pertain to the mid-scale locational maps and black numbers relate to the large-scale flow maps. The index map is located on page 23.

All of the maps produced for this report are also accessible via the World Wide Web. The home address of the project is located at http://terra.geo.orst.edu/users/atwoodn/mp.htm.
Figure 2. Landsat Thematic Mapper image of the Gikey Trench and surrounding area. Light blue regions are ice covered by firn while deeper blue represents areas below the neve line. Notice moraine patterns below the neve line.
Figure 3. The Gilkey Trench from the C-18 Nunnatak. Flow profiles are easily distinguishable by ogives and moraines.
Figure 4. Using the Leica System 500 for GPS surveying on the Taku Glacier
(photo courtesy of Brian White)