THERMAL STUDIES RELATED TO
SURGING GLACIERS

by

GARY TREVOR JARVIS
B.Sc., University of Toronto, 1971

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in the Department
of
GEOPHYSICS

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA
August, 1973
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of GEOPHYSICS

The University of British Columbia
Vancouver 8, Canada

Date August 21, 1973
Deep-ice temperature measurements have been made in two surge-type glaciers in the Yukon Territory, Canada. Cold ice warming towards the bed was found in Trapridge Glacier and a model of basal ice temperatures predicts large regions of basal temperate ice. Thermal regulation of the surge behavior of this small glacier is inferred; theoretical considerations show that this hypothesis can reasonably be extended to large surging glaciers as well.

Temperatures below 0°C were also recorded on Steele Glacier. An anomalously warm layer was detected at a depth of approximately 50 m. This is attributed to the severe crevassing associated with a glacier surge. Numerical modelling of the effects of water-filled crevasses in a cold glacier, refreezing and injecting latent heat into the ice, predicts temperature profiles very similar to that observed. The model further predicts long term maintenance of the resulting trapped water pockets and, in small surging glaciers, a thermal memory of the initial crevassing throughout the entire quiescent phase.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xiii</td>
</tr>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>PART I: TRAPRIDGE GLACIER</strong></td>
<td></td>
</tr>
<tr>
<td>A. FIELD WORK</td>
<td>4</td>
</tr>
<tr>
<td>1. Surface Survey</td>
<td>4</td>
</tr>
<tr>
<td>2. Depth Determination</td>
<td>4</td>
</tr>
<tr>
<td>3. Temperature Regime</td>
<td>6</td>
</tr>
<tr>
<td>3.1 Field Measurements</td>
<td>6</td>
</tr>
<tr>
<td>3.2 Discussion of Cooling Curves</td>
<td>9</td>
</tr>
<tr>
<td>3.3 Basal Temperatures</td>
<td>13</td>
</tr>
<tr>
<td>B. THEORETICAL CONSIDERATIONS</td>
<td>18</td>
</tr>
<tr>
<td>4. One-Dimensional Surge Model</td>
<td>18</td>
</tr>
<tr>
<td>4.1 Basic Elements</td>
<td>18</td>
</tr>
<tr>
<td>4.2 Numerical Solution</td>
<td>22</td>
</tr>
<tr>
<td>4.3 Results - Comparison with Previous Models</td>
<td>23</td>
</tr>
<tr>
<td>5. Temperature Inversions in Holes #3 and #4</td>
<td>24</td>
</tr>
<tr>
<td>6. Existence of a Basal Layer of Temperate Ice</td>
<td>28</td>
</tr>
<tr>
<td>6.1 Trapridge Glacier</td>
<td>28</td>
</tr>
<tr>
<td>6.2 General</td>
<td>30</td>
</tr>
<tr>
<td>6.3 Implications</td>
<td>32</td>
</tr>
</tbody>
</table>
### PART II: STEELE GLACIER

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. FIELD WORK</td>
<td>35</td>
</tr>
<tr>
<td>B. THEORETICAL CONSIDERATIONS</td>
<td>37</td>
</tr>
<tr>
<td>1. Correction of Observed Temperatures to Equilibrium</td>
<td>37</td>
</tr>
<tr>
<td>2. Interpretation of the Corrected Steele Glacier Temperatures</td>
<td>39</td>
</tr>
<tr>
<td>2.1 Qualitative Discussion</td>
<td>39</td>
</tr>
<tr>
<td>2.2 Numerical Model</td>
<td>43</td>
</tr>
</tbody>
</table>

### SUMMARY AND CONCLUSIONS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
</tr>
</tbody>
</table>

### REFERENCES

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
</tr>
</tbody>
</table>

### APPENDIX I: RADIO SOUNDINGS ON TRAPRIDGE GLACIER, YUKON TERRITORY, CANADA [Manuscript]

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>62</td>
</tr>
<tr>
<td>Introduction</td>
<td>63</td>
</tr>
<tr>
<td>Apparatus and Field Procedures</td>
<td>63</td>
</tr>
<tr>
<td>Results</td>
<td>65</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>66</td>
</tr>
<tr>
<td>References</td>
<td>67</td>
</tr>
<tr>
<td>List of Figures</td>
<td>71</td>
</tr>
</tbody>
</table>

### APPENDIX II: CONSTRUCTION OF ISOPACHOUS CONTOUR MAP FOR TRAPRIDGE GLACIER

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
</tr>
</tbody>
</table>

### APPENDIX III: THE THERMAL REGIME OF TRAPRIDGE GLACIER AND ITS RELEVANCE TO GLACIER SURGING [Manuscript]

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>85</td>
</tr>
<tr>
<td>Introduction</td>
<td>86</td>
</tr>
<tr>
<td>Thermistor Preparation and Field Procedure</td>
<td>87</td>
</tr>
</tbody>
</table>
Results 89  
Discussion of Ice Temperatures and 91  
Surge Behavior 93  
Relevance to Large Surging Glaciers 98  
Concluding Remarks 99  
Acknowledgements 100  
References 109  
List of Figures  

APPENDIX IV: INSTRUMENTATION 117  
Thermistor Preparation 117  
Thermistor Cable Construction 117  
Power Cable 121  
Thermal Probes 121  
Power Supply 123  
Probe Performance 125  
Field Measurements 127  

APPENDIX V: TRAPRIDGE GLACIER BASAL TEMPERATURE MODELS 130  

APPENDIX VI: STEADY-STATE TEMPERATURE PROFILE OF COLD ICE OVERLYING A LAYER OF TEMPERATE ICE 144  

APPENDIX VII: THERMAL EFFECTS OF Crevassing ON STEELE GLACIER [Manuscript] 154  

Abstract 154  
Introduction 155  
Crevasse Model 159  
Results 162  
Concluding Remarks 163  
Acknowledgements 164  
References 165  
Appendix A: Freezing of a Cylindrical Water-Filled Hole in Cold Ice 167  

APPENDIX A: Freezing of a Cylindrical Water-Filled Hole in Cold Ice
<table>
<thead>
<tr>
<th>Appendix B: Peaceman-Rachford Numerical Method</th>
<th>170</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>174</td>
</tr>
<tr>
<td>APPENDIX VIII: FURTHER STUDIES OF THE EFFECTS OF WATER-FILLED CREVASSES</td>
<td>181</td>
</tr>
<tr>
<td>The Crevasse Closure Problem</td>
<td>181</td>
</tr>
<tr>
<td>Energy Check and Convergence</td>
<td>186</td>
</tr>
<tr>
<td>Fitting the Model to Observations</td>
<td>188</td>
</tr>
<tr>
<td>APPENDIX IX: DATA TABLES</td>
<td>194</td>
</tr>
<tr>
<td>Thermistor Calibration Data</td>
<td>195</td>
</tr>
<tr>
<td>Distribution of Thermistors</td>
<td>201</td>
</tr>
<tr>
<td>Field Measurements</td>
<td>204</td>
</tr>
<tr>
<td>TABLE</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>I.</td>
<td>A comparison of surge models and observations.</td>
</tr>
<tr>
<td>I.</td>
<td>Characteristics of the high resolution radar.</td>
</tr>
<tr>
<td>II.</td>
<td>Radio sounding data.</td>
</tr>
<tr>
<td>III.</td>
<td>Drill hole characteristics.</td>
</tr>
<tr>
<td>II.</td>
<td>Trapridge Glacier temperature data.</td>
</tr>
<tr>
<td>III.</td>
<td>Range of values of critical depth corresponding to range of flow laws cited by Hodge (unpublished).</td>
</tr>
<tr>
<td>V.</td>
<td>Basal temperature data - Model I.</td>
</tr>
<tr>
<td>II.</td>
<td>Basal temperature data - Model II.</td>
</tr>
<tr>
<td>III.</td>
<td>Basal temperature data - Model III.</td>
</tr>
<tr>
<td>VI.</td>
<td>Convergence of numerical solution.</td>
</tr>
<tr>
<td>VII.</td>
<td>Steele Glacier temperature data.</td>
</tr>
<tr>
<td>II.</td>
<td>Numerical inputs for crevasse model.</td>
</tr>
<tr>
<td>VIII.</td>
<td>Parameters of Model I.</td>
</tr>
<tr>
<td>II.</td>
<td>Finite-difference variables for Models I₁ and I₂.</td>
</tr>
<tr>
<td>IX.</td>
<td>Thermistor calibration data.</td>
</tr>
<tr>
<td>II.</td>
<td>Thermistor distribution</td>
</tr>
<tr>
<td>III.</td>
<td>Field Measurements.</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1. Map of part of western North America where surging glaciers are located. No evidence of surging glaciers has been found in other glacierized mountains of western North America (from Post, 1969). 2

Figure 2. Instrumentation map of Trapridge Glacier. 5

Figure 3. Vertical thermistor distribution: Holes #1 - #4. (Trapridge Glacier - 1972) 7

Figure 4. Vertical thermistor distribution: Holes #5 - #8. (Trapridge Glacier - 1972) 8

Figure 5. Cooling curves: Holes #1 - #4. (Trapridge Glacier - 1972) 10

Figure 6. Cooling curves: Holes #5 - #7. (Trapridge Glacier - 1972) 11

Figure 7. Vertical temperature profiles: Holes #1, #2 and #5. (Trapridge Glacier - 1972) 14

Figure 8. Vertical temperature profiles: Holes #3 and #6. (Trapridge Glacier - 1972) 15

Figure 9. Vertical temperature profiles: Holes #4 and #7. (Trapridge Glacier - 1972) 16

Figure 10. Trapridge Glacier basal ice temperature map. 17

Figure 11. Diffusion of temperature profile at Hole #4 in absence of heat source. 27

Figure 12. Effect of ice displacement across shear plane on a linear temperature profile. 29

Figure 13. Instability of a temperate layer of ice at the base of a shallow cold glacier. 31

Figure 14. Thermal zones of a cold glacier (see text). 33

Figure 15. a. Location of thermal drilling site on Steele Glacier. b. Vertical thermistor distribution. (Steele Glacier - 1972) 36
Figure 16. Vertical 10-day temperature profile.  (Steele Glacier - 1972)  

Figure 17. Drilling log for Holes #4, #5 and #7. (Slopes represent drilling speeds.)  

Figure 18. Cooling curves: theory and observation.  

Figure 19. Theoretical cooling curves for thermistor C8 in Hole #7. Significance of r_c (see text).  

Figure 20. Steele Glacier temperature profiles: recorded, corrected and theoretical. Solid curves are temperature profiles predicted by the crevasse-field model at times indicated (in years) after crevasse formation. Open circles are recorded temperatures, solid circles the corrected values.  

Figure 21. Slow removal by diffusion of a synthetic temperature anomaly similar to that measured in Steele Glacier, in the absence of energy sources.  

Figure 22. Theoretical evolution of temperature profiles midway between crevasses spaced 16 m apart. Time of each profile is indicated in years.  

Figure 23. a. Long term effects of deep crevassing on shallow ice.  

b. Comparison of the crevasse-field model's predictions with observation.  

APPENDIX I  

Figure 1. Location map of Trapridge Glacier. Dashed lines indicate approximate flow divides between adjacent glaciers.  

Figure 2. Block diagram of radar set.  

Figure 3. A typical echogram from Trapridge Glacier survey (site T-13): T = trigger pulse; P_1 = surface return; (P_2) = intraglacial structure; P_3 = bottom return. The vertical scale is the logarithm of amplitude. Al-
though no precise calibration was made, each vertical scale division is approximately a decade.

Figure 4. Trapridge Glacier ice thickness interpretation. The solid circles indicate sounding sites and the alphabetic identifications correspond to 1972 locations of the marker poles placed by Collins.

APPENDIX II

Figure 1. Location of 18 depth profiles constructed from the radar depth sounding data.

Figure 2. Trapridge Glacier cross sections: 1 and 2.

Figure 3. Trapridge Glacier cross sections: 3 and 4.

Figure 4. Trapridge Glacier cross sections: 5 - 7.

Figure 5. Trapridge Glacier cross sections: 8 - 12.

Figure 6. Trapridge Glacier cross sections: 13 - 18.

Figure 7. Trapridge Glacier ice thickness map.

APPENDIX III

Figure 1. a. Portion of Canadian Government air photograph A13136-44 showing Trapridge Glacier region in 1951.
b. Portion of Canadian Government air photograph A20128-10 showing Trapridge Glacier region in 1967.

Figure 2. Vertical temperature profiles: Holes #1, #2 and #5.

Figure 3. Vertical temperature profiles: Holes #3 and #6.

Figure 4. Vertical temperature profiles: Holes #4 and #7.

Figure 5. Trapridge Glacier basal ice temperature map.
Figure 6.  
a. Cross-sectional view of Trapridge Glacier's temperature regime.  
b. Cross-sectional view of Rusty Glacier's temperature regime.  

Figure 7.  
Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are $B(T_0) = 0.173$ bar$^{-n_a-1}$; $n = 3.07$.)  

APPENDIX IV  
Figure 1.  Thermistor calibration circuitry.  
Figure 2.  Thermistor cable colour-code convention.  
Figure 3.  Possible modes of line heating: (a) low line heating; (b) high line heating; (c) line heating dominant.  
Figure 4.  Thermal probe design.  
Figure 5.  Instrument calibration check: a comparison of resistances measured with Fluke multimeter and Wheatstone bridge.  

APPENDIX V  
Figure 1. Reference grid for basal temperature models.  
Figure 2. Trapridge Glacier basal temperature map - Model II.  
Figure 3. Trapridge Glacier basal temperature map - Model III.  

APPENDIX VI  
Figure 1. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various critical depths $H$ (see text).  
Figure 2. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various glacier slopes $\alpha$.  

Figure 3. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various form factors $f$ (see text).  

Figure 4. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various flow law coefficients $B(T_0)$ (see text).  

Figure 5. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various flow law indices $n$ (see text).  

Figure 6. Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are: $B(T_0) = 0.550$; $n = 3.3$ [soft ice].)  

Figure 7. Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are: $B(T_0) = 0.040$; $n = 5.2$ [hard ice].)  

APPENDIX VII  

Figure 1. Portion of Canadian Government air photograph A21523-73 showing confluence region of Steele and Hodgson Glaciers. Inset shows details of crevasses near drilling site.  

Figure 2. Model of crevasse field. Owing to spatial periodicity temperature need only be evaluated in the shaded region.  

Figure 3. Finite-difference grid illustrating model parameters and boundary conditions.  

Figure 4. Theoretical temperature profiles 15 m from nearest crevasse at various times given in years. Measured Steele Glacier temperatures are indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.
Figure 5. Theoretical temperature profiles at various distances from the nearest crevasse at $t = 6.5$ years. Measured Steele Glacier temperatures are indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.

Figure 6. Closure by refreezing of a water-filled crevasse in cold ice. Crevasse cross sections are indicated at times given in years.

APPENDIX VIII

Figure 1. Basic geometry at migrating crevasse wall.

Figure 2. Convergence of numerical solution. Comparison of predicted crevasse cross sections and temperature profiles of Models $I_1$ and $I_2$ at $t = 6.5$ years.

Figure 3. Effect of crevasse separation $S$ on model predictions
- Model I: $S = 20$ m
- Model J: $S = 24$ m
- Model L: $S = 30$ m

Figure 4. a. Effect of varying model parameter $d_c$ on temperature profile.
b. Effect of varying model parameter $d_w$ on temperature profile.
ACKNOWLEDGEMENTS

I would like to thank Dr. Garry K. C. Clarke for his enthusiastic supervision of this study, for many helpful suggestions and for providing a congenial atmosphere in which to work. B. Chandra, W. Green, R. Metcalfe, B. Narod and K. D. Schreiber provided valuable assistance in field preparations for which I am grateful. A special word of thanks is due to R. Metcalfe for his tireless efforts in the field. I would also like to thank Dr. S. G. Collins for his assistance, helpful discussions, and encouragement throughout the field season, and R. Ragle and P. Upton of the Arctic Institute of North America for logistic support. Dr. R. Goodman's generous donation of his time, services and radio echo sounding equipment is greatly appreciated. Finally, I thank my wife Hélène for devoting much of her time to the typing of preliminary drafts and the final manuscript.
INTRODUCTION

A stagnant snout, active upper region, and continuously steepening transition zone, characterize the dormant state of all surge-type glaciers in western North America (Meier and Post, 1969). This quiescent mode of glacier activity is periodically interrupted by short pulses of chaotic ice movement during which flow rates may increase by two orders of magnitude and surface features shift several kilometers downglacier (Hance, 1937; Post, 1960, 1966, 1967, 1969; Stanley, 1969). Generally associated with this rapid movement are severely crevassed surfaces, sheared margins, and bulging, overriding, advancing ice fronts.

Such behavior is limited to a relatively small class of glaciers. Aerial photographs of all of the larger and most of the smaller glaciers in western North America have been studied by Post (1969). Of the several tens of thousands of glaciers examined, only 204 were identified as belonging to the surge type and it is striking that these all occur in the geographically restricted area shown in Figure 1 - SE Alaska, SW Yukon Territory, and NW British Columbia. As yet, no unique glacier geometry, underlying bedrock type, climatic environment, or seismic influence is believed responsible for this localization of the surge phenomenon. The two most likely causes proposed by Post (1969) are "anomalous subglacial temperatures" (due to high geothermal heat flow) and "unusual bed roughness or permeability".

This study is concerned with the temperature regime of surging glaciers and its relevance to their unique flow characteristics. No special assumptions are made concerning bed roughness although, when considering water at the base of a glacier, bedrock is assumed impermeable following the
Fig. 1. Map of part of western North America where surging glaciers are located. No evidence of surging glaciers has been found in other glacierized mountains of western North America (from Post, 1969).

Robin (1955) suggested that in cold glaciers the warming of basal ice, initially below the pressure melting temperature, could result in an ice-deformation rate instability of sufficient magnitude to account for glacier surging. Although Robin later abandoned this idea in favour of stress instability (Robin, 1969; Robin and Barnes, 1969), support for the contention that basal temperatures play a key role in governing surge behavior has been found on Rusty Glacier, Yukon Territory. Deep ice temperatures measured on this small surging glacier indicate localized regions of warm basal ice in an otherwise cold glacier (Classen, unpublished; Classen and Clarke, 1971; Clarke and Goodman, unpublished). This finding inspired quantitative numerical modelling of cold glaciers, frozen to bedrock during quiescence, sliding on a temperate base during the active phase, and regulated by periodic oscillations of basal temperatures (Hoffmann, unpublished; Hoffmann and Clarke, 1972; Clarke, unpublished). These studies demonstrated that thermal instability can account for the observed surge cycles of many sub-polar glaciers, and thereby emphasized the need for additional field measurements on glaciers with known surge histories.

Consequently, in the summer of 1972 a field expedition was undertaken to the Trapridge and Steele Glaciers in the Icefield Ranges of the St. Elias Mountains, Yukon Territory. These two glaciers are situated in a region densely populated with surging glaciers (Figure 1), and occupy the same drainage basin as the Rusty Glacier. Field operations consisting of surface marker surveys, radar depth soundings, and thermal drilling and deep-ice temperature measurements, were conducted on Trapridge Glacier. Towards the end of the field season a single hole was drilled on Steele Glacier enabling a pioneer temperature study of this glacier.
Trapridge Glacier (61°14' N, 140°20' W) is a small valley glacier descending the eastern flanks of Mt. Wood, Yukon Territory. Approximately 3.5 km long, it has a mean surface slope of 11°. Elevation ranges from 2,800 m a.s.l. to 2,000 m a.s.l. Lying within the Steele Creek watershed, a region of intense surge activity (Post, 1969; Goodman and others, unpublished), the Trapridge was last observed surging in 1941 by Sharp (1947, 1951). The glacier has since lain dormant and the chaotically shattered superficial ice photographed in 1951, shortly after the surge (see Figure 1 of Appendix III), has now healed to form a smooth, relatively uncrevassed surface.

A. FIELD WORK

1. Surface Survey

A triangulation survey of 26 marker poles on Trapridge Glacier was begun in 1969 by Collins (1972). By June 1972, five of the original poles had been lost reducing the coverage to 21. This total was supplemented with 9 additional stakes during the 1972 field season. Figure 2 indicates the locations of the 30 survey poles now standing on Trapridge Glacier.

2. Depth Determination

Ice thickness was measured at 26 different locations on the surface of Trapridge Glacier with a 620 MHz radio echo sounder designed by Goodman (1972). (Radar stations are shown
Fig. 2. Instrumentation map of Trapridge Glacier.
on the instrumentation map of Figure 2.) The resulting depth information was used to produce a contour map of ice thickness. This map appears in Appendix I wherein descriptions of the radar apparatus, field procedure, and depth contouring technique are also presented. Further details of the construction of the isopachous contour map are given in Appendix II.

Typical values of ice thickness (in the upper two-thirds of the glacier) lay between 80 and 120 m; maximum measured depth was 143 m. An unusually steep section of the glacier's longitudinal surface profile was found to mark the front of an ice crest, delineating the zones of active and stagnant ice noted by Collins (1972) (refer to Appendix I). Meier and Post (1969) and Post (1969) claim that such a region of localized steepening is indicative of an impending surge, and consequently the quiescent Trapridge is believed to be approaching a critical instability.

3. Temperature Regime

3.1 Field Measurements

An extensive thermal drilling and deep-ice temperature measurement program was conducted on Trapridge Glacier from June 10 to August 10, 1972. Eight holes were drilled at the seven sites shown on Figure 2, and a total of 49 thermistors was embedded at depths ranging from 10 m to 87.5 m*. Thermistor distribution is illustrated schematically in Figures 3 and 4, and listed in Table II of Appendix IX. Temperatures indicated at each thermistor were read every two or three days until the thermal disturbance caused by drilling

* Details of instrumentation and field procedures are given in Appendix IV. Thermistor calibration data are tabulated in Appendix IX.
Fig. 3. Vertical thermistor distribution: Holes #1 - #4.

(Trapridge Glacier - 1972)
Fig. 4. Vertical thermistor distribution: Holes #5 - #8. (Trapridge Glacier - 1972)
had been removed by conduction of heat away from the drill hole. The resulting cooling curves are displayed in Figures 5 and 6 (respective thermistors are identified according to the nomenclature outlined in Appendix IV). Actual field measurements are tabulated in Appendix IX.

3.2 Discussion of Cooling Curves

In most cases the curves level off to constant values of temperature within 20 days. The rising temperatures of certain thermistors observed at holes #1 and #2 are due to the summer "heat" wave propagating downward from the glacier surface. Only those thermistors less than 10 m from the ice surface experience this warming, since the wave amplitude is severely attenuated below this depth (Paterson, 1969). Warming of thermistor D4 at depth 7.6 m is just detectable (Figure 5).

Characteristic of the return to equilibrium of ice initially close to the melting point is a slow and somewhat erratic cooling, as observed at holes #3, #4 and #6. Since temperature gradients in this ice cannot be as steep as those in ice initially much colder, heat flux away from the water-filled drill holes is relatively slow. In contrast ice initially colder than -2°C was found to return quickly and uniformly to its equilibrium temperature, the colder ice stabilizing more rapidly. (This simple pattern is modified when comparing curves from two holes which at the time of drilling had different radii. For example, thermistor C2 of hole #5 (narrow diameter), appeared to have stabilized at -3.18°C after seven days while C8 in hole #7 (wide diameter) was still cooling at -4.20°C after 21 days.)

Of the 42 traces plotted in Figures 5 and 6, only three show signs of not having stabilized by the end of the field season. Thermistors C13 and C15 in hole #6 indicate
Fig. 5. Cooling curves: Holes #1 - #4. (Trapridge Glacier - 1972)
Fig. 6. Cooling curves: Holes #5 - #7. (Trapridge Glacier - 1972)
sudden ice cooling after a prolonged period of pseudo-stability. CI of hole #5 is expected to behave in like fashion and may have been entering this phase when the last measurements were made (Figure 6). These features are believed to be due to the manner in which drill holes #5 and #6 were terminated. At the former site, drill progress was halted when hole closure by refreezing anchored the power cable in place. In an unsuccessful attempt to free the cable, the thermal probe was run at full generator power with high line heating (Appendix IV) for five consecutive hours causing considerable ice melting in the vicinity of the probe. Similarly, when englacial debris was encountered at hole #6, the probe was run for three hours with little progress before drilling was discontinued. A wide diameter hole must have resulted. In both cases slow closure of the resultant water-filled cavities, and hence prolonged release of latent heat, is most likely responsible for maintaining the deep ice at anomalously warm temperatures. Once the energy source is removed (by freezing) ice close to the drilling axis should cool back to its equilibrium state. This would explain the sudden temperature drop at the base of hole #6 after 15 days of persisting warm temperatures. By the same reasoning, temperatures indicated by CI are expected to drop to lower values; the slightly colder final measurement may signal the onset of such cooling. As the water cavity envisaged at the bottom of hole #6 was smaller and more elongated than that at hole #5, it is consistent with the above explanation that the former refroze sooner and that the lower two thermistors in hole #6 (2 m apart) were affected, whereas only the deepest was affected in hole #5.

Deep ice temperatures warmer than -1°C were also observed in holes #1, #3 and #4. Englacial debris was encountered in hole #1 but subsequent probe burn-out prevented the formation of a large water cavity. Cooling curves for this
hole remained level for more than 30 days and are therefore interpreted as indicating true values of ice temperature. At holes #3 and #4 there were no obstructions and probe burn-out, terminating thermistor descent, occurred while drilling at a constant rate. Thus uniform drill holes should have resulted, and the level cooling curves for thermistors in these holes are also thought to imply equilibrium.

3.3 Basal Temperatures

The final temperatures measured on Trapridge Glacier were all below the pressure melting point and generally increased with depth (supporting the results obtained for Rusty Glacier by Classen (unpublished)). Figures 7, 8 and 9 present vertical temperature profiles for Trapridge Glacier. Five of these indicate the presence of temperate basal ice below their respective drill sites. The temperature profiles were employed in conjunction with the radar depth data to construct three separate models of the temperature regime at the base of Trapridge Glacier; large regions of basal temperate ice are predicted (refer to Appendices III and V). The version which gives the most conservative estimate of basal warming (Model I) is reproduced here, for coherence, as Figure 10. The presence of a large region of temperate basal ice upglacier from hole #6 and cold tongue downglacier from this point, suggests a mechanism for the formation of an ice reservoir: the cold snout acts as an ice dam while ice from the upper accumulation zone slides on a film of temperate ice down to the lower reaches. Where active and stagnant ice meet, a continuously steepening transition zone occurs. Consequently an ice reservoir is built up, not necessarily in the accumulation zone, and the stagnant tongue takes the role of "receiving area" as defined by Meier and Post (1969). As outlined in Appendix III such a mechanism can explain, for
Fig. 7. Vertical temperature profiles: Holes #1, #2 & #5. (Trapridge Glacier - 1972)
Fig. 8. Vertical temperature profiles: Holes #3 & #6. (Trapridge Glacier - 1972)
Fig. 9. Vertical temperature profiles: Holes #4 & #7. (Trapridge Glacier - 1972)
Fig. 10. Trapridge Glacier basal ice temperature map.
sub-polar glaciers, all the major characteristics of surging glaciers itemized by Meier and Post (1969), and is consistent with both the radar depth soundings (Goodman and others, unpublished) and the surface movement surveys (Collins, 1972, unpublished) performed on Trapridge Glacier.

B. THEORETICAL CONSIDERATIONS

4. One-Dimensional Surge Model

4.1 Basic Elements

Theoretical evidence for thermal control of glacier surging was presented in a thesis by Hoffmann (unpublished). The numerical solution of the time-dependent temperature distribution in a cold inclined truncated-slab glacier model was computed. The underlying considerations were as follows: If a cold glacier is frozen to its bed and the surface temperature exceeds \( T^* = GY \), where \( G \) is the geothermal temperature gradient, and \( Y \) the ice thickness, the bed will eventually warm to the melting point and the glacier will begin to slide. Geothermal and frictional heat will melt basal ice, resulting in lubrication of the bed and a consequent increase in the sliding velocity (Weertman, 1962; Clarke, in preparation). This is a self-generative process which could produce high surge velocities. Since conservation of mass requires the elongating glacier to thin, advective cooling and reduction of basal shear stress will ensue, contributing to the deceleration of the surge. Development of an effective basal drainage system would reinforce these mechanisms in terminating the rapid advance. When the sliding stops, steepened ice temperature gradients will cause the glacier base to refreeze to bedrock and bed temperatures to drop below the melting point. A period of quiescence should then follow during which accumula-
tion gradually increases $Y$ (causing $T^*$ to decrease) until surface temperature again exceeds $T^*$. The glacier will then have passed through a complete surge cycle and the above sequence of events will recur.

Temperatures were evaluated both in the glacier ice and in the underlying bedrock. Boundary conditions were applied at the ice surface, ice-rock interface, and some point deep in bedrock where the influence of ice temperatures was negligible. At the ice surface, temperature was maintained at the mean annual value; at the deep rock boundary the geothermal gradient $G$ was held constant. The boundary conditions at the ice-rock interface were a function of glacier activity: while dormant the glacier was assumed frozen to bedrock and thus temperature and heat flux were necessarily continuous across the interface; while surging the glacier bed was supposed lubricated by a film of water so that bed temperatures remained constant at the pressure melting point. (Continuity of heat flux was no longer a restriction.)

In this initial study the glacier was assumed to slide as a block and therefore internal viscous heating was not included in the temperature solution. At the end of each surge the glacier was restored to its pre-surge dimensions, which for periodic surges approximates a uniform accumulation rate during quiescence. However, in practice, difficulty was experienced in obtaining satisfactory periodic surge behavior. Hoffmann and Clarke (1972) suggested that this was probably due to their unrealistic treatment of post-surge accumulation.

The surge model was further developed by G. Clarke (personal communication) to include the effects of viscous self-heating and to allow for continuous accumulation at the upper surface. A basal water film theory, following the approach of Weertman (1972), and upward advection during quiescence were also incorporated. This revised model gives good agreement with observations (Table I).
As verification of Clarke's results, an independent mathematical model has been developed incorporating similar physics. The appropriate form of the diffusion equation in ice is

$$\frac{\partial T(y,t)}{\partial t} + V(y,t) \frac{\partial T(y,t)}{\partial y} - \kappa_2 \frac{\partial^2 T(y,t)}{\partial y^2} - \frac{1}{\rho c} A(y,t) = 0$$  \hspace{1cm} (1)$$

and in the underlying bedrock

$$\frac{\partial T(y,t)}{\partial t} - \kappa_1 \frac{\partial^2 T(y,t)}{\partial y^2} = 0$$  \hspace{1cm} (2)$$

where $T$ is temperature, $V$ vertical advection, $\kappa_1$ and $\kappa_2$ the thermal diffusivities of rock and ice respectively, $\rho$ the ice density, $c$ the specific heat of ice, and $y$ the distance above some point fixed in the bedrock (Carslaw and Jaeger, 1959). The internal heat generation term $A(y,t)$ was taken as

$$A(y,t) = \dot{\varepsilon} \tau$$  \hspace{1cm} (3)$$

where $\dot{\varepsilon}$ is the shear strain rate and $\tau$ is the shear stress (Paterson, 1969). With the aid of Glen's flow law for ice this can be expressed as

$$A(y,t) = B_0 \tau^{n+1}(y,t) \cdot \exp\left(-\frac{Q}{RT(y,t)}\right)$$  \hspace{1cm} (4)$$

where $B_0$ and $n$ are constants, $Q$ is the activation energy of ice, $R$ the universal gas constant, and $T$ temperature in °K (Glen, 1953, 1955). For the one-dimensional glacier $\tau$ is given by

$$\tau(y,t) = \rho gh(t) \cdot \sin \alpha$$  \hspace{1cm} (5)$$
where $g$ is the acceleration due to gravity, $h(t)$ the depth from the ice surface, and $\alpha$ the surface slope (Paterson, 1969). If $y_s$ is the coordinate of the ice surface, then $h(t) = y_s(t) - y$. (Accumulation and advection cause the surface coordinate $y_s$ to vary with time.) During quiescence a linear advection was assumed. Thus

$$V(y, t) = V_s(t) \left[ (y - y_b)/(y_s(t) - y_b) \right]$$

(6)

where $y_b$ is the coordinate of the glacier bed and $V_s$ is the rate of surface rising of the ice reservoir less the net accumulation. During the active surge, conservation of mass requires that

$$V(y, t) = -(y - y_b)U(t)/X(t)$$

(7)

where $X(t)$ is the length of the truncated-slab glacier. $U(t)$ is the sliding velocity taken as that given by Weertman (1957, 1964, 1971[b]):

$$U = 2\left( B_0CK/L_\beta^{n_1} \right)^{1/2}(n+1)/2s^{n+1}$$

(8)

where $B_0 = 0.017$ bar$^{-n_1}$, $C$ is the pressure melting coefficient ($7.4 \times 10^{-3}$ °C/bar), $K$ the thermal conductivity of ice, $L$ the latent heat of fusion, $\beta$ the cavitation number, and $s$ the smoothness parameter as defined by Weertman (1969). The treatment of basal water production and boundary conditions at the bed did not differ from that described by Hoffmann (unpublished) and Hoffmann and Clarke (1972) and therefore will not be discussed here.

The finite-difference analogs of Equations (1) and (2) were solved throughout a grid network extending from an arbitrary point fixed in the bedrock to the ice surface. During quiescence the finite-difference grid was continuously in-
creased in size at a rate $V'_q(t)$ given by

$$V'_q(t) = V_S(t) + V'_S(t)$$  \hspace{1cm} (9)

where $V_S$ is the surface advection and $V'_S$ the accumulation rate. Throughout the active phase the grid was decreased in size, due to the glacier's longitudinal extension and consequent thinning, at a rate $V_a(t)$ given by (7) as

$$V_a(t) = -[y_s(t) - y_b]U(t)/X(t)$$  \hspace{1cm} (10)

4.2 Numerical Solution

The numerical technique employed, that of Crank and Nicolson (1947), is illustrated here with the relatively simple equation governing the bedrock temperatures.

For space and time increments of $h$ and $\tau$ respectively the implicit approximation to Equation (2) is written as

$$[T(y,t+\tau) - T(y,t)]/\tau = \theta \kappa_1 [T(y-h,t+\tau) - 2T(y,t+\tau) + T(y+h,t+\tau)]/h^2 + (1 - \theta) \kappa_1 [T(y-h,t) - 2T(y,t) + T(y+h,t)]/h^2$$  \hspace{1cm} (11)

where $\theta$ is an averaging parameter; $0 \leq \theta \leq 1$. The spatial second derivatives approximated at times $t$ and $t+\tau$ have been averaged in order to reduce the discretization error of the approximate solution from $O[\tau + h^2]$ to $O[\tau^2 + h^2]$ (Carnahan and others, 1969). Upon rearrangement and substitution of $\lambda_1 = \kappa_1 \tau/h^2$, Equation (11) becomes

$$-\lambda_1 \theta T(y-h,t+\tau) + [1 + 2\lambda_1 \theta]T(y,t+\tau) - \lambda_1 \theta T(y+h,t+\tau)$$
\[ -23 - \]

\[ = \lambda_1 [1 - \Theta] T(y-h, t) + [1 - 2\lambda_1 (1 - \Theta)] T(y, t) + \lambda_1 [1 - \Theta] T(y+h, t) \]  

(12)

Similarly, the approximation to Equation (1) is

\[ -\lambda_2 \Theta T(y-h, t+\tau) + [1 + 2\lambda_2 \Theta] T(y, t+\tau) - \lambda_2 \Theta T(y+h, t+\tau) = \lambda_2 [1 - \Theta + (hV(y, t)/2\kappa_2)] T(y-h, t) + [1 - 2(1 - \Theta) \lambda_2] T(y, t) + \lambda_2 [1 - \Theta - (hV(y, t)/2\kappa_2)] T(y+h, t) + \]

\[ (\tau/pc) A(y, t) \]  

(13)

where \( \lambda_2 = \kappa_2 \tau/h^2 \), and \( A(y, t) \) is given by

\[ A(y, t) = \left[ B_0 [\rho g(y_s(t) - y) \sin \alpha]^{n+1} \cdot \exp[-Q/RT(y, t)] \right]/J \]  

(14)

where \( J \) is the mechanical equivalent of heat.

At each level \( y = nh \), where \( n \) has integer values, one equation of the form (12) or (13) is written (depending on which medium \( y \) corresponds to) to generate a tridiagonal system of simultaneous linear equations. This system is then solved by standard Gaussian elimination (Carnahan and others, 1969) to yield the solution \( T(y, t+\tau) \) in terms of \( T(y, t) \). At the ice-rock interface \( (y = y_b) \) the two applicable equations (one for each medium) are matched according to the prevailing boundary conditions as discussed above.

4.3 Results - Comparison with Previous Models

This last surge model also predicts periodic instabilities of basal temperatures and glacier sliding. Acceptable surge velocities, glacier advances, and durations of
quiescent and active phases were obtained. For comparative purposes, the three models described above were applied to Tikke Glacier, British Columbia. Table I presents the results along with observational data from Meier and Post (1969). The close agreement between the predictions of the present model and those of Clarke's more elaborate version is considered a satisfactory indication of the modelling procedure's reliability. (An error has been discovered in the Hoffmann model which accounts for his low values of surge velocity and ice displacement (Clarke, personal communication).)

5. Temperature Inversions in Holes #3 and #4

An unusual temperature profile was observed at hole #4 (Figure 9). Ice temperatures increase with depth from 10 m down to approximately 72 m. From this point down to 82 m temperatures decrease; by a depth of 88 m they have begun to rise again.

The possibility that the 6 volt multimeter (used to measure resistances) caused self-heating of the thermistors in warm ice and thereby generated an artificial temperature anomaly, has been ruled out by the results of a measurement check with a Wheatstone bridge (Appendix IV).

It is conceivable that the deep ice had simply not returned to equilibrium by the time of final measurements. If such is the case, the level cooling curves of Figure 5 must represent a period of pseudo-stability similar to that observed at hole #6 (Figure 6). However in contrast to hole #6, no unusual circumstances accompanied the termination of drilling at this site (refer to section 3.2) and it therefore seems unlikely that the deep ice would suddenly cool after 29 days of persisting warm temperatures.

A similar temperature inversion is apparent in the profile of hole #3 (Figure 8). Although drilling did not
TABLE I. A COMPARISON OF SURGE MODELS AND OBSERVATIONS

TIKKE GLACIER, BRITISH COLUMBIA

<table>
<thead>
<tr>
<th>Surge Characteristics</th>
<th>Model Predictions of</th>
<th>Observations of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hoffmann</td>
<td>Clarke</td>
</tr>
<tr>
<td>Duration of active phase (years)</td>
<td>1.75</td>
<td>1.75</td>
</tr>
<tr>
<td>Duration of quiescent phase (years)</td>
<td>24.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Maximum observed annual velocity (km/yr)</td>
<td>.088</td>
<td>1.67</td>
</tr>
<tr>
<td>Maximum observed displacement (km)</td>
<td>.155</td>
<td>2.9</td>
</tr>
</tbody>
</table>
penetrate sufficiently deep for a renewed increase in the ice temperatures to be observed, a continued temperature decrease (with depth) is unreasonable. This feature occurs at lower temperatures in hole #3 than in hole #4, reducing the likelihood of thermistor self-heating or slow return to equilibrium being responsible for the locally high temperatures. Thus it is believed that the unusual "kinks" in the temperature profiles of holes #3 and #4 are due to englacial thermal disturbances rather than to measurement techniques.

It is not immediately evident whether the above distortions of the temperature regime are some form of thermal signature remanent from a previous surge or the result of presently operating englacial heat sources. Since the most recent rapid advance of Trapridge Glacier occurred in 1940-41 (refer to Appendices I and III), a thermal memory of that event would imply a thermally stable condition. The stability of the measured temperatures was investigated by employing the profile from hole #4 as the initial temperature distribution in the numerical surge model described above. The model was run in the quiescent mode (omitting advection and accumulation) for 2.50 years. Diffusion of heat away from the 72-m level rapidly removed the relatively high temperature recorded at this point. As shown in Figure 11, the sharp anomaly present at \( t = 0 \) has smoothed considerably by \( t = 0.25 \) years and has been virtually eliminated after 2.50 years. This demonstrates an inherent instability in the temperature "kink" which therefore cannot have endured since Trapridge Glacier's most recent surge.

Consequently localized heat sources are inferred, operating at present and maintaining the relatively high temperatures measured at 60 m in hole #3 and at 72 m in hole #4. Friction and ice displacement due to slippage across a shear plane could contribute to the formation of an ice temperature structure similar to that observed. If the overlying ice were
Fig. II. Diffusion of temperature profile at Hole #4 in absence of heat source.
to slip upward along a sloped plane, relatively warm ice could be carried above cold ice as illustrated in Figure 12. Nye (1951) claims that such shear planes exist in regions of compressive stress and that the upper ice will in fact over­ride the lower ice if bedrock obstacles are present. As both drilling sites were located in a large surface hollow (and therefore a zone of compressive stress) directly upglacier from a sizeable bedrock knoll (Appendix I), the proposed shear slip mechanism is consistent with Nye's theoretical dis­cussion.

This indication of basal ice activity, together with personal observations of frequent and intense seismic waves (or ice quakes) and the development of new crevasses in areas previously free of such perils, support the belief that Trapridge Glacier is now in the final stages of pre-surge qui­escence.

6. Existence of a Basal Layer of Temperate Ice

6.1 Trapridge Glacier

The temperature profiles displayed in Figures 7, 8 and 9 imply that if ice temperatures continue to rise with depth at a constant rate, a temperate layer of ice (of finite thickness) exists at the glacier base. This would preclude the relevance of the numerical surge models discussed above and contest the pertinence of ice temperatures to glacier surging. It is therefore of prime importance to examine the feasibility of a temperate layer existing at the bottom of a predominantly cold glacier.

A one-dimensional inclined-slab glacier model with internal viscous heating (given by Equation (14)) was con­structed by modifying the previously described surge model. The glacier's surface and base were held isothermal at the mean surface temperature and at the pressure melting point
Fig. 12. Effect of ice displacement across shear plane on a linear temperature profile.
of ice respectively. Bed temperatures were not computed. To model the central region of Trapridge Glacier, a glacier depth of 100 m and surface slope of 10° were chosen. The initial input to the model was a piecewise linear temperature distribution, -8.0°C at the surface, warming uniformly to the pressure melting point at a depth of 80 m, and then following the pressure melting curve down to the glacier bed. Figure 13 displays the resulting temperature evolution over a 20 year period; viscous heating was insufficient to maintain the lower 20 m at the melting point and the temperate layer was rapidly eliminated. From this study one can conclude that the temperature gradients in holes #1 through #6 must become less steep with depth so that on average melting temperatures only occur along the ice-rock interface.

However, similar calculations for larger glaciers demonstrated that viscous heating is capable of maintaining temperate basal ice in some deep glaciers. This result prompted a more general approach to determine the conditions necessary for the existence of a warm layer of ice at the base of an otherwise cold glacier.

6.2 General

The term "critical depth" of a glacier is introduced here as that depth below which temperate ice will occur. In a predominantly cold glacier with ice thickness exceeding its critical depth, no geothermal heat can propagate upwards through the bottom temperate layer (Lliboutry, 1966, 1968; Paterson, 1969) and vertical heat flux at any point must stem from internal viscous heating. In Appendix III a theoretical procedure is developed to evaluate the steady-state temperature profiles in valley glaciers which exceed their critical depths. From these the critical depth $H$ is determined as a function of the mean surface temperature $T_s$, the surface slope $\alpha$, and Nye's "form factor" $f$ (Nye, 1965; Paterson, 1969;
Fig. 13. Instability of a temperate layer of ice at the base of a shallow cold glacier.

Temperature profiles at 5-year intervals.
see Appendices III and VI). Uncertainties in the numerical values of the coefficients in Glen's flow law for ice (Glen, 1953, 1955) result in a range of possible values for $H$ (refer to Appendices III and VI).

6.3 Implications

Let us consider a glacier with ice thickness $d$ decreasing uniformly downglacier. In those regions where $d > H$ a basal layer of temperate ice of thickness $d - H$ will exist (Figure 14). Where $d = H$ melting temperatures will occur only at the ice-bedrock interface. No geothermal heat will enter the ice; all this energy will be used to melt basal ice. Further downglacier where ice becomes thinner the glacier bed can only be maintained at the melting temperature if some of the geothermal heat enters the ice, with a consequent reduction of basal melting. Continuing downglacier, a depth $H^*$ is reached where the total geothermal flux must enter the glacier to maintain bed temperatures at the melting point. No ice melting (due to geothermal heat) occurs. For depths less than $H^*$ the cooling influence of the surface temperature $T_s$ predominates and the glacier bed is frozen to the bedrock. Thus a cold glacier may consist of three separate thermal zones defined in terms of the ice depth as: (1) $d < H^*$, (2) $H^* \leq d \leq H$ and (3) $H < d$ (Figure 14). Zone (1) must occur in all cold glaciers. In large or steep cold glaciers, zones (2) and (3) may also be present.

Figure 7 of Appendix III shows the critical depth of Trapridge Glacier to be approximately 120 m so that with one possible exception the glacier is comprised of zones (1) and (2) (refer to the ice thickness map of Appendix I). Temperate ice may exist in the bedrock hollow (143 m) below drill hole #3 at survey stake R. However, since a uniformly-inclined-bed glacier model is a poor approximation to this location the model predictions cannot be strictly applied.) The ice crest
Fig. 14. Thermal zones of a cold glacier (see text).
observed on Trapridge Glacier delineating the zones of active and stagnant ice (Appendix I) also marks the boundary between thermal zones (1) and (2).
STEELE GLACIER

Steele Glacier (61°12' N, 140°10' W) is a large valley glacier flowing from the north-facing slopes of Mt. Steele, Yukon Territory. It is 35 km long and 1.5 km wide with surface gradients lying between 25 and 50 m/km (Stanley, 1969) and surface elevation ranging from 3,050 m a.s.l. to 1,200 m a.s.l.. Although quiescent for many years prior to 1965, Steele Glacier was observed surging dramatically in the spring of 1966 (Stanley, 1969; Wood, 1972). Until recently, the resulting disruption of the ice surface rendered ground-based geophysical field camps impractical. However, in the summer of 1972 the glacier was found to be traversable by foot and a deep-ice temperature measurement program was initiated.

A. FIELD WORK

A single hole was thermally drilled to a depth of 114 m. Two 8-conductor cables carried a total of 13 thermistors to depths ranging from 25 m to 114 m. The drill site location and the vertical distribution of thermistors are indicated in Figures 15a and 15b respectively. Ten days after the termination of drilling, the resistance of each thermistor was measured and converted into temperature*. As time did not permit a greater delay, equilibrium temperatures were not ob-

* Thermistor calibration procedures are outlined in Appendix IV.
Fig. 15. a. Location of thermal drilling site on Steele Glacier.
b. Vertical thermistor distribution. (STEELE GLACIER - 1972)
tained and a small cooling correction must be applied to each of the recorded temperatures. Figure 16 displays the 10-day temperature profile. The gross features of this curve are unusual and unexpected; relatively warm ice extends from 30 m down to 50 m suggesting a recent and sizeable thermal disturbance of the upper ice.

B. THEORETICAL CONSIDERATIONS

1. Correction of Observed Temperatures to Equilibrium

The measured temperatures were corrected with the aid of a computer program written by G. Clarke to solve the diffusion equation in polar coordinates for a water-filled cylindrical hole in cold ice. The solution, which yields hole closure and ice temperature as functions of time, depends on the initial hole radius \( r_c \). As the thermal probe efficiency (ratio of probe diameter to drill hole diameter) is not 100\%, the probe radius cannot be used as an estimate of \( r_c \). Also, since drilling speed and power input generally differ from one portion of the hole to another, the hole radius will vary with depth and the surface value may not give a good estimate of \( r_c \) either. It was thought that a reasonable value of \( r_c \) could be obtained by assuming that all the thermal energy from the probe was used to melt ice. For constant drilling speed \( v_p \) and power input \( P \), the hole radius \( r_c \) is then determined as

\[
 r_c = \left( \frac{P}{L \rho \pi v_p} \right)^{1/2} \tag{15}
\]

where \( L \) is the latent heat of fusion \( (3.337 \times 10^5 \text{ J kg}^{-1}) \) and \( \rho \) the ice density. Both \( v_p \) and \( P \) were monitored continuously during field operations; they did not change rapidly with probe depth. Thus in the neighbourhood of each thermis-
Fig. 16. Vertical 10-day temperature profile. (STEELE GLACIER -1972)
the drill hole is approximately cylindrical with radius given by (15).

To test this approach, theoretical cooling curves were generated for thermistors in three separate holes on Trapridge Glacier. The theoretical traces were then compared to the observed curves presented above in Figures 5 and 6. Figure 17 attests to the relatively constant drilling speeds and Figure 18 illustrates the good agreement of theory and observation. An example of the error introduced by incorrect choice of \( r_c \) is shown in Figure 19 which compares the results of fitting theoretical curves to the recorded data when the value of \( r_c \) is taken as (A) that measured at the surface and (B) that computed from Equation (15). Although at day six both curves agree with observation, from this point on they diverge with the latter curve tracking the measured temperatures. These results suggest that cooling curves generated for the Steele Glacier drill hole and intersecting the measured 10-day temperatures can predict the equilibrium values to an accuracy of ±0.2°C.

Accordingly, each of the 10-day temperatures of Steele Glacier was corrected with the theoretical cooling model and \( r_c \) given by Equation (15). The resulting equilibrium values are indicated by solid circles on Figure 20 and are tabulated in the formal report of this work found in Appendix VII.

2. Interpretation of the Corrected Steele Glacier Temperatures

2.1 Qualitative Discussion

The anomalously warm ice temperatures are attributed to the recent surge of Steele Glacier. The possibility of a regional climatic amelioration was discounted since no evidence of this has been found in either of the nearby Rusty or Trapridge Glaciers (Classen, unpublished; Classen and
Fig. 17. Drilling log for Holes #4, #5 & #7. (Slopes represent drilling speeds.)
Fig. 18. Cooling curves: theory and observation.
Field Measurements

Theoretical Curves

**Curve A**

A: $r_c = 6.50$ cm (measured surface value)

**Curve B**

B: $r_c = 8.74$ cm (computed from Equation (15))

---

Fig. 19. Theoretical cooling curves for thermistor C8 in Hole #7. Significance of $r_c$ (see text).
Clarke, 1971; Appendix III). Consideration of all available englacial heat sources led to the conclusion that only enclosed water cavities could provide sufficient energy to maintain the observed anomaly for the six or seven years since the surge onset and yet be localized in the vertical sense (refer to Appendix VII).

A band of trapped water pockets at a depth of about 50 m could be formed as follows: At the onset of a glacier surge severe crevassing of the ice surface occurs. This reduces albedo, augmenting surface melting, and inhibits surface run-off. Thus large quantities of water can enter newly formed crevasses and gain access to considerable ice depths. Subsequent freezing of the surface of the trapped water will enclose the liquid in ice. The enclosed water will then freeze along the cold crevasse walls releasing latent heat into the glacier causing ice temperatures to rise. Eventually this heat should diffuse throughout the ice volume between crevasses.

2.2 Numerical Model

To evaluate the thermal effects of trapped water in a cold crevassed glacier, a two-dimensional time-dependent numerical model was developed. Ice temperatures and crevasse widths were computed (as functions of time and space) while freezing of trapped water caused crevasse closure and thermal injection into the glacier ice. Computational details of the crevasse-field model are given in Appendix VII.

Temperature profiles predicted by the model fit the measured profile well. Figure 4 of Appendix VII, reproduced here as Figure 20, shows the evolution of the predicted temperature disturbance at a point midway between crevasses. The curve labelled $t = 6.5$ years is the profile which corresponds to the time of thermal drilling on Steele Glacier. This result was obtained by choosing a crevasse field with crevasses spaced 30 m apart and water level 15 m below the ice surface,
Fig. 20. Steele Glacier temperature profiles: recorded, corrected, and theoretical. Solid curves are temperature profiles predicted by the crevasse-field model at times indicated (in years) after crevasse formation. Open circles are recorded temperatures, solid circles the corrected values.
consistent with field observations (refer to Appendix VII). The crevasse depth was adjusted to give the best fit to the data. A discussion of the model accuracy and influence of each of the relevant parameters is presented in Appendix VIII.

Closure rates of the water-filled crevasses were severely retarded by thermal saturation of the intervening ice volume; Figure 5 of Appendix VII shows that after 6.5 years, ice temperature is almost independent of distance from the crevasses. Hence at points midway between crevasses temperature becomes, approximately, a function of depth alone and horizontal heat flux is thereby inhibited. For models with smaller crevasse spacings this one-dimensional temperature dependence occurs sooner.

The thermal stability of a temperature anomaly in such thermally saturated ice was expected to be high. A quantitative investigation of this hypothesis was performed as follows: The crevasse-field model was run for 4.0 years with a crevasse separation of 24 m. The resulting temperature profile (very similar to that measured on Steele Glacier) was then substituted into the quiescent mode of the one-dimensional surge model described above. Temperatures were allowed to diffuse vertically for five years. This treatment approximates the effect of removing the energy source after four years of ice warming. The slow removal of the thermal anomaly as illustrated in Figure 21 implies that the observed effects of water-filled crevasses may persist for several years after the extinction of the energy source. Combined with the slow crevasse closure this result suggests that such thermal disruptions may endure for a considerable length of time, perhaps comparable to that of a surge cycle.

The thermal effects of crevassing on thin surge-type glaciers (such as the Trapridge) may persist long after a glacier surge and significantly alter the ice-temperature regime throughout the quiescent phase. During this time heat
Fig. 21. Slow removal by diffusion of a synthetic temperature anomaly similar to that measured in Steele Glacier, in the absence of energy sources.
sources would otherwise be limited to internal friction and geothermal heat. For shallow ice viscous heating is minimal (refer to Figure 1 of Appendix VI) and, in the absence of other sources, a linear temperature profile with slope equal to the geothermal gradient would be expected.

In order to examine the long term distortion of a linear temperature profile the crevasse-field model was applied to Trapridge Glacier. The crevasse separation $S$ and width $W$ were taken as 16 m and 4 m respectively, consistent with Canadian Government 1951 aerial photograph A13136-44 (see Figure 1a of Appendix III). The crevasse depth $d_c$ and depth to the water level $d_w$ were arbitrarily designated as 50 m and 5 m respectively, while the value of $d^*$ (refer to Appendix VII) was set at 120 m, representative of the glacier thickness. The mean annual surface temperature $T_s$ and bed temperature $T_d$ were taken as $-8.0^\circ C$ and $0.0^\circ C$. This model was run for forty years; the resulting temperature profiles, at a point midway between crevasses, are displayed in Figure 22 at ten-year intervals.

Due to the close spacing of crevasses, thermal saturation was high and the trapped liquid was not completely frozen until $t = 22.1$ years. Accordingly, as shown in Figure 22, the temperature anomaly is still predominant at $t = 20$ years but has been significantly reduced by $t = 30$ years. Slow diffusion during the subsequent ten-year interval cooled the upper ice somewhat but caused little cooling of the deepest ice. Since surge cycles longer than forty years seem restricted to large surging glaciers (Meier and Post, 1969), the Trapridge will surge again before the deepest ice begins to cool back to the initial temperature. The severe crevassing associated with glacier surging thus acts as a mechanism for delivering thermal energy to the base of small surge-type glaciers.

As the last surge of Trapridge Glacier occurred in 1940-41, the 30-year profile of Figure 22 best corresponds to
Fig. 22. Theoretical evolution of temperature profiles midway between crevasses spaced 16 m apart. Time of each profile is indicated in years.
the time of temperature measurement (August, 1972). This profile has a relatively constant and steep gradient in the upper ice and a decreasing gradient close to the glacier bed, similar in character to the recorded temperature profiles of Rusty and Trapridge Glaciers (Classen and Clarke, 1971; Appendix III). The measured temperature gradients increase towards the glacier surface (implying a growing vertical heat flux) at a rate which is too large to be attributed to viscous heating (see Appendix VI). The most plausible explanation for the observed change in gradient is the diffuse temperature anomaly remanent from the crevasse fields associated with a glacier surge.

It was argued previously, in terms of thermal instability, that although several extrapolations of the observed temperature profiles intersect the melting point well above the glacier bed, temperature gradients must decrease towards the bed so that the pressure melting point of ice is only reached at the ice-rock interface. No explanation of why the shallow ice gradients were so steep was attempted. However it now appears that this is due to crevassing and the subsequent refreezing of trapped water. In the thinner portions of the glacier deep crevasses may penetrate almost to the bed causing an exaggeration of the above thermal effects. To examine this point the model of Trapridge Glacier was rerun with a glacier depth (d*) equal to 70 m, approximating conditions at hole #6. The resulting temperature profiles presented in Figure 23a indicate that the lower half of the glacier was warmed to within 1°C of the melting temperature for at least 30 years after crevasse formation. The trapped water pockets were not completely frozen until \( t = 31.7 \) years accounting for the prolonged duration of the anomaly.

As a final study of long term predictions of the crevasse-field model, the parameters were adjusted to model Trapridge Glacier at the site of hole #5. Mean surface tem-
Fig. 23. a. Long term effects of deep crevassing on shallow ice.
b. Comparison of the crevasse-field model's predictions with observation.
perature $T_s$ was taken as $-9.0^\circ C$ (Figure 7) and $d^*$ was set at 120 m (Appendix I). Crevasse dimensions, spacing and water level were as above. This model was run for forty years; the theoretical temperature profiles are compared to the measured temperatures in Figure 23b. The profile labelled $t = 32$ years has been included on this diagram since the time elapsed from surge onset until temperature measurement was approximately 32 years. Allowing for the simplicity of the model, the agreement of observation and theory at $t = 32$ years is considered satisfactory. This is taken as evidence that the thermal memory of crevassing is in fact apparent on the temperature profiles of small surging glaciers throughout their period of quiescence.
SUMMARY AND CONCLUSIONS

Deep ice temperatures measured in Trapridge Glacier support thermal instability as the control mechanism of glacier surging. Large regions of basal temperate ice are predicted in the upper two-thirds of the glacier, the lower tongue being frozen to bedrock. This distribution of bed temperatures accounts for the formation of an ice crest, revealed by radar depth sounding, along the line separating zones of active and stagnant ice. Temperature inversions in the deep ice profiles of the upper glacier imply basal ice activity. These indications of renewed glacier activity suggest that Trapridge Glacier is now in the final stages of pre-surge quiescence.

Theoretical studies indicate three distinct thermal zones for sub-polar glaciers: Ice in zone 1 is cold throughout and frozen to the bed; that in zone 2 is cold except at the glacier bed and a basal water film may exist. Zone 3 consists of cold upper ice overlying a finite layer of temperate basal ice. Field measurements on the Rusty and Trapridge Glaciers suggest that in surging glaciers zone 1 acts as a dam for ice sliding on a temperate base in zones 2 and 3. An ice reservoir could thus be built up and a continuously steepening surge front would form at the boundary between zones 1 and 2. The claim that zone 3 comprises the major portion of large surging glaciers (Robin and Weertman, 1973) is refuted and it is argued that zone 3 in fact comprises a minor portion of large surging glaciers. Thermal regulation thus remains a strong contender in the debate on control mechanisms for surging glaciers.

Cold ice observed in Steele Glacier (which surged in 1965-66) to a depth of 114 m supports the contention that surges of large glaciers, as well as those of small glaciers,
may be thermally regulated. The Steele Glacier temperature profile illustrates a significant influence of crevassing on the post-surge ice temperatures. A major thermal anomaly is produced in the upper ice by the refreezing of water-filled crevasses, an effect which could lead one to infer temperate ice below 50 m in Steele Glacier if only shallow (less than 50 m) ice temperatures were measured. Numerical modelling of the thermal effects of crevassing demonstrates that crevasse closure by refreezing of trapped water can account for the magnitude and duration of the observed anomaly. The crevasse-field model further predicts the existence of a thermal memory of the initial crevassing for several decades. For small surging glaciers, such as the Trapridge, this corresponds to the length of the entire quiescent period.

When applied to Trapridge Glacier this model predicts 32-year temperature profiles similar to those measured in 1972 (32 years after its most recent surge). Temperature gradients are steep near the surface and then decrease towards the bed. This result explains the discrepancy between the observed temperature profiles and those predicted by the one-dimensional surge model (Hoffmann, unpublished; Hoffmann and Clarke, 1972), which have temperature gradients increasing toward the bed. In shallow glaciers the thermal disturbance of crevassing penetrates to the base of the glacier, a feature which is not included in the above surge model. However, in deep glaciers the warming influence of crevassing is restricted to the upper layers and the omission of this effect should not invalidate predictions of the surge model.

It has been suggested (J. F. Nye, personal communication) that frozen-over water-filled crevasses migrating downwards through cold glacier ice, in the manner described by Weertman (1971[a]), could provide a mechanism for extending the depth range subject to thermal injection. The slow closure of densely spaced crevasses may allow such water pockets to
move significantly lower before refreezing is completed. Although not incorporated into the present crevasse-field model, this consideration provides a promising subject for future research.
REFERENCES


Clarke, G.K.C. Unpublished. [Numerical modelling results.]

Clarke, G.K.C. Thermally-regulated water film instabilities in surging glaciers. [In preparation.]


Jarvis, G.T., and Clarke, G.K.C. Unpublished[a]. Thermal effects of crevassing on Steele Glacier. [Submitted to the Journal of Glaciology.]

Jarvis, G.T., and Clarke, G.K.C. Unpublished[b]. The thermal regime of Trapridge Glacier and its relevance to glacier surging.


APPENDIX I*

RADIO SOUNDINGS ON TRAPRIDGE GLACIER,
YUKON TERRITORY, CANADA

Ron Goodman

Department of the Environment
Water Management Service
Calgary, Canada

Garry K. C. Clarke

Department of Geophysics
University of British Columbia
Vancouver, Canada

Gary T. Jarvis

Department of Geophysics
University of British Columbia
Vancouver, Canada

Sam G. Collins

Arctic Institute of North America
Montreal, Canada

Robert Metcalfe

Department of Geophysics
University of British Columbia
Vancouver, Canada

ABSTRACT

As part of a program to study surge-type glaciers, a radar depth survey has been made of Trapridge Glacier, Yukon Territory, using a 620 MHz apparatus. Soundings were taken at 26 locations on the glacier surface and a maximum ice thickness of 143 m was measured. A rapid change in surface slope in the lower ablation region marks the boundary between active and stagnant ice and is suggestive of an "ice dam" or the water "collection zone" postulated by Robin and Weertman for surging glaciers.
INTRODUCTION

Trapridge Glacier (61°14' N, 140°20' W) is a small valley glacier in the Steele Creek drainage basin, Yukon Territory, Canada (Figure 1). Identified by Post (1969) as a surge-type glacier, it is located in a region of intense surge activity: the neighbouring Steele, Hodgson, Hazard, Backe and Rusty Glaciers are all known to surge. Evidence for a surge of the Trapridge Glacier is quite extensive. Collins (1972) refers to unpublished photographs of Wood taken in 1939 which show little crevassing of the Trapridge. Photographs in 1941 show extensive crevassing and Sharp (1947) remarks that his "Glacier 13" is advancing rapidly. Sharp's Glacier 13 is the Trapridge (formerly "Hyena"). Air photographs of 1951 show extensive crevassing but those of 1967 show a healed surface. From this evidence, it would appear that the most recent rapid advance of the Trapridge occurred about 1940. Annual surveys begun in 1969 of 26 marker poles on Trapridge Glacier give a maximum flow rate of 20.5 m/yr during the quiescent stage of the surge cycle (Collins, 1972).

Geophysical studies consisting of radio echo soundings and deep ice-temperature measurements were initiated in 1972. The purpose of the radio sounding survey was to provide information on channel geometry, to guide the selection of thermal drilling sites, and to field test in cold glacier ice the 620 MHz sounder designed by Goodman (1970). The radar system weight was approximately 150 kg which was movable by man-drawn sleigh across the glacier.

APPARATUS AND FIELD PROCEDURES

There has been a great deal of controversy concerning the optimum frequency for radio echo soundings. Workers in Greenland and Antarctica such as Evans and Smith (1969) and
Gudmandsen (1969) have advocated low frequencies and accepted the resolution loss to gain increased penetration. For temperate and thin polar glaciers it is possible to design high-frequency equipment with excellent time and spatial resolution. Macroscopic losses in ice are practically frequency independent until nearly 1 GHz, but the volume scattering increases with frequency (Smith and Evans, 1972). Such scattering causes signal loss and a clutter of return echoes which could limit the utility of high-frequency systems. However, the increase in resolution and the ability to focus the power (a narrow beam-width antenna reduces the volume scanned) compensates for the scattering losses and gives a strong return echo.

The radar echo sounder used for the present measurements (Figure 2) was a subsystem of a more elaborate device described by Goodman (1972); the computer analysis and positioning systems were not used. Table I summarizes the radar characteristics. The transmitter produces a "sync" pulse which can be used either as an external trigger or as an input to the oscilloscope. While initially the external mode was used, it was found more convenient to use internal triggering and to scale the time differences from the resulting display. A typical display is illustrated in Figure 3. The differences between the 480 MHz results in Norway (Smith and Evans, 1972) and the 620 MHz results (Figure 3) from the Trapridge Glacier are clear evidence of the ability of a high-resolution system to reduce interference caused by scattering from intraglacial structures. Short pulse lengths and a wide band-width were used so the highest possible resolution was achieved. The zero delay was calibrated using a small dipole placed in the beam of the antenna. The delay between the trigger point and the dipole echo was measured and after correcting for cable delays, the intrinsic equipment delay was
found to be 80 ns, which corresponds to a depth correction of 7 m.

The radio soundings on the Trapridge Glacier were performed at 26 sites, established at surveyed stakes (Collins, 1972) or at intermediate locations determined by chaining. In order to discriminate against reflections from the valley walls, two soundings were made at each site; one with the antenna rotated in a horizontal plane by an angle of 90° from the other. Most spectra were uncomplicated and no difficulty was experienced in identifying the bottom return echo. The radar echoes obtained on the lower part of the glacier provide some evidence for glacial infrastructure which may be due to compressive and emergent flow in this region. There is, however, no indication of any features similar to the extensive intraglacial horizons that have been observed in temperate glaciers (Goodman, 1972). Spectra from each site were photographically recorded for further analysis.

RESULTS

The measured ice thicknesses are presented in Table II. From these data in combination with elevation survey results, a total of 18 longitudinal, transverse and diagonal depth profiles was constructed and the bedrock topography deduced. The longitudinal profile is well established by the number of points along it and was used as a control for the transverse and diagonal profiles. Where interpolated curves from two or more profiles intersected, the mean depth was taken and each profile was readjusted accordingly. The largest discrepancy where two profiles intersected was 10 m and this is an indication of the consistency, though not necessarily the accuracy, of the interpolation scheme. From the depth profiles ice thicknesses were contoured (Figure 4).
The maximum measured ice thickness was 143 m recorded at Stake R in the accumulation region. The bedrock high near Stake L correlates with a crevasse field, the maximum observed flow velocity (Collins, 1972), and a rapid change in surface slope. Near Stake G the flow is strongly emergent and below this point the glacier is inactive. The ice crest in this region does not appear to reflect bedrock topography and Collins (1972) suggests the presence of a dam of stagnant ice. Similar crests are predicted by Robin and Weertman (1973) in their recent surge theory; the zone near Stake G might correspond to their "collection zone". The Robin-Weertman surge theory relies on certain stress conditions which favour basal water collection and is particularly useful in explaining surges of presumably temperate glaciers: the Trapridge, however, is sub-polar. Ice temperature measurements to be published separately indicate that below Stake G the base of Trapridge Glacier is cold and therefore frozen to the bed, while above Stake G a large "hot spot" exists. We therefore conclude that for this glacier the presence of basal water is thermally rather than mechanically controlled. Similar conclusions have been reached for the nearby Rusty Glacier (Classen and Clarke, 1971) and some form of thermally-regulated water-film instability is therefore believed to control the surge behavior of both glaciers.

ACKNOWLEDGEMENTS

We thank M. Botting and P. Parish for assistance in the field and R. H. Ragle and P. Upton of the Icefield Ranges Research Project for logistic support. The financial support of the University of British Columbia Committee on Alpine and Arctic Research, the Department of Environment, and the National Research Council of Canada is gratefully acknowledged.
REFERENCES


<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRANSMITTER</strong></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>620 MHz</td>
</tr>
<tr>
<td>Peak pulse power</td>
<td>3 kW</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>20,000 pulses/s</td>
</tr>
<tr>
<td>Antenna beam width</td>
<td>5.2°</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>15 dB</td>
</tr>
<tr>
<td>Pulse width</td>
<td>70 ns</td>
</tr>
<tr>
<td><strong>RECEIVER</strong></td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>110 dB</td>
</tr>
<tr>
<td>Noise</td>
<td>6 dB above thermal</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>90 dB</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>30 MHz</td>
</tr>
<tr>
<td>Overload recovery</td>
<td>150 ns</td>
</tr>
<tr>
<td><strong>SYSTEM</strong></td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td>169 dB</td>
</tr>
<tr>
<td>Minimum range</td>
<td>30 m</td>
</tr>
<tr>
<td>Range resolution</td>
<td>2.5 m</td>
</tr>
</tbody>
</table>
## TABLE II. RADIO SOUNDING DATA

<table>
<thead>
<tr>
<th>Station Identification</th>
<th>Map Location</th>
<th>Depth (m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>≈ 40 m SE of Q</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>T-2</td>
<td>Q</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>T-3</td>
<td>≈ 60 m WNW of Q</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>T-4</td>
<td>≈ 140 m N of Q</td>
<td>?</td>
<td>no apparent reflection</td>
</tr>
<tr>
<td>T-5</td>
<td>≈ 180 m SW of Q</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>T-6</td>
<td>≈ 230 m NW of R</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>T-7</td>
<td>≈ 100 m NW of R</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>T-8</td>
<td>R</td>
<td>143</td>
<td>some internal structure</td>
</tr>
<tr>
<td>T-9</td>
<td>≈ 130 m WSW of R</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>T-10</td>
<td>≈ 180 m SW of R</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>T-11</td>
<td>≈ 300 m SSW of R</td>
<td>96</td>
<td>multiple bottom structure</td>
</tr>
<tr>
<td>T-12</td>
<td>≈ 200 m S of R</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>T-13</td>
<td>≈ 90 m SE of R</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>T-14</td>
<td>≈ 100 m E of R</td>
<td>107</td>
<td>double bottom peak</td>
</tr>
<tr>
<td>T-15</td>
<td>M</td>
<td>93</td>
<td>multiple bottom structure</td>
</tr>
<tr>
<td>T-16</td>
<td>L</td>
<td>73</td>
<td>crevasse zone; multiple peaks</td>
</tr>
<tr>
<td>T-17</td>
<td>J1</td>
<td>93</td>
<td>double peak</td>
</tr>
<tr>
<td>T-18</td>
<td>KX</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>T-19</td>
<td>J2</td>
<td>101</td>
<td>internal structure; crevasses</td>
</tr>
<tr>
<td>T-20</td>
<td>I4</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>T-21</td>
<td>I2</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>T-22</td>
<td>I</td>
<td>80</td>
<td>internal structure</td>
</tr>
<tr>
<td>T-23</td>
<td>H3</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>T-24</td>
<td>H</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>T-25</td>
<td>G</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>T-26</td>
<td>≈ 100 m E of G</td>
<td>&lt;35</td>
<td>depth less than minimum</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Fig. 1. Location map of Trapridge Glacier. Dashed lines indicate approximate flow divides between adjacent glaciers.

Fig. 2. Block diagram of radar set.

Fig. 3. A typical echogram from Trapridge Glacier survey (site T-13):

- \( T \) = trigger pulse
- \( P_1 \) = surface return
- \( (P_2) \) = intraglacial structure
- \( P_3 \) = bottom return

The vertical scale is the logarithm of amplitude. Although no precise calibration was made, each vertical scale division is approximately a decade.

Fig. 4. Trapridge Glacier ice thickness interpretation. The solid circles indicate sounding sites and the alphabetic identifications correspond to 1972 locations of the marker poles placed by Collins.
Fig. 1. Location map of Trapridge Glacier. Dashed lines indicate approximate flow divides between adjacent glaciers.
Fig. 2. Block diagram of radar set.
Fig. 3. A typical echogram from Trapridge Glacier survey (site T-13): T = trigger pulse; P₁ = surface return; (P₂) = intraglacial structure; P₃ = bottom return. The vertical scale is the logarithm of amplitude. Although no precise calibration was made, each vertical scale division is approximately a decade.
Fig. 4. Trapridge Glacier ice thickness interpretation. The solid circles indicate sounding sites and the alphabetic identifications correspond to 1972 locations of the marker poles placed by Collins.
APPENDIX II

CONSTRUCTION OF ISOPACHOUS CONTOUR MAP
FOR TRAPRIDGE GLACIER

Thirteen of the twenty-six radar depth sounding stations on Trapridge Glacier were located at surface survey markers, the positions of which were established by theodolite survey to an accuracy of ±0.40 m. Locations of the remaining thirteen stations were determined to a similar accuracy by chaining the distances from nearby survey stakes. The survey markers and radar stations are indicated on Figure 2 of the main text.

A series of glacier cross sections was constructed along the profiles shown in Figure 1. Profiles 1 through 12 were drawn to pass through as many of the radar stations as possible. Numbers 13 through 18 were designed to intersect the previous profiles thereby furnishing internal control to the subsequent interpolation procedures. The surface elevation at survey markers along each cross section was taken from the 1973 survey data of Collins. Between markers the glacier surface was interpolated with the aid of the hand-sketched topographic contour map presented for Trapridge Glacier in Collins (1972). Vertical lines dropped from radar sites on each surface profile, with lengths corresponding to the appropriate depths, determined sets of points along the glacier bed beneath each profile. Smooth interpolation between these points, accounting for rock outcrops and major surface features, produced the eighteen glacier cross sections displayed in Figures 2 through 6. Where two or more of profiles 1 to 12 intersected, the mean depth was taken and profiles were readjusted when necessary. These were then used as depth control in constructing profiles 13 to 18. The solid vertical lines in Figures 2 through 6 indicate measured depths. The broken lines
Fig. 1. Location of 18 depth profiles constructed from the radar depth sounding data.
indicate points where profiles have intersected, and the accompanying number is that of the intersected profile. Alphabetic identifications correspond to the 1972 locations of survey marker poles placed by Collins (refer to Figure 4 of Appendix I).

Ice thicknesses were read off each cross section at 200-m intervals to obtain estimates of glacier depth at 155 locations. These depths were contoured by hand in 10-m intervals to produce Figure 7. Due to a lack of data in some of the inaccessible regions, the above scheme cannot reasonably claim a 10-m accuracy. Hence for formal presentation Figure 7 has been stripped of contours which are odd multiples of 10 m (Goodman and others, unpublished).
Fig. 2. Trapridge Glacier cross sections: 1 & 2.
Fig. 3. Trapridge Glacier cross sections: 3 & 4.
Fig. 4. Trapridge Glacier cross sections: 5 - 7.
Fig. 5. Trapridge Glacier cross sections: 8 - 12.
Fig. 6. Trapridge Glacier cross sections: 13 - 18.
Fig. 7. Trapridge Glacier ice thickness map.
ABSTRACT

A deep-ice temperature measurement program has been conducted on Trapridge Glacier, Yukon Territory. Large regions of temperate ice are predicted at the base of the otherwise cold glacier. The glacier snout, frozen to bedrock, appears to act as an ice dam allowing the build up of an ice reservoir in the upper regions. Thermal regulation of the surges of Trapridge Glacier is suggested and the relevance of basal temperatures in large surging glaciers is discussed.

* Manuscript for submission to the Journal of Glaciology. Submission of this paper awaits 1973 temperature data.
INTRODUCTION

Trapridge Glacier (61°14' N, 140°20' W) is one of three small glaciers whose melt streams join to form a tributary of Hazard Creek on the eastern flanks of Mt. Wood, Yukon Territory. Located within the Steele Creek drainage basin, wherein at least sixteen glaciers are known to surge, the Trapridge and neighbouring Rusty and Backe Glaciers (Figure 1) have been identified as surge-type glaciers by Post (1969). Rusty Glacier experienced a surge sometime prior to 1950 from which its extended tongue, very apparent in 1951 aerial photographs, is now rapidly receding. Backe Glacier, inactive in 1951 (Figure 1a) was surging in 1967 overriding the Rusty Glacier (Figure 1b). At present a steep surge front and heavily crevassed surface remain; the Backe is unlikely to surge again for at least twenty years. Trapridge Glacier, although quiescent in 1939 (Wood, 1940), was advancing rapidly in 1941 (Sharp, 1947, 1951). As Figures 1a and 1b show its surface disrupted in 1951 (shortly after the surge) and smooth again by 1967, we believe that this advance was its most recent. The glacier has now lain dormant for more than twenty years and, since the surge cycle of glaciers in this area is typically 20-30 years (Meier and Post, 1969), we anticipate a surge of Trapridge Glacier within the near future.

Deep ice temperatures measured on Rusty Glacier in the summers of 1969 and 1970 indicate a region of temperate basal ice in an otherwise cold glacier (Classen and Clarke, 1971; Classen and Clarke, 1972). This discovery suggested thermal control of glacier surging, and subsequent numerical modelling has shown thermal instability to be an acceptable surge mechanism for many sub-polar glaciers (Hoffmann, unpublished; Hoffmann and Clarke, 1972; Clarke, unpublished). As a further field test of this mechanism a thermal drilling and deep-ice temperature measurement program was conducted on
Trapridge Glacier in the summer of 1972. In addition, radar depth sounding and surface stake triangulation surveys were carried out by Goodman and others (unpublished) and S. G. Collins of the Arctic Institute of North America, respectively. The radar depths were used to guide the selection of thermal drilling sites, temperate ice being most likely to occur at the deepest points. The triangulation survey, a continuation of work begun in 1969 (Collins, 1972), established the locations of radar stations and drilling sites to an accuracy of ±0.40 m.

THERMISTOR PREPARATION AND FIELD PROCEDURE

Fenwal GB34P2 glass bead thermistors, with nominal resistance 11,000 ohms at 0°C, were used throughout the project. These were calibrated in a Colora KT20S constant temperature bath containing 80% water and 20% alcohol. The bath temperature was read digitally from a standard quartz thermometer to an accuracy of ±0.005°C. The corresponding thermistor resistances were measured with a Wheatstone bridge to an accuracy of ±5.0 ohms or ±0.05%. The resistance R of each thermistor was measured at four temperatures T in the range -10.00°C to 0.00°C and curves of the form $R = \exp(A + B/T + C/T^2)$, where A, B and C are constants, were fit to the resulting data. The calibrated thermistors were then installed in 8-conductor #22 AWG cables following standard methods (Raspet and others, 1966; Robertson and others, 1966).

Electrically powered, cable suspended, hot point drills similar in design to those designed by Classen (unpublished) were used throughout the field project and thermistor cables taped to the power lines were drawn into the ice by the descending probes. Further details of thermistor calibration and instrumentation are given in a thesis by Jarvis (unpublished).

The thermal drilling program produced eight instru-
mented holes at seven locations on the glacier surface. A total of forty-nine thermistors was implanted in the depth range 10 - 87 m and the location of a single thermistor left in the lower tongue of the glacier by Classen (unpublished) was re-established. The positions of the drill sites as determined from surface survey data are indicated on the basal temperature map of Figure 5.

The average drilling speed was 4 m/hr and the maximum depth attained was 87.5 m at hole #4. Drilling was terminated at each site for one of three reasons: sudden and prolonged reduction of drill speed (presumably due to englacial debris), probe burn-out, or hole closure by refreezing (Table I).

Hot point drilling alters the thermal regime of the glacier in the neighbourhood of each hole. After drilling has ceased, several weeks must pass before thermal contamination diffuses away. Temperatures indicated by newly installed thermistors will at first drop rapidly with time and then gradually approach the equilibrium temperatures which existed before drilling. To determine when each hole reached equilibrium the resistances of all thermistors were measured every two or three days until the ice temperatures appeared stable. (Resistances were measured with a Fluke 8100A digital multimeter to an accuracy of ±10 ohms, which corresponds to a temperature sensitivity of ±0.02°C.) In most cases the temperatures became constant within twenty days. However, ice which was initially warmer than -1°C took much longer to return to equilibrium, and by the end of the field season there was still uncertainty in the final values of some of the warmer measurements. Also no temperatures were recorded at hole #8 since it was completed just three days before evacuation of the field camp. Consequently, in the summer of 1973 Trapridge Glacier was revisited and final temperatures were measured where possible. The ice temperatures recorded at the end of the 1972 field season and those observed in 1973 are listed in Table II.
RESULTS

The data of Table II are presented as vertical temperature profiles in Figures 2, 3 and 4. All measured values were less than 0.00°C and without exception the ice temperatures increased with depth. Results of radar depth sounding on Trapridge Glacier using a 620 MHz apparatus (Goodman and others, unpublished) enabled extrapolation of the observed temperature profiles down to the glacier bed. Linear extrapolation from the two deepest temperatures of each profile indicates the presence of temperate basal ice below five of the seven drill sites (Figures 2, 3 and 4). This result supports thermal instability as the mechanism governing the surge behavior of Trapridge Glacier.

Although the extended temperature profiles of holes #1 through #6 all intersect the pressure melting point well above the glacier bed, we do not interpret this as indicating the presence of a finite layer of temperate ice below the respective drilling sites. Such a situation would be thermally unstable as no geothermal heat could propagate upwards through the temperate ice. The total heat flux implied by the observed temperature gradients would then be due to viscous heat generation and latent energy exchange at the interface of cold and temperate ice. Lliboutry (1966) has shown that in sufficiently deep ice sheets, strain heating may be able to account for measured heat fluxes. However the maximum measured depth on Trapridge Glacier was only 143 ±10 m. Viscous heating in such shallow ice is insignificant (Jarvis, unpublished) and liquid inclusions in a basal layer of temperate ice would rapidly freeze (releasing latent heat) until the layer was removed. Hence it seems reasonable that the temperature gradients decrease close to the bed so that on average the pressure melting point is achieved only at the ice-rock interface, thereby allowing some of the geothermal heat to flow into the cold ice (Lliboutry, 1966, 1968; Paterson, 1969).
A model of temperatures at the base of the glacier was constructed from the above observations. Depth control was obtained from a contour map of ice thickness, presented by Goodman and others (unpublished), which was produced from the depth sounding results. The glacier was divided into six zones centred on the drilling sites, boundaries being determined by the right bisectors of lines joining adjacent centres. For each region the 10-m temperature and deep-ice temperature gradient observed at the central drill site was applied over the whole zone. Below any point on the glacier the basal temperature could then be predicted by extrapolating along the appropriate gradient from the 10-m temperature down to the radar sounding depth. The extrapolation was performed for 101 points on the glacier bed and the predicted temperatures were contoured in one-degree intervals producing the basal ice-temperature map of Figure 5.

A cross-sectional view of the temperature regime of Trapridge Glacier was constructed from the vertical temperature profiles and the predicted basal temperatures. In Figure 6, this is superimposed on an ice depth profile given by Goodman and others (unpublished). According to the model, the bedrock knoll between holes #1 and #4 prevents ice in this region from reaching its pressure melting point at the bed (Figure 6). However, no measurements have been made in this area due to the associated crevasse field and it is possible that the isotherms converge to follow the bed topography rather than cut through the local bedrock high. (Deep crevasses formed where ice flows over the rock dome allow summer meltwater access to considerable ice depths. Refreezing of this water would contribute to the raising of basal temperatures (Jarvis and Clarke, unpublished).) In this case one continuous zone of temperate basal ice could exist from the neighbourhood of hole #3 down to hole #6 (Figure 5).
DISCUSSION OF ICE TEMPERATURES AND SURGE BEHAVIOR

The large regions of warm basal ice correlate well with the surface movement data of Collins (1972). Upglacier from survey marker G (indicated on Figure 6) as far as stake L our model of the bed temperatures predicts basal ice at the pressure melting point and hence the regelation mechanism of glacier sliding could operate; in fact all measurable ice movement occurs above stake G. Downglacier from G the basal ice is frozen to bedrock and Collins finds that this ice is stagnant. Between these regions of active and stagnant ice exists a zone of positive ice emergence where flow lines bend upwards above the horizontal. Collins suggests that this deflection is caused by the lower tongue acting as an ice dam and our measurements indicate that the damming action is likely due to this ice being frozen to the bed. Consistent with this view of a cold glacier sliding on a partially temperate base, is the observed strain rate distribution (Collins, 1972). Above L tensile stresses exist, while below L compressive stress increases downglacier culminating at G and rapidly decreasing thereafter. The line marking the lower limit of temperate basal ice follows very closely the zone of maximum compressive stress.

The cold tongue of Trapridge Glacier must also act as a thermal barrier to the flow of water which is produced by sliding friction and geothermal heat in the temperate zones. As each region of warm basal ice is encompassed by cold ice (Figure 5) this water cannot escape along the bed and is therefore trapped beneath the glacier. (Some freezing will occur along the margins of the temperate ice zone.) As this water accumulates the bed roughness will be reduced locally by obstacle drowning (Weertman, 1969) and the longitudinal stresses on either side of the lubricated zone will increase (Robin and Weertman, 1973). Ablation of the stagnant lower glacier will continually weaken the ice dam and it is possible that a wave of
ice thickening is slowly moving downglacier on the leading edge of the large zone of basal temperate ice. This would account for the ice crest revealed by radar soundings (Figure 6), the unusually large positive ice emergence, and the intense zone of compressive longitudinal stress, concurrent near survey stake G. Consequent advection of cold surface ice away from the bed may permit geothermal heat to extend the zone of temperate ice. Latent heat released by refreezing of some of the basal water also contributes to this effect (Weertman, 1966). Thus an ice reservoir could be formed in the ablation area of the glacier causing it to thicken where it would otherwise thin. The ice crest on Trapridge Glacier is in fact one kilometer, or one-third of the total length of the glacier, below the firm line.

Eventually the stress concentration below the ice crest should cause mechanical failure of the ice and the reservoir will discharge overriding the inactive lower tongue, as shown in the 1941 photographs of Sharp (1947, 1951). In fact, Sharp refers to his Glacier 13 (the Trapridge) as a small "superimposed glacier". By 1951 the inactive snout was totally engulfed by the advancing surge front (Figure 1a).

The speed and duration of the surge may be determined to a great extent by the amount of water accumulated at the bed. Although at the surge onset basal water production is greatly augmented by sliding friction this is believed counteracted by the establishment of a basal drainage system allowing stored water to escape. As a result the glacier acquires a rougher bed, which retards sliding and thereby reduces water production. This may explain why the active phase of the surge cycle commences violently but, characteristically, is short-lived (Meier and Post, 1969).

Temperature, depth and surface movement studies of the nearby Rusty Glacier (Classen and Clarke, 1971; Clarke and Goodman, unpublished; Collins, 1972) show results strikingly
similar to those presented here for Trapridge Glacier. The temperature distribution for Rusty Glacier is displayed in Figure 6 as isotherms along a longitudinal cross section. As in the case of Trapridge Glacier, ice movement is detected above the warm basal ice but not in the cold tongue. The snout of this cold glacier also appears to act as an ice dam (Collins, 1972). In view of the observed temperature regimes of Rusty and Trapridge Glaciers, we feel that in cold glaciers the formation of an "ice reservoir" and "receiving area", as discussed by Meier and Post (1969), is probably due to the lower regions being frozen to bedrock.

RELEVANCE TO LARGE SURGING GLACIERS

Few temperature measurements have been made on large surge-type glaciers and it has been suggested that these are probably too deep to be cold at the bed (Robin and Weertman, 1973). However measurements have been made on Steele Glacier, Yukon Territory, (35 km long) to a depth of 114 m (Jarvis and Clarke, unpublished). The 114-m temperature was -6.7°C. For any reasonable ice temperature gradient, this observation implies cold ice for the upper few hundred meters so that the lower tongue of Steele Glacier may well be frozen to its bed during the quiescent phase.

The depth of Steele Glacier is not known, but 500 m would seem to be a reasonable upper value since the largest depth estimate tabulated by Meier and Post (1969) for typical surging glaciers of western North America was 480 m. The suggestion that this glacier may never be cold at its base implies that no geothermal heat flows into the ice and hence that the 114-m temperature stems from the mean annual surface temperature and internal viscous heating. Viscous heat generation would cause the ice temperature to increase with depth down to the bedrock or until the ice temperature attains the
pressure melting point. The latter occurs at what we refer to as the critical depth. Below the critical depth further viscous energy is dissipated in the formation of water within a layer of temperate ice which extends down to the glacier bed (Lliboutry, 1966, 1968; Paterson, 1969). If the glacier depth is less than the critical depth, the basal ice must either be cold or at the melting point along the ice-rock interface and in either case some (or all) of the incident geothermal heat must enter the glacier ice.

The steady-state temperature regime of a glacier with ice thickness greater than the critical depth can readily be calculated if a simple glacier geometry is assumed and flow law constants are known. The boundary conditions for this problem are the mean surface temperature and the temperature at the critical depth (the pressure melting point of ice). At any intermediate level, the temperature gradient must represent a heat flux which is equal to the integrated viscous heat generation from the critical depth up to that level. If we consider an inclined-slab glacier model with coordinates $x$ parallel to the glacier surface, $y$ upward normal to the surface, and origin at the critical depth, the heat flux $\phi$ at any level $y$ is given by

$$\phi(y) = -KdT(y)/dy$$  \hspace{1cm} (1)

(where $K$ is thermal conductivity of ice and $T$ the temperature), and shear stress $\tau$ is

$$\tau = \rho gh\cdot\sin\alpha$$  \hspace{1cm} (2)

where $\rho$ is ice density, $g$ the gravitational acceleration, $h$ the depth from the ice surface and $\alpha$ the slope of the glacier surface. If the glacier surface is at $y = H$, then $h = (H - y)$. Viscous heat generation is simply
\[ \dot{\xi}_{xy}(y) \tau_{xy}(y) = \frac{d\phi(y)}{dy} \quad (3) \]

where \( \dot{\xi}_{xy}(y) \) is the shear strain rate and \( \tau_{xy}(y) \) is the shear stress. Using Glen's flow law for ice, Equation (3) reduces to

\[ B \tau^{n+1}(y) = \frac{d\phi(y)}{dy} \quad (4) \]

where \( \tau(y) \) has been substituted for \( \tau_{xy}(y) \), \( B \) is the temperature dependent coefficient and \( n \) the power index of the flow law (Glen, 1953, 1955).

For valley glaciers, \( \tau \) can be approximated by the introduction of a "form factor" \( f \) which accounts for the fact that some of the weight of the glacier is supported by the valley walls. Thus \( \tau = f \rho g h \cdot \sin \alpha \). Values of \( f \) lie between zero and one, typically \( 0.7 \leq f \leq 0.9 \) (Nye, 1965; Paterson, 1969). Theoretical considerations suggest that the flow law coefficient \( B \) varies with temperature in the following manner

\[ B(T) = B_0 \cdot \exp\left[-\frac{Q}{RT}\right] \quad (5) \]

where \( B_0 \) is a constant, \( Q \) the activation energy of ice, \( R \) the universal gas constant, and \( T \) the temperature in °K (Glen, 1953, 1955). Since values of \( B(T) \) are usually measured near \( T_0 = 273 \text{°K} \), it is convenient to express \( B(T) \) in terms of \( B(T_0) \). Thus Equation (4) becomes

\[ \frac{d\phi(y)}{dy} = B(T_0) \cdot \exp\left[\left(\frac{Q}{RT_0}\right)(T - T_0)/T\right] A^{n+1}(H - y)^{n+1} \quad (6) \]

where the substitutions \( A = f \rho g \cdot \sin \alpha \) and \( h = (H - y) \) have been made.

Substitution of (1) into (6) yields the nonlinear differential equation
\[ d^2T(y)/dy^2 = C(H - y)^{n+1} \cdot \exp[D(T(y) - T_0)/T(y)] \]

(7)

where \( C = -B(T_0)A^{n+1}/K \) and \( D = Q/RT_0 \). Equation (7) was solved by standard finite-difference methods to generate the complete solution \( T(y) \). In particular, the unique surface temperature \( T_S \) corresponding to critical depth \( H \) is determined as \( T_S = T(H) \). In our calculations the spatial increment was chosen so that \( T_S \) would have an accuracy of ±0.01°C.

The theoretical uniqueness of the relation between \( T_S \) and \( H \) (for a given \( A \)) is lost in numerical calculations due to uncertainties in the values of the constants \( B(T_0) \), \( n \) and \( Q \). Hodge (unpublished), for example, has cited seventeen different measurements of \( B(T_0) \) and \( n \). Values of \( B(T_0) \) range from 0.040 bars\(^{-n} a^{-1} \) to 0.849 bars\(^{-n} a^{-1} \) and those of \( n \) from 2.1 to 5.2. Measured values of \( Q \) vary from 58,520 J mole\(^{-1} \) to 132,924 J mole\(^{-1} \) (Glen, 1953, 1955; Raraty and Tabor, 1958). We have evaluated \( T_S \) as a function of \( H \) for various glacier geometries (0.5 ≤ \( f \) ≤ 0.9; 1° ≤ \( \alpha \) ≤ 15°) over the above range of flow law parameters and activation energy. A typical example is shown in Figure 7 in which the flow law parameters are according to Nye (1953). Contours on this diagram connect points of equal critical depth \( H \) corresponding, in the steady state, to different combinations of \( T_S \) and \( A \). The uncertainty in \( Q \) has been incorporated by the broadening of the contours. The lower edge of each broadened contour corresponds to \( Q = 132,924 \) J mole\(^{-1} \) while the upper edge is the curve for \( Q = 58,520 \) J mole\(^{-1} \). The graph is relatively insensitive to this variance.

With the aid of Figure 7 the critical depth of a particular glacier can be determined once the geometrical term \( A \) and surface temperature \( T_S \) are known. In the case of Steele Glacier the surface slope \( \alpha \) is approximately 2° (Wood, 1972) and \( f \) is likely between 0.5 (semicircular cross section) and 1.0 (infinitely wide slab). Hence \( A \) may be anywhere between
15.4 \times 10^{-5} \text{ Nt} \text{ and } 30.9 \times 10^{-5} \text{ Nt}. \text{ The mean surface temperature } T_s \text{ is believed to be } -8.0 \pm 1^\circ C \text{ (Jarvis and Clarke, unpublished). This scope for } A \text{ and } T_s \text{ is indicated as a rectangular section on Figure 7. Contours passing through this region imply that the critical depth for Steele Glacier is between 350 m and 600 m. Specifically, for } f = 0.7 \text{ (a typical value for valley glaciers (Paterson, 1969; Robin and Weertman, 1973)) and } T_s = -8.0^\circ C, \text{ the critical depth is 450 m. This implies that wherever the glacier thickness does not exceed 450 m, geothermal heat must enter the glacier ice and a finite layer of temperate ice cannot exist. Further calculations show that for regions of glacier depth less than (approximately) 300 m, a value of } T_s = -8^\circ C \text{ can only be obtained by assuming } \phi(0) = G, \text{ the geothermal gradient, and } T(0) < 0^\circ C. \text{ Thus if the flow law parameters of Nye (1953) are valid for Steele Glacier, large regions of this glacier may be frozen to the bedrock.}

Also indicated on Figure 7 are the areas appropriate to Finsterwalder and Trapridge Glaciers. The surface temperature and slope of Finsterwalder Glacier, Spitsbergen, are taken from Schytt (1969) and Liestøl (1969) and } f \text{ is assumed to lie between 0.5 and 1.0. The critical depths indicated for Finsterwalder and Trapridge Glaciers are approximately 400 m and 120 m respectively. No temperate layer of ice should exist at the base of these glaciers if their respective ice thicknesses are less than these values.}

The above discussion has been based on Nye's values of the flow law constants, chosen because they lie in the middle of the range of possible values. More, or less viscous flow laws will naturally yield different critical depths. The critical depths of Steele, Finsterwalder and Trapridge Glaciers as predicted with the most viscous and least viscous flow laws tabulated by Hodge (unpublished) are presented in Table III. Although the critical depths vary significantly over the range of flow law constants, there is no reason to exclude the pos-
sibility of cold ice at the base of these sub-polar glaciers, particularly in the lower tongue regions.

CONCLUDING REMARKS

Robin and Weertman (1973) have proposed an attractive hypothesis for cyclic surging of presumably temperate glaciers which includes an active ice reservoir, with a steepening front, and stagnant receiving area. The Finsterwalder Glacier was cited as a surge-type glacier exhibiting the properties predicted by this hypothesis. However the gravity depth profile presented for this glacier (Robin and Weertman, 1973) never exceeds 350 m, in which case our calculations would indicate large regions of cold basal ice (Figure 7). Melting temperatures should only prevail along the ice-rock interface under the deepest ice. Consequently the flow of Finsterwalder Glacier may be thermally regulated in the same manner as that proposed for the Rusty and Trapridge Glaciers. The Robin-Weertman theory presupposes the ice reservoir to be totally within the accumulation zone with the ice crest or "triggering zone" at the firn line, contrary to the statement by Meier and Post (1969) that "the ice reservoir is not identical with the accumulation zone; the reservoir can be entirely within the ablation zone". Our observations on the cold Trapridge Glacier are consistent with the above statement.

It is interesting to note that the glaciers in Spitsbergen, where surging is a common mode of glacier advance, are all sub-polar (Liestøl, 1969; Schytt, 1969) and that the 23-m temperature measured on Brasvellbreen (which has made the largest surge recorded in Spitsbergen) was -6.0°C. Schytt claims that the outer edges of ice caps in this region form a "ring of cold ice" frozen to the bed and Hollins (in discussion to Schytt, 1969) suggested that cold ice holding back warm ice may be favourable to surge development.
In conclusion it appears likely that a cold stagnant tongue acting both as a thermal and mechanical barrier may be responsible for the building up of ice reservoirs on many of the sub-polar glaciers in Alaska, Yukon Territory and Spitsbergen.

ACKNOWLEDGEMENTS

We thank B. Chandra, B. B. Narod and K. D. Schreiber for assistance in field preparations, and S. G. Collins, P. Dillon, R. H. Ragle and P. Upton of the Arctic Institute of North America for encouragement and logistic support. We are especially grateful to Robert Metcalfe who was extremely valuable as a field assistant. Financial support was provided by the University of British Columbia, Environment Canada and the National Research Council (Canada).
REFERENCES

Clarke, G.K.C. Unpublished. [Numerical modelling results.]


Jarvis, G.T., and Clarke, G.K.C. Unpublished. Thermal effects of crevassing on Steele Glacier. [Submitted to the Journal of Glaciology.]


<table>
<thead>
<tr>
<th>Hole</th>
<th>Depth (m)</th>
<th>Average Drilling Speed (m/hr)</th>
<th>Cause of Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.7</td>
<td>3.0</td>
<td>Burn-out</td>
</tr>
<tr>
<td>2</td>
<td>29.6</td>
<td>1.2</td>
<td>Freeze-in</td>
</tr>
<tr>
<td>3</td>
<td>64.5</td>
<td>4.2</td>
<td>Burn-out</td>
</tr>
<tr>
<td>4</td>
<td>87.5</td>
<td>4.6</td>
<td>Burn-out</td>
</tr>
<tr>
<td>5</td>
<td>50.3</td>
<td>5.7</td>
<td>Freeze-in</td>
</tr>
<tr>
<td>6</td>
<td>43.6</td>
<td>3.2</td>
<td>Englacial debris</td>
</tr>
<tr>
<td>7</td>
<td>11.6</td>
<td>2.5</td>
<td>Englacial debris</td>
</tr>
<tr>
<td>8</td>
<td>37.4</td>
<td>0.8</td>
<td>Freeze-in</td>
</tr>
</tbody>
</table>
TABLE II. TRAPRIDGE GLACIER TEMPERATURE DATA

Hole #1

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>-2.76'</td>
<td></td>
</tr>
<tr>
<td>21.7</td>
<td>-3.60</td>
<td></td>
</tr>
<tr>
<td>41.7</td>
<td>-2.03</td>
<td></td>
</tr>
<tr>
<td>56.7</td>
<td>-1.07</td>
<td></td>
</tr>
<tr>
<td>66.7</td>
<td>-0.32</td>
<td></td>
</tr>
<tr>
<td>71.7</td>
<td>-0.23</td>
<td></td>
</tr>
</tbody>
</table>

Hole #2

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>-0.23</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>-1.30</td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>-3.70</td>
<td></td>
</tr>
<tr>
<td>11.3</td>
<td>-3.99</td>
<td></td>
</tr>
<tr>
<td>14.3</td>
<td>-3.83</td>
<td></td>
</tr>
<tr>
<td>17.4</td>
<td>-3.77</td>
<td></td>
</tr>
<tr>
<td>20.4</td>
<td>-3.54</td>
<td></td>
</tr>
<tr>
<td>23.5</td>
<td>-3.45</td>
<td></td>
</tr>
<tr>
<td>26.5</td>
<td>-3.25</td>
<td></td>
</tr>
<tr>
<td>29.6</td>
<td>-3.08</td>
<td></td>
</tr>
<tr>
<td>Depth (m)</td>
<td>1972 Temperatures (°C)</td>
<td>1973 Temperatures (°C)</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>7.6</td>
<td>-5.63</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>-3.89</td>
<td></td>
</tr>
<tr>
<td>34.5</td>
<td>-2.01</td>
<td></td>
</tr>
<tr>
<td>49.5</td>
<td>-1.32</td>
<td></td>
</tr>
<tr>
<td>59.5</td>
<td>-1.03</td>
<td></td>
</tr>
<tr>
<td>64.5</td>
<td>-1.12</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.9</td>
<td>-3.37</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>-3.10</td>
<td></td>
</tr>
<tr>
<td>37.5</td>
<td>-2.14</td>
<td></td>
</tr>
<tr>
<td>57.5</td>
<td>-1.10</td>
<td></td>
</tr>
<tr>
<td>72.5</td>
<td>-0.20</td>
<td></td>
</tr>
<tr>
<td>82.5</td>
<td>-0.56</td>
<td></td>
</tr>
<tr>
<td>87.5</td>
<td>-0.45</td>
<td></td>
</tr>
</tbody>
</table>
### Hole #5

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3</td>
<td>-8.43</td>
<td></td>
</tr>
<tr>
<td>25.3</td>
<td>-4.86</td>
<td></td>
</tr>
<tr>
<td>35.3</td>
<td>-3.94</td>
<td></td>
</tr>
<tr>
<td>45.3</td>
<td>-3.19</td>
<td></td>
</tr>
<tr>
<td>50.3</td>
<td>-0.72</td>
<td></td>
</tr>
</tbody>
</table>

### Hole #6

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.6</td>
<td>-6.28</td>
<td></td>
</tr>
<tr>
<td>21.6</td>
<td>-4.45</td>
<td></td>
</tr>
<tr>
<td>29.6</td>
<td>-3.57</td>
<td></td>
</tr>
<tr>
<td>35.6</td>
<td>-2.78</td>
<td></td>
</tr>
<tr>
<td>41.6</td>
<td>-1.48</td>
<td></td>
</tr>
<tr>
<td>43.6</td>
<td>-1.15</td>
<td></td>
</tr>
</tbody>
</table>

### Hole #7

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1972 Temperatures (°C)</th>
<th>1973 Temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
<td>-4.20</td>
<td></td>
</tr>
<tr>
<td>11.6</td>
<td>-3.37</td>
<td></td>
</tr>
</tbody>
</table>
### Table III. Range of Values of Critical Depth Corresponding to Range of Flow Laws Cited by Hodge (Unpublished)

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Flow Laws</th>
<th>Least Viscous</th>
<th>Most Viscous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( B = 0.550 \text{ bar}^{-n} \text{ a}^{-1} )</td>
<td>( B = 0.040 \text{ bar}^{-n} \text{ a}^{-1} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( n = 3.3 )</td>
<td>( n = 5.2 )</td>
</tr>
<tr>
<td>Steele</td>
<td></td>
<td>400 m</td>
<td>600 m</td>
</tr>
<tr>
<td>Finsterwalder</td>
<td></td>
<td>350 m</td>
<td>500 m</td>
</tr>
<tr>
<td>Trapridge</td>
<td></td>
<td>90 m</td>
<td>130 m</td>
</tr>
</tbody>
</table>

**Critical Depths**
LIST OF FIGURES

Fig. 1. a. Portion of Canadian Government air photograph A13136-44 showing Trapridge Glacier region in 1951. b. Portion of Canadian Government air photograph A20128-10 showing Trapridge Glacier region in 1967.

Fig. 2. Vertical temperature profiles: Holes #1, #2 and #5.

Fig. 3. Vertical temperature profiles: Holes #3 & #6.

Fig. 4. Vertical temperature profiles: Holes #4 & #7.

Fig. 5. Trapridge Glacier basal ice temperature map.

Fig. 6. a. Cross-sectional view of Trapridge Glacier's temperature regime.
   b. Cross-sectional view of Rusty Glacier's temperature regime.

Fig. 7. Contours of critical depth H (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and A, a geometric term as defined in text. (Flow law constants are $B(T_0) = 0.173 \text{ bar}^{-n \alpha^{-1}}$; $n = 3.07$.)
Fig. 1. a. Portion of Canadian Government air photograph A13136-44 showing Trapridge Glacier region in 1951.
b. Portion of Canadian Government air photograph A20128-10 showing Trapridge Glacier region in 1967.
Fig. 2. Vertical temperature profiles: Holes #1, #2 & #5.
Fig. 3. Vertical temperature profiles: Holes #3 & #6.
Fig. 4. Vertical temperature profiles: Holes #4 & #7.
Fig. 5. Trapridge Glacier basal ice temperature map.
Fig. 6. a. Cross-sectional view of Trapridge Glacier's temperature regime.

b. Cross-sectional view of Rusty Glacier's temperature regime.
Fig. 7. Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are $B(T_0) = 0.173 \text{ bar}^{-n_a^{-1}}$; $n = 3.07$.)
APPENDIX IV

INSTRUMENTATION

Thermistor Preparation

A total of 120 Fenwal GB34P2 glass bead thermistors was calibrated prior to the field expedition. A brief discussion of the calibration procedures was given in Appendix III; additional details are presented here.

Batch calibration of thermistors immersed in a Colora KT20S constant temperature bath was accomplished with a bank of six 24-pole selector switches connected to the thermistors via multiconductor #22 AWG cables (Figure 1). The switches were labelled A, B, C, D, E, and F and the poles of each denoted 0, 1, 2, 3, ..., 22 and L. The pole labelled 0 was reserved for an open circuit or "off" position. Each of those marked 1, 2, 3 and so on up to 22 was wired to one terminal of a specific thermistor while a common lead wire (to which the other terminal of each thermistor was soldered) was connected to pole L. Thermistors were then identified according to the switch and pole to which they were connected during calibration. For example, thermistor A3 is that which was connected to pole 3 on switch A (Figure 1, inset). This nomenclature was maintained throughout the project and reference to individual thermistors in this report adheres to the same notation.

Resistances of all thermistors, measured at four temperatures in the range \(-10.00^\circ\text{C}\) to \(0.00^\circ\text{C}\), are tabulated in Appendix IX.

Thermistor Cable Construction

Thermistor cables were constructed in the field im-
Fig. 1. Thermistor calibration circuitry.
mediately before each drilling venture. This practice prevented in-transit damage to the thermistors and permitted their spacing along the cable to vary according to the measured ice depth at each drilling site. The Belden 8757 8-conductor #22 AWG cable, employed as thermistor cable, is colour coded to facilitate identification of the individual conductors. The wires are twisted in four separate pairs, each consisting of one black and one coloured wire. The four distinct colours are red, green, blue and white. The black wire which is paired with the red will henceforth be referred to as "red's black" or "R-Black", that with the green as "green's black" or "G-Black", that with the blue as "blue's black" or "B-Black" and that with the white as "white's black" or "W-Black". Seven thermistors were installed in each length of cable, and a convention was established whereby the thermistors' relative positions were governed by the colour of their lead conductors. In every cable "white's black" was taken as a common lead, while the remaining seven conductors led to individual thermistors (Figure 2). The deepest thermistor on every cable was connected across "red" and "white's black", the second deepest across "red's black" and "white's black", and so on. Figure 2 illustrates the complete colour scheme.

Prior to thermistor installation the desired position of each sensor was indicated on the cable with coloured tape. At each location the cable jacket was slit and opened, and the appropriate lead wire cut and stripped. This conductor was soldered to one terminal of the selected thermistor, the terminal being covered with plastic tubing to prevent electrical shorting. The other terminal, also covered with plastic tubing, was then soldered directly across to a bared section of the cable's common conductor. (To protect the thermistors from thermal shock a low temperature solder, cool iron, and metal heat sink were used.) Each connection was further insulated with plastic tape and wrapped in self-vulcanizing cold-
Fig. 2. Thermistor cable colour-code convention.
setting rubber tape. Finally the thermistors were cushioned and bound securely into place with several layers of the rubber tape. This process sealed the tear in the cable jacket forming a pod about 10 cm long.

**Power Cable**

Belden 8620 four-conductor #16 AWG cable with chrome-vinyl jacket was employed as a power supply cable for the thermal probes. This relatively high gauge wire (for the anticipated power input) enabled ohmic heating to occur along the power line, thereby inhibiting hole closure due to re-freezing. Some flexibility in the amount of heat so dissipated was achieved by use of the four-conductor cable. Where the cable joined the probe the four wires were paired (red with white, black with green) and one pair was soldered to each of the heating element's lead wires. At the end of the cable leading to the electric generator, different contact arrangements of the four conductors allowed a choice of three degrees of line heating (Figure 3). The low line heating mode was most often employed.

**Thermal Probes**

Electrically powered thermal drills were constructed with basic design consisting of a Firerod heating element embedded in a solid copper point and mounted on the end of a cylindrical shaft of fibercast tubing (Figure 4). The heater's #12 AWG nichrome lead wires were bolted to the #16 AWG copper power line with AMP crimp-on terminals to obtain solid mechanical and electrical contact. Electrical insulation was ensured by casting the leads in a hard setting epoxy resin. The weight of the apparatus was borne by a hard rubber cap bolted to the cold end of the probe. This allowed the power line, which passed through a hole in the cap, to make a stress
Fig. 3. Possible modes of line heating: (a) low line heating; (b) high line heating; (c) line heating dominant.
free electrical contact with the heating element.

Two different models were designed and for each model, probes were constructed in two distinct diameters. The four versions will henceforth be referred to as Model $I_w^*$, Model $I_n^*$, Model $II_w^*$, and Model $II_n^*$, where the subscripts $w$ and $n$ indicate wide and narrow diameters respectively. Models I and II differ in that in the former the heating element is totally embedded in the copper point whereas in the latter it protrudes through the tip (Figure 4). Furthermore, the Firerod heaters of Model II were capable of delivering twice the power of those of Model I (5,000 watts as opposed to 2,500 watts). The drill shafts were either 6.033 or 7.303 cm in diameter and generally 1 m long. No buoyancy chamber or steering rod was considered necessary.

One small Stacey-type probe (Stacey, 1960) was also used.

**Power Supply**

A 5 kVA Kohler electric light plant, model 5RMS65, supplied power to the thermal probes at six of the eight holes drilled on Trapridge Glacier and at the single hole drilled on Steele Glacier. This generator, rated at 120 V a.c., 40.6 A a.c. or 240 V a.c., 20.3 A a.c., proved extremely reliable in diverse weather conditions. A small transformer with step-up ratio of 1.5 was necessary for efficient operation of the relatively high resistance Model II drills. No transformer was required with the Model I design. Generator output was typically 4.5 kVA with the Model I probes and 3.6 kVA with the Model II.

At holes #2 and #8 power was supplied by a smaller 1.5 kVA Onan generator rated at 120 V a.c., 15 A a.c. Though reliable under rugged conditions, it operated inefficiently at high altitudes. Furthermore, the resistances of the Model I and II probes were too low and too high respectively for this unit to perform satisfactorily.
Fig. 4. Thermal probe design.

MODEL I

- Rubber cap
- Copper power line
- Nichrome leads
- Firerod heater

MODEL II

- Rubber cap
- Copper power line
- Fibercast tubing
- Epoxy resin
- Nichrome leads
- Copper point
- Firerod heater
A thermal drill with the same specifications as Model $I_w$ was employed on the Rusty Glacier, Yukon Territory, by Classen (unpublished). This probe achieved a drill speed of 1.0 - 1.5 m/hr (with considerable side wall melting) as compared to an anticipated rate of 4.0 m/hr. The various designs described above were efforts to increase this rate of probe descent. The small diameter probes, having to melt less ice, were expected to progress more rapidly although the narrow drill hole produced would be more susceptible to closure by refreezing. The Model II probes were designed to deliver more power to the heating element and dissipate less along the line. Also, the radial symmetry of the Firerod heater, believed responsible for the lateral melting observed by Classen, was to be utilized by the protruding tip in widening its pilot hole out to the drill shaft diameter.

The performance of each probe depended on the power supply and line heating mode (controlled as shown in Figure 3). The highest drilling speed was obtained with Model $I_n$ probes. Average rate of descent at hole #5 with a Model $I_n$ probe, low line heating, and generator output of 3.4 kVA was 5.6 m/hr for nine hours. However, the resulting narrow hole allowed the cable to freeze in at a depth of 50 m, 67 m above the glacier bed. A second attempt with generator power increased to 4.2 kVA yielded a drill rate of 9 m/hr for twenty minutes followed by probe burn-out. These two attempts indicate that usefulness of the Model $I_n$ drill is limited to shallow ice where it can be run at low power thus avoiding probe burn-out without the fear of premature hole closure. The most successful drilling on Trapridge Glacier was accomplished with Model $I_w$ probes, low line heating and generator power of 4.3 kVA. This combination was used to complete holes #1, #3, #4 and #6. The average drilling speed over the total length of these four holes was
4.0 m/hr. However when coupled with a smaller 1.5 kVA generator, a Model I probe at hole #8 averaged a meagre 0.9 m/hr for 44 hours before refreezing locked the power cable in place.

The Model II design at first proved unsuccessful. Attempts at hole #1 with a Model II probe (6.0 cm in diameter), low line heating and generator power of 4.3 kVA gave drill speeds of 0.5 m/hr creating a hole approximately 30 cm in diameter. This was due to the fact that the protruding heating element had a relatively cool tip. Hence the envisaged pilot hole was never formed and side wall melting dominated. To direct heat to the probe tip, a small copper sheath was machined to fit over the end of the Firerod element. Although this addition enabled Model II probes to average 3.0 m/hr for four hours at hole #7 and for 40 hours on the Steele Glacier, drilling remained somewhat inefficient with holes approximately 12 cm in diameter being produced. However this may be a desirable feature when drilling in cold ice as a means of retarding hole closure. Also the larger heating elements of the Model II probes are not expected to burn out as readily as those in Model I. Model I probes burned out in three out of six holes on Trapridge Glacier, and were halted by hole closure in another two. Hence it is felt that for deep holes in cold ice, the Model II probes are superior.

The Model II design was never field tested but it is thought that the resulting hole would be too wide to be practical.

The Stacey-type probe, used for hole #2 with low line heating and a small 1.5 kVA generator, progressed at a rate of 1.2 m/hr for 25 hours before freezing in at a depth of 30 m.

The progress of all thermal probes was severely hindered by such dust layers and pebbles as were encountered. Clean superimposed ice was often found to mask the previous summer's debris laden ablation surface, necessitating careful
selection of drilling sites. Similarly the drill hole itself was always approached with caution for a single pebble dislodged from a climbing boot tred could wreak havoc on probe progress.

Field Measurements

A 6 volt Fluke 8100A digital multimeter and a 0.7 volt Wheatstone bridge (with matched 5,400 ohm legs) were employed in the field to measure resistances across the leads of the implanted thermistors. The readings from the two instruments generally differed by approximately 125 ohms, the Fluke multimeter giving the larger value. Since a higher resistance indicates a lower temperature, this discrepancy cannot be due to self-heating of thermistors induced by the multimeter. As a check on instrument calibration, the resistances of two precision wound resistors, specified as 5,400 ohms ±0.1% and 10,800 ohms ±0.1% were measured with both the multimeter and the bridge. The former gave values of 5,402 ±0.5 ohms and 10,800 ±0.5 ohms, whereas the latter indicated resistances of 5,384 ±5.0 ohms and 10,700 ±5.0 ohms. Hence the multimeter values were considered the more reliable.

Some indication of thermistor self-heating was observed with the Fluke multimeter. As the measured values were electronically displayed, transient resistances could be monitored immediately after connecting the thermistor leads to the multimeter. Resistance generally dropped 10 - 30 ohms (which corresponds to a maximum temperature increase of 0.05°C) before settling to a constant value. However the initial value of resistance was consistently reproduced to within ±10 ohms on several trial runs by as many as three different operators. The accuracy of measurement is therefore considered to be ±10 ohms or ±0.02°C.

Although self-heating caused by the multimeter was
minimal for thermistors embedded in cold glacier ice, significant heating was observed in a thermistor lying on the snow surface and exposed to the air. The resistance of thermistor A22, which remained above hole #2 when refreezing terminated drilling, dropped from an initial value of 9,800 ohms to 9,750 ohms in the three seconds normally required for stability and continued to decrease to a value of 9,650 in the following ten seconds. Consequently the multimeter cannot be considered useful for resistance measurements of thermistors in air. The marked difference in thermistor behavior in these two media is due to the thermal conductivity of ice being approximately four orders of magnitude greater than that of air (Weast, 1969).

A comparison of the resistances of forty separate thermistors, as measured by the two instruments discussed above, is displayed graphically in Figure 5. The relation appears to be linear with an intercept on the multimeter resistance axis of 125 ohms, suggesting that the Wheatstone bridge had a calibration error of 125 ohms in this range of resistance. It is noteworthy that points corresponding to warm temperatures (resistance less than 11,500 ohms) lie on or close to the best fitting straight line. This implies that even in ice close to the melting point significant heating does not occur. Consequently the discrepancy between the two measured values of resistance can be wholly accounted for by the calibration error in the bridge.
Fig. 5. Instrument calibration check: a comparison of resistances measured with Fluke multimeter and Wheatstone bridge.
The model of basal temperature distribution discussed in Appendix III is herein referred to as Model I. The six zones into which the glacier was subdivided, central drilling sites, and grid points at which basal temperatures were predicted, are indicated on Figure 1.

In the construction of Model I, temperature gradients were computed from the two deepest points of the measured temperature profiles. As the gradients generally become less steep with depth, this procedure likely gives an underestimate of the temperature gradients and a "cool" model results. (In the case of hole #3, the deepest point on the observed profile was ignored in the temperature gradient calculation as it would imply a negative increase of temperature with depth.) The data contoured to form the basal temperature map of Appendix III are tabulated here in Table I.

To demonstrate that the prediction of warm ice at the base of Trapridge Glacier does not depend on the specific extrapolation procedures followed in deriving Model I, two additional models were constructed. For Model II, the appropriate gradient for each zone was determined from the 10-m temperature and that at the greatest depth achieved. Basal temperatures predicted with these gradients are listed in Table II and have been contoured to produce the map of bed isotherms shown in Figure 2. For Model III, the average value of the six gradients calculated for Model II was applied over the entire glacier. The temperatures predicted by this model are given in Table III and contoured in Figure 3.

In both Figures 2 and 3 a partially temperate base and cold lower tongue are observed, corroborating the predic-
Fig. 1. Reference grid for basal temperature models.
tions of Model I. Furthermore, the regions of ice at the pressure melting point are more extensive in Models II and III than in Model I. This suggests that the latter gives a conservative estimate of the amount of temperate ice at the base of Trapridge Glacier.
Fig. 2. Trapridge Glacier basal temperature map - Model II.
Fig. 3. Trapridge Glacier basal temperature map - Model III.
<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3.30</td>
<td>0.0352</td>
<td>-3.47</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.89</td>
</tr>
<tr>
<td>3</td>
<td>65</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.36</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.36</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.89</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>3.85</td>
<td>0.0448</td>
<td>-3.17</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>3.85</td>
<td>0.0448</td>
<td>-3.40</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>3.85</td>
<td>0.0448</td>
<td>-1.61</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>3.85</td>
<td>0.0448</td>
<td>-0.27</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>3.85</td>
<td>0.0448</td>
<td>-1.61</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>3.30</td>
<td>0.0352</td>
<td>-2.07</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.36</td>
</tr>
<tr>
<td>14</td>
<td>75</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.01</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.84</td>
</tr>
<tr>
<td>16</td>
<td>90</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.48</td>
</tr>
<tr>
<td>17</td>
<td>55</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.72</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>3.85</td>
<td>0.0448</td>
<td>-1.61</td>
</tr>
<tr>
<td>19</td>
<td>80</td>
<td>3.85</td>
<td>0.0448</td>
<td>-0.71</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>3.85</td>
<td>0.0448</td>
<td>-0.04</td>
</tr>
<tr>
<td>21</td>
<td>65</td>
<td>3.85</td>
<td>0.0448</td>
<td>-1.39</td>
</tr>
<tr>
<td>22</td>
<td>20</td>
<td>3.30</td>
<td>0.0352</td>
<td>-2.95</td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.89</td>
</tr>
<tr>
<td>24</td>
<td>70</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.19</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.01</td>
</tr>
<tr>
<td>26</td>
<td>95</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.31</td>
</tr>
<tr>
<td>27</td>
<td>110</td>
<td>3.30</td>
<td>0.0352</td>
<td>+0.22-&gt;0.00</td>
</tr>
<tr>
<td>28</td>
<td>90</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.48</td>
</tr>
<tr>
<td>29</td>
<td>75</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.01</td>
</tr>
<tr>
<td>30</td>
<td>125</td>
<td>3.85</td>
<td>0.0448</td>
<td>+1.30-&gt;0.00</td>
</tr>
<tr>
<td>31</td>
<td>105</td>
<td>3.85</td>
<td>0.0448</td>
<td>+0.41-&gt;0.00</td>
</tr>
<tr>
<td>32</td>
<td>80</td>
<td>3.85</td>
<td>0.0448</td>
<td>-0.49</td>
</tr>
<tr>
<td>33</td>
<td>40</td>
<td>3.30</td>
<td>0.0352</td>
<td>-2.24</td>
</tr>
<tr>
<td>34</td>
<td>65</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.36</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.19</td>
</tr>
<tr>
<td>36</td>
<td>85</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.66</td>
</tr>
<tr>
<td>37</td>
<td>90</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.48</td>
</tr>
<tr>
<td>38</td>
<td>75</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.01</td>
</tr>
<tr>
<td>39</td>
<td>95</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.31</td>
</tr>
<tr>
<td>40</td>
<td>135</td>
<td>3.85</td>
<td>0.0448</td>
<td>+1.75-&gt;0.00</td>
</tr>
</tbody>
</table>
### BASAL TEMPERATURE DATA

**MODEL NUMBER I**

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>100</td>
<td>3.85</td>
<td>0.0448</td>
<td>+0.18-&gt;0.00</td>
</tr>
<tr>
<td>42</td>
<td>20</td>
<td>3.85</td>
<td>0.0448</td>
<td>-3.40</td>
</tr>
<tr>
<td>43</td>
<td>30</td>
<td>3.30</td>
<td>0.0352</td>
<td>-2.60</td>
</tr>
<tr>
<td>44</td>
<td>50</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.89</td>
</tr>
<tr>
<td>45</td>
<td>65</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.36</td>
</tr>
<tr>
<td>46</td>
<td>75</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.01</td>
</tr>
<tr>
<td>47</td>
<td>70</td>
<td>3.30</td>
<td>0.0352</td>
<td>-1.19</td>
</tr>
<tr>
<td>48</td>
<td>90</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.48</td>
</tr>
<tr>
<td>49</td>
<td>95</td>
<td>3.30</td>
<td>0.0352</td>
<td>-0.31</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>3.85</td>
<td>0.0448</td>
<td>-3.28</td>
</tr>
<tr>
<td>51</td>
<td>30</td>
<td>7.00</td>
<td>0.0979</td>
<td>-5.04</td>
</tr>
<tr>
<td>52</td>
<td>65</td>
<td>7.00</td>
<td>0.0979</td>
<td>-1.62</td>
</tr>
<tr>
<td>53</td>
<td>70</td>
<td>7.00</td>
<td>0.0979</td>
<td>-1.13</td>
</tr>
<tr>
<td>54</td>
<td>70</td>
<td>3.85</td>
<td>0.0535</td>
<td>-0.64</td>
</tr>
<tr>
<td>55</td>
<td>90</td>
<td>3.85</td>
<td>0.0535</td>
<td>+0.43-&gt;0.00</td>
</tr>
<tr>
<td>56</td>
<td>35</td>
<td>3.85</td>
<td>0.0535</td>
<td>-2.51</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>7.00</td>
<td>0.0979</td>
<td>-7.98</td>
</tr>
<tr>
<td>58</td>
<td>80</td>
<td>7.00</td>
<td>0.0979</td>
<td>-0.15</td>
</tr>
<tr>
<td>59</td>
<td>110</td>
<td>7.00</td>
<td>0.0979</td>
<td>+0.27-&gt;0.00</td>
</tr>
<tr>
<td>60</td>
<td>105</td>
<td>3.85</td>
<td>0.0535</td>
<td>+1.23-&gt;0.00</td>
</tr>
<tr>
<td>61</td>
<td>80</td>
<td>3.85</td>
<td>0.0535</td>
<td>-0.10</td>
</tr>
<tr>
<td>62</td>
<td>55</td>
<td>3.85</td>
<td>0.0535</td>
<td>-1.44</td>
</tr>
<tr>
<td>63</td>
<td>0</td>
<td>7.00</td>
<td>0.0979</td>
<td>-7.98</td>
</tr>
<tr>
<td>64</td>
<td>80</td>
<td>7.00</td>
<td>0.0979</td>
<td>-0.15</td>
</tr>
<tr>
<td>65</td>
<td>90</td>
<td>7.00</td>
<td>0.0979</td>
<td>+0.83-&gt;0.00</td>
</tr>
<tr>
<td>66</td>
<td>80</td>
<td>6.60</td>
<td>0.1598</td>
<td>+4.59-&gt;0.00</td>
</tr>
<tr>
<td>67</td>
<td>50</td>
<td>6.60</td>
<td>0.1598</td>
<td>-0.21</td>
</tr>
<tr>
<td>68</td>
<td>35</td>
<td>6.60</td>
<td>0.1598</td>
<td>-2.61</td>
</tr>
<tr>
<td>69</td>
<td>65</td>
<td>6.60</td>
<td>0.1598</td>
<td>+2.19-&gt;0.00</td>
</tr>
<tr>
<td>70</td>
<td>75</td>
<td>6.60</td>
<td>0.1598</td>
<td>+3.79-&gt;0.00</td>
</tr>
<tr>
<td>71</td>
<td>65</td>
<td>6.60</td>
<td>0.1598</td>
<td>+2.19-&gt;0.00</td>
</tr>
<tr>
<td>72</td>
<td>20</td>
<td>6.60</td>
<td>0.1598</td>
<td>-5.00</td>
</tr>
<tr>
<td>73</td>
<td>15</td>
<td>6.60</td>
<td>0.1598</td>
<td>-5.80</td>
</tr>
<tr>
<td>74</td>
<td>35</td>
<td>6.60</td>
<td>0.1598</td>
<td>-2.61</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>6.60</td>
<td>0.1598</td>
<td>-1.01</td>
</tr>
<tr>
<td>76</td>
<td>30</td>
<td>6.60</td>
<td>0.1598</td>
<td>-3.40</td>
</tr>
<tr>
<td>77</td>
<td>20</td>
<td>6.60</td>
<td>0.1598</td>
<td>-5.00</td>
</tr>
<tr>
<td>78</td>
<td>5</td>
<td>4.00</td>
<td>0.3649</td>
<td>-5.82</td>
</tr>
<tr>
<td>79</td>
<td>0</td>
<td>4.00</td>
<td>0.3649</td>
<td>-7.65</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>4.00</td>
<td>0.3649</td>
<td>-0.35</td>
</tr>
</tbody>
</table>
### BASAL TEMPERATURE DATA

#### MODEL NUMBER 1

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>82</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>83</td>
<td>5</td>
<td>4.00</td>
<td>0.3649</td>
<td>-5.82</td>
</tr>
<tr>
<td>84</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>85</td>
<td>5</td>
<td>4.00</td>
<td>0.3649</td>
<td>-5.82</td>
</tr>
<tr>
<td>86</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>87</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>88</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>89</td>
<td>15</td>
<td>4.00</td>
<td>0.3649</td>
<td>-2.18</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>91</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>92</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>93</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>94</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>95</td>
<td>15</td>
<td>4.00</td>
<td>0.3649</td>
<td>-2.18</td>
</tr>
<tr>
<td>96</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>97</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>98</td>
<td>15</td>
<td>4.00</td>
<td>0.3649</td>
<td>-2.18</td>
</tr>
<tr>
<td>99</td>
<td>0</td>
<td>4.00</td>
<td>0.3649</td>
<td>-7.65</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>4.00</td>
<td>0.3649</td>
<td>-4.00</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
<td>4.00</td>
<td>0.3649</td>
<td>-5.82</td>
</tr>
</tbody>
</table>
### TABLE II.

**BASAL TEMPERATURE DATA**

**MODEL NUMBER II**

<table>
<thead>
<tr>
<th>GRID</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3.30</td>
<td>0.0368</td>
<td>-3.48</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.83</td>
</tr>
<tr>
<td>3</td>
<td>65</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.28</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.28</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.83</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>3.85</td>
<td>0.0501</td>
<td>-3.10</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>3.85</td>
<td>0.0501</td>
<td>-3.35</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>3.85</td>
<td>0.0501</td>
<td>-1.35</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>3.85</td>
<td>0.0501</td>
<td>+0.16-&gt;0.00</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>3.85</td>
<td>0.0501</td>
<td>-1.35</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>3.30</td>
<td>0.0368</td>
<td>-3.48</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>3.30</td>
<td>0.0368</td>
<td>-2.01</td>
</tr>
<tr>
<td>13</td>
<td>65</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.28</td>
</tr>
<tr>
<td>14</td>
<td>75</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.91</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.72</td>
</tr>
<tr>
<td>16</td>
<td>90</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.35</td>
</tr>
<tr>
<td>17</td>
<td>55</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.64</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>3.85</td>
<td>0.0501</td>
<td>-1.35</td>
</tr>
<tr>
<td>19</td>
<td>80</td>
<td>3.85</td>
<td>0.0501</td>
<td>-0.34</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>3.85</td>
<td>0.0501</td>
<td>+0.41-&gt;0.00</td>
</tr>
<tr>
<td>21</td>
<td>65</td>
<td>3.85</td>
<td>0.0501</td>
<td>-1.09</td>
</tr>
<tr>
<td>22</td>
<td>20</td>
<td>3.30</td>
<td>0.0368</td>
<td>-2.93</td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.83</td>
</tr>
<tr>
<td>24</td>
<td>70</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.09</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.91</td>
</tr>
<tr>
<td>26</td>
<td>95</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.17</td>
</tr>
<tr>
<td>27</td>
<td>110</td>
<td>3.30</td>
<td>0.0368</td>
<td>+0.38-&gt;0.00</td>
</tr>
<tr>
<td>28</td>
<td>90</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.35</td>
</tr>
<tr>
<td>29</td>
<td>75</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.91</td>
</tr>
<tr>
<td>30</td>
<td>125</td>
<td>3.85</td>
<td>0.0501</td>
<td>+1.91-&gt;0.00</td>
</tr>
<tr>
<td>31</td>
<td>105</td>
<td>3.85</td>
<td>0.0501</td>
<td>+0.91-&gt;0.00</td>
</tr>
<tr>
<td>32</td>
<td>80</td>
<td>3.85</td>
<td>0.0501</td>
<td>-0.09</td>
</tr>
<tr>
<td>33</td>
<td>40</td>
<td>3.30</td>
<td>0.0368</td>
<td>-2.20</td>
</tr>
<tr>
<td>34</td>
<td>65</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.28</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.09</td>
</tr>
<tr>
<td>36</td>
<td>85</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.54</td>
</tr>
<tr>
<td>37</td>
<td>90</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.36</td>
</tr>
<tr>
<td>38</td>
<td>75</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.91</td>
</tr>
<tr>
<td>39</td>
<td>95</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.17</td>
</tr>
<tr>
<td>40</td>
<td>135</td>
<td>3.85</td>
<td>0.0501</td>
<td>+2.41-&gt;0.00</td>
</tr>
</tbody>
</table>
### BASAL TEMPERATURE DATA

#### MODEL NUMBER II

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>100</td>
<td>3.85</td>
<td>0.0501</td>
<td>+0.66-&gt;0.00</td>
</tr>
<tr>
<td>42</td>
<td>20</td>
<td>3.85</td>
<td>0.0501</td>
<td>-3.35</td>
</tr>
<tr>
<td>43</td>
<td>30</td>
<td>3.30</td>
<td>0.0368</td>
<td>-2.56</td>
</tr>
<tr>
<td>44</td>
<td>50</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.83</td>
</tr>
<tr>
<td>45</td>
<td>65</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.28</td>
</tr>
<tr>
<td>46</td>
<td>75</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.91</td>
</tr>
<tr>
<td>47</td>
<td>70</td>
<td>3.30</td>
<td>0.0368</td>
<td>-1.09</td>
</tr>
<tr>
<td>48</td>
<td>90</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.36</td>
</tr>
<tr>
<td>49</td>
<td>95</td>
<td>3.30</td>
<td>0.0368</td>
<td>-0.17</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>3.85</td>
<td>0.0501</td>
<td>-3.35</td>
</tr>
<tr>
<td>51</td>
<td>30</td>
<td>7.00</td>
<td>0.1558</td>
<td>-3.88</td>
</tr>
<tr>
<td>52</td>
<td>65</td>
<td>7.00</td>
<td>0.1558</td>
<td>-1.57</td>
</tr>
<tr>
<td>53</td>
<td>70</td>
<td>7.00</td>
<td>0.1558</td>
<td>-2.35</td>
</tr>
<tr>
<td>54</td>
<td>70</td>
<td>3.85</td>
<td>0.0558</td>
<td>-0.50</td>
</tr>
<tr>
<td>55</td>
<td>90</td>
<td>3.85</td>
<td>0.0558</td>
<td>-0.61</td>
</tr>
<tr>
<td>56</td>
<td>35</td>
<td>3.85</td>
<td>0.0558</td>
<td>-2.46</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>7.00</td>
<td>0.1558</td>
<td>-8.56</td>
</tr>
<tr>
<td>58</td>
<td>80</td>
<td>7.00</td>
<td>0.1558</td>
<td>+3.91-&gt;0.00</td>
</tr>
<tr>
<td>59</td>
<td>110</td>
<td>7.00</td>
<td>0.1558</td>
<td>+8.58-&gt;0.00</td>
</tr>
<tr>
<td>60</td>
<td>105</td>
<td>3.85</td>
<td>0.0558</td>
<td>+1.45-&gt;0.00</td>
</tr>
<tr>
<td>61</td>
<td>80</td>
<td>3.85</td>
<td>0.0558</td>
<td>+0.06-&gt;0.00</td>
</tr>
<tr>
<td>62</td>
<td>55</td>
<td>3.85</td>
<td>0.0558</td>
<td>-1.34</td>
</tr>
<tr>
<td>63</td>
<td>0</td>
<td>7.00</td>
<td>0.1558</td>
<td>-8.56</td>
</tr>
<tr>
<td>64</td>
<td>80</td>
<td>7.00</td>
<td>0.1558</td>
<td>+3.91-&gt;0.00</td>
</tr>
<tr>
<td>65</td>
<td>90</td>
<td>7.00</td>
<td>0.1558</td>
<td>+5.46-&gt;0.00</td>
</tr>
<tr>
<td>66</td>
<td>80</td>
<td>6.60</td>
<td>0.1622</td>
<td>+4.75-&gt;0.00</td>
</tr>
<tr>
<td>67</td>
<td>50</td>
<td>6.60</td>
<td>0.1622</td>
<td>-0.11</td>
</tr>
<tr>
<td>68</td>
<td>35</td>
<td>6.60</td>
<td>0.1622</td>
<td>-2.55</td>
</tr>
<tr>
<td>69</td>
<td>65</td>
<td>6.60</td>
<td>0.1622</td>
<td>+2.32-&gt;0.00</td>
</tr>
<tr>
<td>70</td>
<td>75</td>
<td>6.60</td>
<td>0.1622</td>
<td>+3.94-&gt;0.00</td>
</tr>
<tr>
<td>71</td>
<td>65</td>
<td>6.60</td>
<td>0.1622</td>
<td>+2.32-&gt;0.00</td>
</tr>
<tr>
<td>72</td>
<td>20</td>
<td>6.60</td>
<td>0.1622</td>
<td>-4.98</td>
</tr>
<tr>
<td>73</td>
<td>15</td>
<td>6.60</td>
<td>0.1622</td>
<td>-5.79</td>
</tr>
<tr>
<td>74</td>
<td>35</td>
<td>6.60</td>
<td>0.1622</td>
<td>-2.55</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>6.60</td>
<td>0.1622</td>
<td>-0.92</td>
</tr>
<tr>
<td>76</td>
<td>30</td>
<td>6.60</td>
<td>0.1622</td>
<td>-3.36</td>
</tr>
<tr>
<td>77</td>
<td>20</td>
<td>6.60</td>
<td>0.1622</td>
<td>-4.98</td>
</tr>
<tr>
<td>78</td>
<td>5</td>
<td>4.00</td>
<td>0.3938</td>
<td>-5.97</td>
</tr>
<tr>
<td>79</td>
<td>0</td>
<td>4.00</td>
<td>0.3938</td>
<td>-7.94</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>4.00</td>
<td>0.3938</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
### Basal Temperature Data

**Model Number II**

<table>
<thead>
<tr>
<th>Grid</th>
<th>Depth (M)</th>
<th>10-M Temp. (Deg C)</th>
<th>Temp. Gradient (Deg C/M)</th>
<th>Basal Temp. (Deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>82</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>83</td>
<td>5</td>
<td>4.00</td>
<td>0.3938</td>
<td>-5.97</td>
</tr>
<tr>
<td>84</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>85</td>
<td>5</td>
<td>4.00</td>
<td>0.3938</td>
<td>-5.97</td>
</tr>
<tr>
<td>86</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>87</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>88</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>89</td>
<td>15</td>
<td>4.00</td>
<td>0.3938</td>
<td>-2.03</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>91</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>92</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>93</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>94</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>95</td>
<td>15</td>
<td>4.00</td>
<td>0.3938</td>
<td>-2.03</td>
</tr>
<tr>
<td>96</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>97</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>98</td>
<td>15</td>
<td>4.00</td>
<td>0.3938</td>
<td>-2.03</td>
</tr>
<tr>
<td>99</td>
<td>0</td>
<td>4.00</td>
<td>0.3938</td>
<td>-7.94</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>4.00</td>
<td>0.3938</td>
<td>-4.00</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
<td>4.00</td>
<td>0.3938</td>
<td>-5.97</td>
</tr>
</tbody>
</table>
### TABLE III.  BASAL TEMPERATURE DATA

**MODEL NUMBER III**

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>3.30</td>
<td>0.1429</td>
<td>-4.01</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>3.30</td>
<td></td>
<td>+2.42 -&gt; 0.00</td>
</tr>
<tr>
<td>3</td>
<td>65</td>
<td>3.30</td>
<td></td>
<td>+4.56 -&gt; 0.00</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
<td>3.30</td>
<td></td>
<td>+4.56 -&gt; 0.00</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>3.30</td>
<td></td>
<td>+2.42 -&gt; 0.00</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>3.85</td>
<td></td>
<td>-1.71</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>3.85</td>
<td></td>
<td>-2.42</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>3.85</td>
<td></td>
<td>+3.30 -&gt; 0.00</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>3.85</td>
<td></td>
<td>+7.58 -&gt; 0.00</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>3.85</td>
<td></td>
<td>+3.30 -&gt; 0.00</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
<td>3.30</td>
<td></td>
<td>-4.01</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>3.30</td>
<td></td>
<td>+1.70 -&gt; 0.00</td>
</tr>
<tr>
<td>13</td>
<td>65</td>
<td>3.30</td>
<td></td>
<td>+4.56 -&gt; 0.00</td>
</tr>
<tr>
<td>14</td>
<td>75</td>
<td>3.30</td>
<td></td>
<td>+5.99 -&gt; 0.00</td>
</tr>
<tr>
<td>15</td>
<td>80</td>
<td>3.30</td>
<td></td>
<td>+6.70 -&gt; 0.00</td>
</tr>
<tr>
<td>16</td>
<td>90</td>
<td>3.30</td>
<td></td>
<td>+8.13 -&gt; 0.00</td>
</tr>
<tr>
<td>17</td>
<td>55</td>
<td>3.30</td>
<td></td>
<td>+3.13 -&gt; 0.00</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>3.85</td>
<td></td>
<td>+3.30 -&gt; 0.00</td>
</tr>
<tr>
<td>19</td>
<td>80</td>
<td>3.85</td>
<td></td>
<td>+6.15 -&gt; 0.00</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>3.85</td>
<td></td>
<td>+8.30 -&gt; 0.00</td>
</tr>
<tr>
<td>21</td>
<td>65</td>
<td>3.85</td>
<td></td>
<td>+4.01 -&gt; 0.00</td>
</tr>
<tr>
<td>22</td>
<td>20</td>
<td>3.30</td>
<td></td>
<td>1.87</td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>3.30</td>
<td></td>
<td>+2.42 -&gt; 0.00</td>
</tr>
<tr>
<td>24</td>
<td>70</td>
<td>3.30</td>
<td></td>
<td>+5.27 -&gt; 0.00</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>3.30</td>
<td></td>
<td>+5.99 -&gt; 0.00</td>
</tr>
<tr>
<td>26</td>
<td>95</td>
<td>3.30</td>
<td></td>
<td>+8.85 -&gt; 0.00</td>
</tr>
<tr>
<td>27</td>
<td>110</td>
<td>3.30</td>
<td></td>
<td>+10.99 -&gt; 0.00</td>
</tr>
<tr>
<td>28</td>
<td>90</td>
<td>3.30</td>
<td></td>
<td>+8.13 -&gt; 0.00</td>
</tr>
<tr>
<td>29</td>
<td>75</td>
<td>3.30</td>
<td></td>
<td>+5.99 -&gt; 0.00</td>
</tr>
<tr>
<td>30</td>
<td>125</td>
<td>3.85</td>
<td></td>
<td>+12.58 -&gt; 0.00</td>
</tr>
<tr>
<td>31</td>
<td>105</td>
<td>3.85</td>
<td></td>
<td>+9.73 -&gt; 0.00</td>
</tr>
<tr>
<td>32</td>
<td>80</td>
<td>3.85</td>
<td></td>
<td>+6.87 -&gt; 0.00</td>
</tr>
<tr>
<td>33</td>
<td>40</td>
<td>3.30</td>
<td></td>
<td>+0.99 -&gt; 0.00</td>
</tr>
<tr>
<td>34</td>
<td>65</td>
<td>3.30</td>
<td></td>
<td>+4.56 -&gt; 0.00</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>3.30</td>
<td></td>
<td>+5.27 -&gt; 0.00</td>
</tr>
<tr>
<td>36</td>
<td>85</td>
<td>3.30</td>
<td></td>
<td>+7.42 -&gt; 0.00</td>
</tr>
<tr>
<td>37</td>
<td>90</td>
<td>3.30</td>
<td></td>
<td>+8.13 -&gt; 0.00</td>
</tr>
<tr>
<td>38</td>
<td>75</td>
<td>3.30</td>
<td></td>
<td>+5.99 -&gt; 0.00</td>
</tr>
<tr>
<td>39</td>
<td>95</td>
<td>3.30</td>
<td></td>
<td>+12.15 -&gt; 0.00</td>
</tr>
<tr>
<td>40</td>
<td>135</td>
<td>3.85</td>
<td></td>
<td>+14.01 -&gt; 0.00</td>
</tr>
</tbody>
</table>
BASAL TEMPERATURE DATA

MODEL NUMBER III

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>100</td>
<td>3.85</td>
<td>0.1429</td>
<td>+9.01-&gt;0.00</td>
</tr>
<tr>
<td>42</td>
<td>20</td>
<td>3.85</td>
<td></td>
<td>-2.42</td>
</tr>
<tr>
<td>43</td>
<td>30</td>
<td>3.30</td>
<td></td>
<td>-0.44</td>
</tr>
<tr>
<td>44</td>
<td>50</td>
<td>3.30</td>
<td></td>
<td>+2.42-&gt;0.00</td>
</tr>
<tr>
<td>45</td>
<td>65</td>
<td>3.30</td>
<td></td>
<td>+4.56-&gt;0.00</td>
</tr>
<tr>
<td>46</td>
<td>75</td>
<td>3.30</td>
<td></td>
<td>+5.99-&gt;0.00</td>
</tr>
<tr>
<td>47</td>
<td>70</td>
<td>3.30</td>
<td></td>
<td>+5.27-&gt;0.00</td>
</tr>
<tr>
<td>48</td>
<td>90</td>
<td>3.30</td>
<td></td>
<td>+8.13-&gt;0.00</td>
</tr>
<tr>
<td>49</td>
<td>95</td>
<td>3.30</td>
<td></td>
<td>+8.85-&gt;0.00</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>3.85</td>
<td></td>
<td>-2.42</td>
</tr>
<tr>
<td>51</td>
<td>30</td>
<td>7.00</td>
<td></td>
<td>-4.14</td>
</tr>
<tr>
<td>52</td>
<td>65</td>
<td>7.00</td>
<td></td>
<td>+0.86-&gt;0.00</td>
</tr>
<tr>
<td>53</td>
<td>70</td>
<td>7.00</td>
<td></td>
<td>+1.57-&gt;0.00</td>
</tr>
<tr>
<td>54</td>
<td>70</td>
<td>3.85</td>
<td></td>
<td>+4.72-&gt;0.00</td>
</tr>
<tr>
<td>55</td>
<td>90</td>
<td>3.85</td>
<td></td>
<td>+5.78-&gt;0.00</td>
</tr>
<tr>
<td>56</td>
<td>35</td>
<td>3.85</td>
<td></td>
<td>-0.28</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>7.00</td>
<td></td>
<td>-8.43</td>
</tr>
<tr>
<td>58</td>
<td>80</td>
<td>7.00</td>
<td></td>
<td>+3.00-&gt;0.00</td>
</tr>
<tr>
<td>59</td>
<td>110</td>
<td>7.00</td>
<td></td>
<td>+7.29-&gt;0.00</td>
</tr>
<tr>
<td>60</td>
<td>105</td>
<td>3.85</td>
<td></td>
<td>+9.73-&gt;0.00</td>
</tr>
<tr>
<td>61</td>
<td>80</td>
<td>3.85</td>
<td></td>
<td>+6.15-&gt;0.00</td>
</tr>
<tr>
<td>62</td>
<td>55</td>
<td>3.85</td>
<td></td>
<td>+2.58-&gt;0.00</td>
</tr>
<tr>
<td>63</td>
<td>0</td>
<td>7.00</td>
<td></td>
<td>-8.43</td>
</tr>
<tr>
<td>64</td>
<td>80</td>
<td>7.00</td>
<td></td>
<td>+3.00-&gt;0.00</td>
</tr>
<tr>
<td>65</td>
<td>90</td>
<td>7.00</td>
<td></td>
<td>+4.43-&gt;0.00</td>
</tr>
<tr>
<td>66</td>
<td>80</td>
<td>6.60</td>
<td></td>
<td>+3.40-&gt;0.00</td>
</tr>
<tr>
<td>67</td>
<td>50</td>
<td>6.60</td>
<td></td>
<td>-0.88</td>
</tr>
<tr>
<td>68</td>
<td>35</td>
<td>6.60</td>
<td></td>
<td>-3.03</td>
</tr>
<tr>
<td>69</td>
<td>65</td>
<td>6.60</td>
<td></td>
<td>+1.26-&gt;0.00</td>
</tr>
<tr>
<td>70</td>
<td>75</td>
<td>6.60</td>
<td></td>
<td>+2.69-&gt;0.00</td>
</tr>
<tr>
<td>71</td>
<td>65</td>
<td>6.60</td>
<td></td>
<td>+1.26-&gt;0.00</td>
</tr>
<tr>
<td>72</td>
<td>20</td>
<td>6.60</td>
<td></td>
<td>-5.17</td>
</tr>
<tr>
<td>73</td>
<td>15</td>
<td>6.60</td>
<td></td>
<td>-5.89</td>
</tr>
<tr>
<td>74</td>
<td>35</td>
<td>6.60</td>
<td></td>
<td>-3.03</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>6.60</td>
<td></td>
<td>-1.60</td>
</tr>
<tr>
<td>76</td>
<td>30</td>
<td>6.60</td>
<td></td>
<td>-3.74</td>
</tr>
<tr>
<td>77</td>
<td>20</td>
<td>6.60</td>
<td></td>
<td>-5.17</td>
</tr>
<tr>
<td>78</td>
<td>5</td>
<td>4.00</td>
<td></td>
<td>-4.71</td>
</tr>
<tr>
<td>79</td>
<td>0</td>
<td>4.00</td>
<td></td>
<td>-5.43</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>4.00</td>
<td></td>
<td>-2.57</td>
</tr>
</tbody>
</table>
### BASAL TEMPERATURE DATA

##### MODEL NUMBER III

<table>
<thead>
<tr>
<th>GRID PT.</th>
<th>DEPTH (M)</th>
<th>10-M TEMP. (DEG C)</th>
<th>TEMP. GRADIENT (DEG C/M)</th>
<th>BASAL TEMP. (DEG C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>10</td>
<td>4.00</td>
<td>0.1429</td>
<td>-4.00</td>
</tr>
<tr>
<td>82</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>83</td>
<td>5</td>
<td>4.00</td>
<td></td>
<td>-4.71</td>
</tr>
<tr>
<td>84</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>85</td>
<td>5</td>
<td>4.00</td>
<td></td>
<td>-4.71</td>
</tr>
<tr>
<td>86</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>87</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>88</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>89</td>
<td>15</td>
<td>4.00</td>
<td></td>
<td>-3.29</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>91</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>92</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>93</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>94</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>95</td>
<td>15</td>
<td>4.00</td>
<td></td>
<td>-3.29</td>
</tr>
<tr>
<td>96</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>97</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>98</td>
<td>15</td>
<td>4.00</td>
<td></td>
<td>-3.29</td>
</tr>
<tr>
<td>99</td>
<td>0</td>
<td>4.00</td>
<td></td>
<td>-5.43</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>4.00</td>
<td></td>
<td>-4.00</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
<td>4.00</td>
<td></td>
<td>-4.71</td>
</tr>
</tbody>
</table>
A thermal instability mechanism for glacier surging can operate only in cold glacier ice (Robin, 1955, 1969; Hoffmann and Clarke, 1972). The glacier base may attain the pressure melting point during the active phase of the surge cycle, but a finite layer of basal temperate ice would rule out thermal regulation of glacier flow. Robin and Weertman (1973) have argued that large surging glaciers are probably too deep to be cold at the bed and hence cannot be thermally regulated. It is therefore of prime concern to establish ice depths for which a thermal instability mechanism is applicable.

A simple numerical method for evaluating the steady-state temperature profile of cold ice overlying temperate ice is outlined in Appendix III. The surface temperature is climatically controlled. Ice temperatures increase with depth due to internal viscous heating until the pressure melting point is attained. This occurs at a depth denoted as the critical depth $H$. Below $H$ temperate ice exists through which no geothermal heat can be propagated (Paterson, 1969; Lliboutry, 1966, 1968).

The viscous heating depends primarily on the flow law constants $B(T_0)$ and $n$ (refer to Appendix III) and the shear stress $\tau$ given by

$$\tau(y) = (\rho g \cdot \sin \alpha) (H - y)$$  \hspace{1cm} (1)

where $\rho$ is ice density, $g$ acceleration due to gravity, $\alpha$ the slope of the glacier surface, $H$ the critical depth, $y$ the height above the critical depth and $f$ a "form factor" which
accounts for some of the glacier's weight being supported by the valley walls (see Appendix III). Following the procedure outlined in Appendix III, for given values of \( H, \alpha, f, B(T_0), n, \rho \) and \( g \), a complete temperature profile can be evaluated from the critical depth to the ice surface. (As \( \rho \) and \( g \) can reasonably be considered constants, five variables remain.)

The accuracy of the numerical technique was tested by varying the spatial increment of the finite-difference method over the range 10 m to 0.1 m. A comparison of values of \( T_s \), the surface temperature, as computed for a critical depth of 500 m and various grid sizes is shown in Table I. An increment of 2 m was chosen for the calculations in this report; Table I indicates that this corresponds to an accuracy of \( \pm0.01^\circ\text{C} \).

The dependence of the steady-state profile on each of the parameters \( H, \alpha, f, B(T_0) \) and \( n \) is illustrated in Figures 1 through 5 wherein each parameter is varied in turn, the others being held constant. The correct interpretation of each of these temperature profiles is that in order for a steady-state temperature regime to exist with the prescribed parameter values the mean annual surface temperature must be equal to \( T_s \), that computed for a depth of 0 m. Hence for a glacier whose geometric terms \( f \) and \( \alpha \) are known and for a given flow law, the appropriate critical depth is that for which the numerical solution predicts a surface temperature \( T_s \) equal to the observed mean annual surface temperature.

Figures 1, 2 and 3 indicate a high sensitivity of \( T_s \) to the glacier geometry thus emphasizing the importance of accurate field measurements. Figures 4 and 5 show a strong dependence of \( T_s \) on the flow law constants so that even for a glacier whose values of \( f \) and \( \alpha \) are accurately known \( T_s \) will be a multi-valued function of \( H \). Conversely if the surface temperature is known, the appropriate steady-state value of \( H \) will have a large uncertainty due to the range of possible values of \( B(T_0) \) and \( n \).
TABLE I. CONVERGENCE OF NUMERICAL SOLUTION

Parameter Values

\[ H = 500 \text{ m} \]
\[ \alpha = 2^\circ \]
\[ f = 0.67 \]
\[ B(T_0) = 0.173 \text{ bars}^{-\text{n}_a^{-1}} \]
\[ n = 3.07 \]

<table>
<thead>
<tr>
<th>Spatial Increment:</th>
<th>Computed Surface Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta y )</td>
<td>( T_s )</td>
</tr>
<tr>
<td>10.00 m</td>
<td>-10.67°C</td>
</tr>
<tr>
<td>5.00 m</td>
<td>-10.71°C</td>
</tr>
<tr>
<td>2.00 m</td>
<td>-10.73°C</td>
</tr>
<tr>
<td>1.00 m</td>
<td>-10.74°C</td>
</tr>
<tr>
<td>0.50 m</td>
<td>-10.74°C</td>
</tr>
<tr>
<td>0.25 m</td>
<td>-10.74°C</td>
</tr>
<tr>
<td>0.10 m</td>
<td>-10.74°C</td>
</tr>
</tbody>
</table>
Fig. 1. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various critical depths $H$ (see text).

Fig. 2. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various glacier slopes $\alpha$. 
Fig. 3. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various form factors $f$ (see text).
Fig. 4. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various flow law coefficients $B(T_0)$ (see text).

Fig. 5. Steady-state temperature profiles in a cold ice layer overlying temperate ice for various flow law indices $n$ (see text).
To facilitate the presentation of numerical results it is convenient to combine the geometric variables $f$ and $\alpha$ with the constants $p$ and $g$ in the term $A = fpg \cdot \sin \alpha$. Figure 7 of Appendix III shows contours of critical depth $H$ in a two-dimensional space with Cartesian coordinates $T_s$ and $A$. With the aid of this diagram the critical depth of a particular glacier can be read directly if the relevant coordinates $T_s$ and $A$ are known. However this value of $H$ is only correct if the flow law of ice has values of $B(T_0)$ and $n$ as given by Nye (1953). Hodge (unpublished) has cited 16 additional sets of values for $B(T_0)$ and $n$. The analogous contour plots of $H$ in $T_s - A$ space for the least viscous and most viscous flow laws quoted by Hodge are presented here in Figures 6 and 7. (The activation energy $Q$ was taken as 58,520 J mole$^{-1}$; see Appendix III.) These graphs indicate that for large glaciers such as Steele Glacier, Yukon Territory and Finsterwalder Glacier, Spitsbergen, the numerical uncertainty in the values of the flow law constants induces a corresponding uncertainty in the computed critical depths of approximately 200 m.

Although this is a substantial depth range, it is encouraging (from the thermal instability point of view) that the shallowest values of critical depth computed for Finsterwalder and Steele Glaciers are 350 m and 400 m respectively. The published longitudinal depth profile of Finsterwalder Glacier nowhere exceeds 350 m (Robin and Weertman, 1973) so that zones of basal temperate ice of finite thickness should not occur, and hence thermal instability may regulate the surge behavior of this glacier. No depth measurements have been made on Steele Glacier but, should it exceed 400 m, temperate basal ice may occur. However Figure 7 shows that warm basal ice need not occur even in areas of ice depth as great as 600 m. Hence thermal control of sliding likely operates in all areas of Steele Glacier where ice thickness is less than 400 m - believed to comprise a major portion of the gla-
Fig. 6. Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are: $B(T_o) = 0.550$; $n = 3.3$ [soft ice].)
Fig. 7. Contours of critical depth $H$ (see text) in a Cartesian space with coordinates $T_s$, the glacier's mean surface temperature, and $A$, a geometric term as defined in text. (Flow law constants are: $B(T_0) = 0.040; \ n = 5.2$ [hard ice].)
cier (Appendix III).

Depth estimates of Muldrow and Walsh Glaciers (290 m and 220 m respectively (Meier and Post, 1969)), two large surge-type glaciers in the Yukon-Alaska region (Post, 1960, 1966), also lie within the depth range at which thermal regulation of sliding can occur. Therefore, provided the surface temperature is sufficiently low, there is no apparent justification for the rejection of thermal instability as a control mechanism for large surging glaciers.
THERMAL EFFECTS OF CREVASSING ON STEELE GLACIER

Gary T. Jarvis
and
Garry K. C. Clarke

Department of Geophysics and Astronomy
University of British Columbia
Vancouver 8, Canada

ABSTRACT

Ice-temperature measurements have been made in Steele Glacier to a depth of 114 m. All measured temperatures were below 0°C, the coldest being -6.5°C at a depth of 114 m. The temperature profile indicates an anomalously warm layer of ice between 30 m and 50 m, which is probably due to the freezing of water in crevasses opened during the 1965-66 surge. A two-dimensional model of a cold glacier with partially water-filled crevasses predicts temperature profiles very similar to that observed.

INTRODUCTION

The Steele Glacier is a large valley glacier in the St. Elias Mountains, Yukon Territory, Canada. Explorations by Wood (1936) and Sharp (1951) indicate that for at least thirty years prior to 1965, the 10 - 15 km lower zone was inactive and provided a safe, relatively uncrevassed route into the Icefield Ranges. Austin Post finds photographic evidence for "an extensive surge which severely fractured the surface of the upper glacier" around 1940 and "must have faded out near the 'big bend' of the Steele", some 12 km from the present terminus (M. Meier, personal communication). By summer 1966 Steele Glacier was in the midst of a spectacular surge which displaced surface features 8 km within one year. Premonitory signs, apparent on aerial photographs, led Post in 1960 to predict the Steele's surge, but unfortunately none witnessed the onset of the active phase. Stanley (1969) and Meier (personal communication) refer to aerial photographs, taken by Post in the summer of 1965, which show extensive crevassing of the glacier surface, and indicate the advance probably began in 1965. From August 1966 the surge is well documented (Bayrock, 1967; Stanley, 1969; Wood, 1967[a], 1967[b]; Thomson, 1972) and Wood (1972) has published an historical review containing striking pre-surge and post-surge photographs.

The cause of the Steele surge is unknown, but as the nearby Rusty and Trapridge Glaciers appear to surge by a thermal instability mechanism, temperature measurements in Steele Glacier could prove diagnostic. Consequently in July 1972 a reconnaissance program of ice-temperature measurement was begun and a single hole was thermally drilled to a depth of 114 m in the central region of the glacier (Figure 1). Two 8-conductor cables attached to the thermal probe's power cable carried thirteen calibrated thermistors to depths ranging from 25 m to 114 m.
The drilling and temperature measurement procedures were essentially the same as those described by Classen and Clarke (1972). Thermistor resistances were measured ten days after the termination of drilling and converted to ice temperatures.

Cooling curves obtained from holes drilled with thermal probes of various diameters on the nearby Trapridge Glacier show that thermal equilibrium is not reached in ten days. To correct the measured temperatures, theoretical cooling curves were computed. The diffusion equation was solved in cylindrical polar coordinates, by finite-difference methods, for a water-filled cylindrical hole in cold ice (Appendix A). The solution yields both hole closure and ice temperature as a function of time, and the resulting cooling curves can be compared to observational data if the initial hole radius is known. The thermal probe radius is not a good estimate of the initial hole radius because the probe efficiency is not 100%. A better estimate of this radius is obtained by assuming that all the thermal energy from the probe is used to melt ice. For drilling speed $v_p$ the radius of the hole $r_c$ can be calculated as

$$r_c = \left(\frac{P}{L \rho \pi v_p}\right)^{1/2}$$

where $P$ is the input power to the probe, $L$ the latent heat of fusion ($3.337 \times 10^5$ J/kg), and $\rho$ the ice density. As both $P$ and $v_p$ were monitored continuously during field operations, the appropriate values of $r_c$ can be computed at each thermistor depth. $P$ and $v_p$ did not change rapidly with probe depth so that in the neighbourhood of each thermistor the hole was nearly cylindrical with $r_c$ given by (1). Comparisons of theoretical cooling curves and data recorded at three sites on Trapridge Glacier (Jarvis, unpublished) show good agreement, and the corrected Steele Glacier temperatures are expected to be within ± 0.2°C of the true equilibrium values.
The observed ten-day temperatures and the values corrected to equilibrium are given in Table I.

In the region of the drill site, the upper 114 m of the glacier is cold but the temperature profile is unusual and unexpected. Below 50 m the ice cools with depth suggesting the presence of a heat source near 40 m. No similar anomaly has been observed on the nearby Rusty and Trapridge Glaciers, two surge-type glaciers in the quiescent phase (Classen and Clarke, 1971; Clarke and Goodman, unpublished; Jarvis and Clarke, unpublished). Geothermal heat causes the temperature in these cold glaciers to increase with depth. Thus the anomaly does not appear to reflect a regional climatic amelioration but is probably a consequence of the Steele Glacier's most recent surge. The ice thickness is thought to be considerably greater than 114 m, so a continued temperature decrease to the glacier bed seems unlikely. If one makes the reasonable assumption that prior to the surge the temperature increased monotonically with depth, the upper 114 m must have been colder than -6.5°C before the advance began. Measurements on the Rusty and Trapridge Glaciers suggest that -8.0°C is a good estimate of the mean annual surface temperature.

The apparent heat source near 40 m must be localized in the vertical sense and be of sufficient strength to have maintained the observed anomaly for the six or seven years since the surge onset. Available energy sources are internal viscous heating, friction from sliding along shear planes, and internal water cavities. Thermal anomalies might also be generated by advective heat transfer or large displacements along shear planes. Viscous heating and sliding friction are insufficient to produce the observed effect. Aerial photographs analyzed by Stanley (1969) show that the drill site was in a zone of surface lowering and active extensional
flow throughout the surge so that neither advection nor ice displacement along shear planes could account for the anomalously warm temperatures near 40 m. (Even in a region of passive compressive flow a temperature anomaly of 6.0°C would require an unreasonably large upward mass transport.) We therefore conclude that englacial water cavities are the most probable energy source.

During the Steele Glacier surge, crevasses as wide as 20 m and as deep as 100 m were not uncommon. Since extensive crevassing reduces albedo and inhibits surface runoff, large quantities of meltwater can enter newly-formed crevasses and gain access to considerable depths within the glacier. Collins (Neilsen, 1969) remarked that this should have a noticeable effect on the temperature of a cold surge-type glacier and speculated that on some surging glaciers water might even be admitted to the glacier bed. Our observations support the first suggestion but not the latter.
CREVASSE MODEL

To evaluate the thermal effects of trapped water in a cold crevassed glacier, a two-dimensional, time-dependent numerical model was developed. The ice temperature $T$ was assumed to be a function of the space variables $x$, measured in the direction of flow, and $y$, the depth measured perpendicular to the glacier surface. Prior to the surge onset at $t = 0$ the glacier surface was assumed to be a plane maintained at a temperature which varied sinusoidally with time. (As might be expected the time-dependence of the surface boundary condition played a negligible role in the final results except near the surface-air boundaries.) The temperature at a depth $d^*$ far below the glacier surface was held constant at $T_d$. Therefore the pre-surge temperature profile is linear with depth except near the glacier surface, and the temperature gradient is simply the apparent geothermal gradient.

At the surge onset severe crevassing of the upper surface occurs allowing meltwater to partially fill the crevasses. Both the crevasse-formation and water-filling were assumed to occur instantaneously at $t = 0$. This assumption is justified if one is interested in ice temperatures several years after the surge has terminated. By that time the exact details of crevasse-formation and water-filling have an insignificant effect on the observed temperatures. For simplicity the crevasse field was assumed to be spatially periodic with infinitely-long, symmetric crevasses at constant separation (Figure 2). The initial shape of each crevasse was taken as a triangular wedge, although freezing of the trapped water modified the cross section with time. These assumptions yield a high degree of symmetry and it is only necessary to calculate the ice temperatures within the shaded region of Figure 2 to obtain the complete temperature solution.
Because the crevasses are assumed to contain water, the usual arguments predicting maximum crevasse depths based on creep rates do not apply (Weertman, 1971). When the crevasse is open at the surface, hydrostatic pressure of the trapped water resists creep closure; when it is sealed by surface freezing, incompressibility of the water cavity prevents creep closure entirely so that freezing is the dominant mechanism of crevasse closure.

The model parameters are defined as illustrated in Figure 3. The crevasse separation S was estimated from an aerial photograph of the drilling site taken in 1970 after termination of the surge (Figure 1, inset). The crevasse width W could only be crudely estimated from the same photograph, but this parameter proved to have a minor influence on the temperature distributions calculated. The crevasse depth \( d_c \) could not be estimated and was adjusted to give the best fit to the data. Finally the depth to the initial water surface \( d_w \) was taken to be 15 m, the approximate depth to the present crevasse bottoms which are interpreted as ice bridges.

The thermal effects of the surge are complex and unknown. Hence, to isolate the effects of crevassing we shall omit the advection and heat generation terms from the diffusion equation and solve

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\kappa} \frac{\partial T}{\partial t}
\]

(2)

(where \( \kappa \) is the thermal diffusivity of ice) subject to the appropriate boundary conditions. At the moving ice-water interface the boundary condition is somewhat complicated and makes the crevasse closure problem a close relative of the classical Stefan problem (Carslaw and Jaeger, 1959). Conservation of thermal energy at the phase boundary gives

\[
K \vec{V} \nabla T - K_w \vec{V} \nabla T_w = \rho_w L \vec{V}
\]

(3)

where \( K \) is the thermal conductivity of ice, \( K_w \) the thermal...
conductivity of water, $T_w$ the water temperature, $\rho_w$ the density of water, $L$ the latent heat of fusion and $v$ the velocity of the interface. The water can be assumed isothermal at $T_m = 0°C$ so that $K_w \vec{v}_T w$ vanishes. The time-dependent crevasse half-profile $X(y,t)$ as obtained from equation (3) is

$$X(y,t) = X(y,0) - \frac{K}{\rho_w L} \int_0^t \left\{ \frac{\vec{v}_T(x,y,t)}{\cos \alpha(x,y,t)} \right\} dt$$

where $\alpha$ is the angle between the vector $\vec{v}_T$ and the x-axis, and the subscript $i$ refers to points along the interface.

The remaining boundary conditions are straightforward. At all ice-air interfaces the temperature is $T_s + A \sin 2\pi f_0 t$ where $T_s$ is the mean annual temperature, $A$ is the amplitude of annual temperature variation and $f_0 = 1 \text{ cycle-a}^{-1}$. At depth $d^*$ well below the region influenced by the crevasses the temperature is $T_d$. The air-water interface is assumed to vanish almost instantly and is replaced by an ice-air interface. At the vertical boundaries of the grid the horizontal heat flux vanishes by virtue of the spatial periodicity of crevassing; thus $\partial T/\partial x$ vanishes at these boundaries.

Equation (2) was written as a finite-difference equation and solved by the Peaceman-Rachford implicit alternating-direction technique (Peaceman and Rachford, 1955; Forsythe and Wasow, 1960; Carnahan, and others, 1969). Details of this numerical method are given in

* The traditional Stefan problem deals with two-phase boundaries and constant density $\rho$ across the interface. In the crevasse closure problem the two phases have different densities and the question arises as to which value of $\rho$ should be used. All the latent energy of the water must go into the glacier ice. Some of this energy will initially be stored as elastic strain, but eventually is converted to thermal energy as the strained ice relaxes. Thus to ensure conservation of energy we take the density in (3) to be that of water $\rho_w$, although we ignore the details of elastic strain in our calculations.
Appendix B. The time evolution of the crevasse cross section was computed by finite-difference evaluation of (4) at each time step.

RESULTS

For reasonable parameter values the model predicts ice temperatures which agree well with those measured in Steele Glacier. Theoretical temperature profiles from the model, with parameters as listed in Table II, are displayed in Figures 4 and 5, along with the observed temperature profile. In these calculations the crevasse spacing was taken as 30 m so that 15 m is the maximum possible distance between a drilling site and the central plane of the nearest crevasse. Figure 4 is a sequence of profiles, midway between crevasses, at successive times ranging from 1 - 10 years after crevasse formation. The 6.5-year profile corresponds to the time of thermal drilling on Steele Glacier. Temperatures predicted at various distances from the crevasse at $t = 6.5$ years are shown in Figure 5. The curves are closely similar for distances 9 - 15 m from the crevasse. The model, then, seems capable of explaining the gross features of the observed anomaly provided the drilling site was located 15 ± 6 m from the nearest crevasse at a time 7 ± 3 years after the surge onset. Neither of these conditions is very stringent and both are satisfied by the drill site.

The model also presents an interesting study of crevasse closure in cold ice. Since equation (4) was solved at each time step, a plot of $X(y,t)$ gives a graphic illustration of crevasse closure (Figure 6). Surprisingly slow closure takes place after the first four years. However, Figure 4 shows that after four years the ice between the water-filled portions of the crevasses, even at the furthest points from them, has warmed to within two
degrees of the water temperature. Consequently horizontal temperature gradients are very small and heat flux from the crevasse is minimal, except at the top and bottom of each water cavity where vertical heat flux can carry energy away from the crevasse. This slow closure is due to the close spacing of the large crevasses, which concentrates the thermal energy into a small volume. Increasing the crevasse separation was found to greatly increase the rate of closure; an isolated crevasse could be studied by choosing a very large crevasse spacing.

CONCLUDING REMARKS

Our modelling study indicates that partially water-filled crevasses can have a significant effect on the temperature distribution within a cold glacier and that the observed temperature anomaly in Steele Glacier is probably due to this energy source. Similar anomalies are likely to occur in other cold surge-type glaciers and remain for many years after the active phase terminates. If the Steele Glacier's surges are thermally regulated, as seems reasonable in view of the very cold ice below 100 m, the thermal effects of water in crevasses may influence the surge cycle. Thin surging glaciers would be particularly sensitive to such a major disturbance of their temperature regime.
ACKNOWLEDGEMENTS

We thank B. Chandra, B. B. Narod and K. D. Schreiber for assistance in field preparations, S. G. Collins, R. H. Ragle, P. Upton and W. A. Wood of the Arctic Institute of North America for encouragement and logistic support, and M. F. Meier, A. S. Post and A. D. Stanley for providing photographs and important unpublished information about the Steele Glacier surge. We are especially grateful to R. Metcalfe who proved to be an invaluable assistant in the field. Financial support was provided by the University of British Columbia, Environment Canada and the National Research Council (Canada).
REFERENCES


APPENDIX A

FREEZING OF A CYLINDRICAL WATER-FILLED HOLE IN COLD ICE

To compute hole closure rates and cooling curves for a water-filled cylindrical hole in cold ice, diffusion equations of the form

\[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{1}{\kappa} \frac{\partial T}{\partial t} \]  

(A1)

must be solved in ice and water. At the ice-water interface the boundary conditions are

\[ K \frac{\partial T}{\partial r} - K_w \frac{\partial T_w}{\partial r} = \rho_w L \frac{dr_c}{dt} \]  

(A2)

and

\[ T(r_c, t) = T_w(r_c, t) = T_m \]  

(A3)

where \( r_c \) is the radius of the water-filled cylinder and \( T_m \) the melting temperature of ice. The remaining boundary conditions are

\[ \lim_{r \to \infty} T(r, t) = T_0 \]  

(A4)

and

\[ 2\pi r_0 K_w \frac{\partial T_w(r_0, t)}{\partial r} = -q_L(t) \]  

(A5)

where \( T_0 \) is the ambient ice temperature, \( q_L(t) \) the strength of a line heating source, and \( r_0 \) its radius. Boundary condition (A5) allows the possibility of evaluating the effect of ohmic dissipation in the power cable leading
to the thermal probe. In the calculations discussed above
$q_L$ was negligible and the water phase was essentially iso-
thermal at temperature $T_m$. Solutions for large values of
$q_L$ have also been computed to determine whether line heating
can be used to inhibit hole closure during thermal drilling.

In passing to a finite-difference approximation
of (A1) it is convenient to introduce a logarithmic grid
by the transformation $R = \ln r$; thus (A1) becomes

$$e^{-2R} \frac{\partial^2 T}{\partial R^2} = \frac{1}{\kappa} \frac{\partial T}{\partial t}$$

(A6)

with $T = T(R,t)$, and (A2) gives

$$\frac{dR_c}{dt} = \frac{e^{-2R_c}}{\rho_w L} \left\{ \frac{K}{\partial R} \frac{\partial T}{\partial R} - \frac{K_w}{\partial R} \frac{\partial T_w}{\partial R} \right\}$$

(A7)

where $R_c = \ln r_c$.

Following the Crank-Nicolson approach, the
solutions of (A6) for times $t$ and $t+\tau$ are averaged to
reduce the discretization error giving as the finite-
difference equation in the $i$th medium

$$-\lambda_i \theta e^{-2R} T_i(R-h,t+\tau) + [1+2\lambda_i \theta e^{-2R}] T_i(R,t+\tau) +$$

$$-\lambda_i \theta e^{-2R} T_i(R+h,t+\tau) = \lambda_i (1-\theta)e^{-2R} T_i(R-h,t) +$$

$$[1-2\lambda_i (1-\theta)e^{-2R}] T_i(R,t) + \lambda_i (1-\theta)e^{-2R} T_i(R+h,t)$$

(A8)

where $h$ is the space increment of the logarithmic grid,
$\tau$ the time increment, $\lambda_i = \kappa_i \tau/h^2$, and $\theta$ is an averaging
parameter which is usually set to the value $\theta = 0.5$.
The variables $R$ and $t$ take discrete values $mh$ and $nt$
respectively, where $m$ and $n$ are integers.
In Equation (A8) the right-hand-side terms are known and the left-hand-side terms are unknown. If similar equations are written at each grid point one obtains a tridiagonal set of linear equations which can be solved for the unknown temperatures $T(R,t+\tau)$.

Infinitely large grids are not feasible so that the boundary condition (A4) is replaced by $T(R_{\text{max}},t) = T_0$ where $R_{\text{max}}$ is some suitably large value of $R = \ln r$. At $R_0 = \ln r_0$ we have the condition

$$2\pi K_w \frac{\partial T(R_0,t)}{\partial R} = -q_L(t) \quad (A9)$$

and at $R_c = \ln r_c$, the ice-water interface, $T(R_c,t) = T_m$. The finite-difference equations (A8) are solved subject to the above boundary conditions and the migration of the ice-water interface is evaluated at each time step by substituting finite-difference approximations of $\partial T(R_c,t)/\partial t$ and $\partial T_w(R_c,t)/\partial t$ into (A2). When the condition $R_c < R_0$ is satisfied, the water phase is considered to vanish and a simple one-phase problem results.
PEACEMAN-RACHFORD NUMERICAL METHOD

For a finite-difference grid with space intervals $\Delta x$, $\Delta y$ and time step $\tau$, the standard implicit finite-difference approximation to Equation (2) yields

\[-\lambda_x T(x-\Delta x,y,t+\tau) - \lambda_y T(x,y-\Delta y,t+\tau) + (1+2\lambda_x+2\lambda_y)T(x,y,t+\tau)\]

\[-\lambda_y T(x,y+\Delta y,t+\tau) - \lambda_x T(x+\Delta x,y,t+\tau) = T(x,y,t) \quad (B1)\]

where $\lambda_x = \kappa \tau / (\Delta x)^2$, $\lambda_y = \kappa \tau / (\Delta y)^2$, and the variables $x, y,$
and $t$ have the discrete values $x = i \Delta x$, $y = j \Delta y$, and $t = n \tau$ for integer values of $i$, $j$, and $n$. Equations (B1) are implicit in both $x$- and $y$-directions and have five unknowns per equation. Direct solution of this system of equations requires the inversion of a large five-band diagonal matrix and is computationally expensive.

In the Peaceman-Rachford implicit-alternating-direction method, two systems of equations are used in turn over successive time steps of duration $\tau/2$. The first equation is implicit in the $x$-direction only, the second in the $y$-direction. Using the notation $T^*(x,y)$ to represent the intermediate values of $T$ half way through the time step $\tau$, for implicit $x$ we have

\[-T^*(x-\Delta x,y) + 2(1/\lambda_x+1)T^*(x,y) - T^*(x+\Delta x,y) =
\]

\[\lambda_y/\lambda_x T(x,y-\Delta y,t) + 2(1/\lambda_x-\lambda_y/\lambda_x)T(x,y,t) + \lambda_y/\lambda_x T(x,y+\Delta y,t) \quad (B2)\]

and for implicit $y$

\[-T(x,y-\Delta y,t+\tau) + 2(1/\lambda_y+1)T(x,y,t+\tau) - T(x,y+\Delta y,t+\tau) =
\]

\[\lambda_x/\lambda_y T^*(x-\Delta x,y) + 2(1/\lambda_y-\lambda_x/\lambda_y)T^*(x,y) + \lambda_x/\lambda_y T^*(x+\Delta x,y) \quad (B3)\]
The system of equations (B2) and (B3) have only three unknowns per equation and the implicit solution of each system merely involves the inversion of tridiagonal matrices for which simple and efficient algorithms are readily available.

Holding y constant, one equation of the form (B2) is written for each value of x and the resultant tridiagonal system of equations is solved simultaneously. Equations (B2) are solved in this manner once for each value of y to generate the complete solution $T^*(x,y)$. Equations (B3) are now solved by substituting the solution $T^*(x,y)$ obtained from (B2) into (B3). Holding x constant, one equation of the form (B3) can be written for each value of y and the new system of equations solved simultaneously. Equations (B3) are solved once for each value of x to generate $T(x,y,t+\tau)$, the temperature distribution advanced one full time step. This procedure is unconditionally stable for any value of $\tau$ and the discretization error is $O[\tau^2 + (\Delta x)^2]$. 
<table>
<thead>
<tr>
<th>Thermistor depth (m)</th>
<th>Measured ice temperature (°C)</th>
<th>Corrected temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>-1.54</td>
<td>-1.85</td>
</tr>
<tr>
<td>33</td>
<td>-0.96</td>
<td>-1.44</td>
</tr>
<tr>
<td>40</td>
<td>-1.14</td>
<td>-1.55</td>
</tr>
<tr>
<td>47</td>
<td>-0.54</td>
<td>-1.36</td>
</tr>
<tr>
<td>54</td>
<td>-1.38</td>
<td>-1.75</td>
</tr>
<tr>
<td>61</td>
<td>-2.14</td>
<td>-2.45</td>
</tr>
<tr>
<td>70</td>
<td>-3.90</td>
<td>-4.11</td>
</tr>
<tr>
<td>82</td>
<td>-4.77</td>
<td>-4.98</td>
</tr>
<tr>
<td>92</td>
<td>-5.43</td>
<td>-5.65</td>
</tr>
<tr>
<td>100</td>
<td>-5.88</td>
<td>-6.10</td>
</tr>
<tr>
<td>106</td>
<td>-6.13</td>
<td>-6.35</td>
</tr>
<tr>
<td>112</td>
<td>-6.41</td>
<td>-6.63</td>
</tr>
<tr>
<td>114</td>
<td>-6.46</td>
<td>-6.68</td>
</tr>
</tbody>
</table>
TABLE II. NUMERICAL INPUTS FOR CREVASSE MODEL

**Model Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crevasse separation</td>
<td>S</td>
<td>30 m</td>
</tr>
<tr>
<td>Crevasse width</td>
<td>W</td>
<td>5 m</td>
</tr>
<tr>
<td>Crevasse depth</td>
<td>d&lt;sub&gt;c&lt;/sub&gt;</td>
<td>80 m</td>
</tr>
<tr>
<td>Depth to water surface</td>
<td>d&lt;sub&gt;w&lt;/sub&gt;</td>
<td>15 m</td>
</tr>
<tr>
<td>Mean surface temperature</td>
<td>T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>-8.0° C</td>
</tr>
<tr>
<td>Amplitude of annual temperature variation</td>
<td>A</td>
<td>8.0° C</td>
</tr>
<tr>
<td>Deep ice boundary condition</td>
<td>T&lt;sub&gt;d&lt;/sub&gt;</td>
<td>-6.25° C</td>
</tr>
</tbody>
</table>

**Physical Constants**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice density</td>
<td>ρ</td>
<td>9.0 x 10&lt;sup&gt;2&lt;/sup&gt; Kg m&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Water density</td>
<td>ρ&lt;sub&gt;w&lt;/sub&gt;</td>
<td>1.0 x 10&lt;sup&gt;3&lt;/sup&gt; Kg m&lt;sup&gt;-3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thermal conductivity of ice</td>
<td>K</td>
<td>2.219 W m&lt;sup&gt;-1&lt;/sup&gt;deg&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Specific heat of ice</td>
<td>C</td>
<td>2.101 x 10&lt;sup&gt;3&lt;/sup&gt; J Kg&lt;sup&gt;-1&lt;/sup&gt;deg&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thermal diffusivity of ice</td>
<td>κ</td>
<td>1.173 x 10&lt;sup&gt;-6&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt;sec&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Latent heat of fusion in ice</td>
<td>L</td>
<td>3.337 x 10&lt;sup&gt;5&lt;/sup&gt; J Kg&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Finite Difference Variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal spatial increment</td>
<td>Δx</td>
<td>0.50 m</td>
</tr>
<tr>
<td>Vertical spatial increment</td>
<td>Δy</td>
<td>5.00 m</td>
</tr>
<tr>
<td>Time increment (t ≤ 1.0 yr)</td>
<td>τ</td>
<td>0.01 yr</td>
</tr>
<tr>
<td>Time increment (t &gt; 1.0 yr)</td>
<td>τ</td>
<td>0.02 yr</td>
</tr>
<tr>
<td>Spatial grid size</td>
<td></td>
<td>31 x 31</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Fig. 1. Portion of Canadian Government air photograph A21523-73 showing confluence region of Steele and Hodgson Glaciers. Inset shows details of crevasses near drilling site.

Fig. 2. Model of crevasse field. Owing to spatial periodicity temperatures need only be evaluated in the shaded region.

Fig. 3. Finite-difference grid illustrating model parameters and boundary conditions.

Fig. 4. Theoretical temperature profiles 15 m from nearest crevasse at various times given in years. Measured Steele Glacier temperatures are indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.

Fig. 5. Theoretical temperature profiles at various distances from the nearest crevasse at $t = 6.5$ years. Measured Steele Glacier temperatures indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.

Fig. 6. Closure by refreezing of a water-filled crevasse in cold ice. Crevasse cross sections are indicated at times given in years.
Fig. 1. Portion of Canadian Government air photograph A21523-73 showing confluence region of Steele and Hodgson Glaciers. Inset shows details of crevasses near drilling site.
Fig. 2. Model of crevasse field. Owing to spatial periodicity temperatures need only be evaluated in the shaded region.
Fig. 3. Finite-difference grid illustrating model parameters and boundary conditions.
Fig. 4. Theoretical temperature profiles 15 m from nearest crevasse at various times given in years. Measured Steele Glacier temperatures are indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.
Fig. 5. Theoretical temperature profiles at various distances from the nearest crevasse at $t = 6.5$ years. Measured Steele Glacier temperatures indicated by open circles; temperatures corrected to equilibrium are indicated by solid circles.
Fig. 6. Closure by refreezing of a water-filled crevasse in cold ice. Crevasse cross sections are indicated at times given in years.
APPENDIX VIII

FURTHER STUDIES OF THE EFFECTS
OF WATER-FILLED Crevasses

The Crevasse Closure Problem

The unusual temperatures measured on Steele Glacier, Yukon Territory (Jarvis and Clarke, unpublished [a]; Appendix VII), have indicated the important influence of crevassing on the thermal regime of sub-polar glaciers. Water within a crevasse freezes along the cold ice walls. Continued growth of an ice film along the crevasse boundaries causes the ice-water interface to migrate inwards toward the central plane of the crevasse. For a symmetric crevasse, the half-width \( X(y,t) \) at a depth \( y \) measured perpendicularly down from the glacier surface, and time \( t \) is given in Appendix VII as

\[
X(y,t) = X(y,0) - \left( \frac{K}{\rho_w L} \right) \int_0^t \left| \nabla T_i(x,y,t) \right| \cos \alpha_i(x,y,t) \, dt
\]

where \( K \) is the thermal conductivity of ice, \( \rho_w \) the density of water, \( L \) the latent heat of fusion and \( \alpha \) the angle between the vector \( \mathbf{v} \) and the \( x \)-axis (Figure 1). The subscript \( i \) refers to points along the interface. This follows from conservation of thermal energy at the phase boundary which requires that

\[
K \mathbf{v} T_i(x,y,t) = \rho_w L \mathbf{v} (y,t)
\]

where \( \mathbf{v} \) is the velocity of the moving interface (see Appendix VII).

The heat flow \( \phi \) across an infinitesimal length \( dl \) of
Fig. 1. Basic geometry at migrating crevasse wall.
the crevasse boundary (of vertical extent dy) in time interval dt is

\[ \phi = -K(\nabla T \cdot \hat{n})dl \cdot dt = -p_w l (\mathbf{v} \cdot \hat{n})dl \cdot dt \]  

(3)

where \( \hat{n} \) is a unit vector normal to the crevasse boundary (Figure 1). Since the submerged crevasse wall is isothermal at 0°C, \( \nabla T \), and hence \( \mathbf{v} \), are normal to the boundary and in the opposite sense of \( \hat{n} \). Equation (3) can therefore be written

\[ \phi = K|\nabla T|dl \cdot dt = p_w l |\mathbf{v}|dl \cdot dt \]  

(4)

With the aid of Figure 1a, \( |\mathbf{v}| \) is seen to be ds/dt where ds is the thickness of ice film formed on the crevasse wall in time dt. Hence

\[ \phi = \rho_w L ds \cdot dl \]  

(5)

From Figure 1a we also see that

\[ ds = dX^* \cos \alpha \]  

(6)

and

\[ dl = dy / \cos \alpha \]  

(7)

where \( \alpha \) is the angle between the crevasse wall and vertical, and \( dX^* \) is the horizontal distance the phase boundary migrates corresponding to ice film thickness ds (Figure 1a). Substituting (6) and (7) into (5) gives

\[ \phi = \rho_w L dX^* dy \]  

(8)
or,
\[ dX^* = \frac{\phi}{dy} \rho_w L \tag{9} \]

With Equation (4), (9) becomes
\[ dX^* = \left( \frac{K}{\rho_w L} \right) \left\{ |V_T| \frac{dl}{dy} \right\} dt \tag{10} \]

and substituting (7) into (10) we have
\[ dX^* = \left( \frac{K}{\rho_w L} \right) \left\{ \frac{|V_T|}{\cos \alpha} \right\} dt \tag{11} \]

Since \( X \) is the half-width of the crevasse, \( dX = -dX^* \)
and hence
\[ dX = -\left( \frac{K}{\rho_w L} \right) \left\{ \frac{|V_T|}{\cos \alpha} \right\} dt \tag{12} \]

Integration of (12) yields Equation (1). The numerical integration of (1) was performed with a finite time interval \( \tau \) and lengths \( \Delta l, \Delta y \) and \( \Delta X \). At the end of each time step, \( X(y, t) \) was obtained from the recursion formula
\[ X(y, t+\tau) = X(y, t) + (\partial X/\partial t) \tau \tag{13} \]

which with the aid of Equation (12) can be written
\[ X(y, t+\tau) = X(y, t) - \left( \frac{K}{\rho_w L} \right) \left\{ \frac{|V_T|}{\cos \alpha} \right\} \tau \tag{14} \]

The problem thus reduces to evaluating, at each time step, the magnitude of \( \Delta X \) where
\[ \Delta X = -\left( \frac{K}{\rho_w L} \right) \left\{ \frac{|V_T|}{\cos \alpha} \right\} \tau \tag{15} \]
Retracing the previous logic for finite space and time steps we have

\[ \Delta X = K(\vec{\nabla} T \cdot \hat{n}) \Delta l \tau / \Delta y \rho_w L \] (16)

and since

\[ \hat{n} = \cos \alpha \hat{x} + \sin \alpha \hat{y} \] (17)

where \( \hat{x} \) and \( \hat{y} \) are unit vectors parallel to the coordinate axes, then

\[ \Delta X = K[(\partial T / \partial x) \cos \alpha + (\partial T / \partial y) \sin \alpha] \Delta l \tau / (\Delta y \rho_w L) \] (18)

Figure 1b shows that

\[ \cos \alpha \Delta l = \Delta y \] (19)

and

\[ \sin \alpha \Delta l = \delta x \] (20)

where \( \delta x \) is the horizontal extent of the section of crevasse wall of length \( \Delta l \). Hence (18) becomes

\[ \Delta X = K[(\partial T / \partial x) + (\partial T / \partial y)(\delta x / \Delta y)] \tau / (\rho_w L) \] (21)

and straightforward calculation of the terms \( \partial T / \partial x, \partial T / \partial y \) and \( \delta x \) at each depth \( y \) and time \( t \), enables evaluation of (14).
Energy Check and Convergence

The Peaceman-Rachford semi-implicit alternating direction technique for generating finite-difference approximations to parabolic partial differential equations, in two space dimensions, is unconditionally stable for any ratio of time and space increments ($\Delta x : \tau$) provided the solution is obtained in a rectangular finite-difference grid (Forsythe and Wasow, 1960). In this problem the crevasse boundary defines a non-rectangular grid. Consequently it was necessary to choose the grid cell size with care in order to avoid numerical instability. The chance of encountering problems of numerical instability was reduced by including the air-filled portion of the crevasse in the grid. Points in this region were held isothermal at the time-dependent surface temperature. However the temperature variations along the exposed crevasse wall constituted an internal boundary condition so that the grid could not be considered rectangular. For values of $\lambda$ less than 1.5 (where $\lambda = \kappa \tau / (\Delta x)^2$ and $\kappa$ is the thermal diffusivity of ice) instability did not occur.

The formal approximations made to the diffusion equation were

$$
\left[ T^*(x,y) - T(x,y,t) \right] / (\tau/2) = \kappa \left[ T^*(x-\Delta x,y) - 2T^*(x,y) + T^*(x+\Delta x,y) \right] / (\Delta x)^2 + \kappa \left[ T(x,y-\Delta y,t) - 2T(x,y,t) + T(x,y+\Delta y,t) \right] / (\Delta y)
$$

and

$$
\left[ T(x,y,t+\tau) - T^*(x,y) \right] / (\tau/2) = \kappa \left[ T^*(x-\Delta x,y) - 2T^*(x,y) + T^*(x+\Delta x,y) \right] / (\Delta x)^2 + \kappa \left[ T(x,y-\Delta y,t+\tau) \right.
$$
This scheme is "consistent" with Equation (2) of Appendix VII since in the limit as $\Delta x$, $\Delta y$ and $\tau$ approach zero, Equations (22) and (23) converge to this equation regardless of the manner in which the grid dimensions approach zero (Carnahan and others, 1969). Hence whenever the method is "stable" the "convergence" of the approximate solution to the true solution is assured and the discretization error is $O(\Delta x^2 + \tau^2)$ (Carnahan and others, 1969). Although the numerical method can therefore yield valid approximations to the temperature field, a test of the reliability of the computer program written to execute the above approximations was desired. Conservation of energy was called upon as an independent check. The latent heat of fusion released when water freezes onto the crevasse wall must all enter the glacier ice. The volume of new ice formed in the crevasse must therefore represent a quantity of energy release equal to the thermal energy gain of the grid. For numerical simplicity a crevasse field consisting of water-filled rectangular crevasses 0.60 m wide, 11.0 m deep, spaced 20 m apart and set in an isothermal glacier at -8.00°C, was taken as the reference energy level. This model was run for a prescribed length of time, during which the heat flux out of the grid was monitored and at the end of which the thermal gain $C\Delta T\delta A$ at each point (where $C$ is the specific heat of ice, $\Delta T$ is the temperature rise above -8.00°C and $\delta A$ is the area of the grid represented by each grid point) was integrated over the whole grid. The sum of total thermal gain and heat flux out of the grid was compared to the latent energy release given by the product $L \cdot V$, where $L$ is the latent heat of fusion of water and $V$ is the volume of water frozen. The discrepancy $\varepsilon$ was represented as a percentage of $L \cdot V$. It was found that for values of $\Delta x$, $\Delta y$ and $\tau$ equal to 1.0 m, 2.0 m and 0.005 years respectively, $\varepsilon$ had a
value of 3.9% after 0.5 years. By this time 91% of the initial volume of water had become ice. If, in order to remove the extreme effects of the physically unrealistic temperature-gradient discontinuity existing across the crevasse wall at $t = 0$, the reference energy level is taken as that at $t = 0.03$ years, the value of $\varepsilon$ is then reduced to 0.42%. From this evidence it was concluded that the model was capable of giving reliable results. However $\varepsilon$ is not a satisfactory estimate of the degree of convergence since accuracy of the integration of thermal gain throughout the grid proved to be as sensitive to cell size as to the grid temperatures. Therefore the convergence of the numerical approximation was studied by comparing results of a common model run with different grid cell sizes. Figure 2 shows the results of Model I with parameters as given in Table I and with the two sets of finite-difference variables listed in Table II. As these curves agree very well the cell sizes employed are considered adequate to give convergence. The discretization error in the above models is $\approx 0.005$.

**Fitting the Model to Observations**

The critical parameters of the crevasse-field model are crevasse separation $S$, crevasse width $W$, crevasse depth $d_c$ and depth to the water surface $d_w$. Each of these has a significant effect on the model's predictions. $S$ controls both the value of the maximum temperature of the resulting profile and the rate of crevasse closure, the temperature maximum decreasing and the closure rate increasing with increasing crevasse separation. For larger values of $S$ the latent heat released at the crevasse walls diffuses throughout a greater ice volume producing lower anomalous temperatures. Since temperature gradients near the phase boundaries determine the rate of heat flux away from the
TABLE I. PARAMETERS OF MODEL I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model I</th>
<th>Model I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crevasse separation</td>
<td>S</td>
<td>20 m</td>
</tr>
<tr>
<td>Crevasse width</td>
<td>W</td>
<td>5 m</td>
</tr>
<tr>
<td>Crevasse depth</td>
<td>d_c</td>
<td>80 m</td>
</tr>
<tr>
<td>Depth to water surface</td>
<td>d_w</td>
<td>15 m</td>
</tr>
<tr>
<td>Mean surface temperature</td>
<td>T_s</td>
<td>-8.0°C</td>
</tr>
<tr>
<td>Deep ice boundary condition</td>
<td>T_d</td>
<td>-6.25°C</td>
</tr>
</tbody>
</table>

TABLE II. FINITE-DIFFERENCE VARIABLES FOR MODELS I₁ and I₂

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model I₁</th>
<th>Model I₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δx</td>
<td>1.0 m</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Δy</td>
<td>5.0 m</td>
<td>5.0 m</td>
</tr>
<tr>
<td>τ</td>
<td>0.02 yr</td>
<td>0.05 yr</td>
</tr>
</tbody>
</table>
Fig. 2. Convergence of numerical solution. Comparison of predicted crevasse cross sections and temperature profiles of Models $I_1$ and $I_2$ at $t = 6.5$ years.
crevasse, lower ice temperatures result in higher heat flux and therefore more rapid crevasse closure. Figure 3 illustrates these effects by a sequence of temperature profiles and crevasse profiles corresponding to various values of S. For times shortly after crevasse formation the value of W has little effect on the temperature distribution, especially at points distant from the crevasse wall. However, for long term calculations W should play a major role since the cross-sectional area of the crevasse, and hence the volume of water, is proportional to W. Consequently the energy source will remain longer for large values of W and warm ice temperatures will persist for greater periods of time. The crevasse depth $d_c$ also controls the volume of water in the crevasse (for a given $d_w$) but does not exert such strong influence on the duration of the heat source since the increased water volume is exposed to a greater ice surface area. Rather, the major effect of $d_c$ is to determine how deep the energy source penetrates the cold ice, and it is therefore the prime factor controlling the shape of the deep portion of the model's predicted temperature profile. The influence of $d_c$ on the model temperature profiles is shown in Figure 4a where $d_c$ takes on a different value for each of the curves of the graph. The shallow ice temperatures are greatly modified by raising the water level $d_w$. This causes thermal injection into shallower ice and the vertical extent of the anomalously warm region can be extended upwards in this manner. The sequence of temperature profiles corresponding to various values of $d_w$, presented in Figure 4b, illustrates this effect of $d_w$ on the shallow ice temperatures.
Fig. 3. Effect of crevasse separation $S$ on model predictions.

Model I: $S = 20$ m
Model J: $S = 24$ m
Model L: $S = 30$ m
Fig. 4.

(a) Effect of varying model parameter $d_c$ on temperature profile.

- Model Q: $d_c = 80$ m
- Model O: $d_c = 90$ m

(b) Effect of varying model parameter $d_w$ on temperature profile.

- Model G: $d_w = 20$ m
- Model D: $d_w = 35$ m
APPENDIX IX

DATA TABLES

I. Thermistor Calibration Data

II. Distribution of Thermistors

III. Field Measurements
### TABLE I. THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>-0.03</td>
<td>12.043</td>
<td>A12</td>
<td>-0.03</td>
<td>10.004</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.950</td>
<td></td>
<td>-9.73</td>
<td>16.158</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>16.245</td>
<td></td>
<td>-6.40</td>
<td>13.798</td>
</tr>
<tr>
<td>A2</td>
<td>-0.03</td>
<td>11.523</td>
<td>A13</td>
<td>-0.03</td>
<td>11.063</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.682</td>
<td></td>
<td>-9.73</td>
<td>17.933</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>16.012</td>
<td></td>
<td>-6.40</td>
<td>15.318</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.031</td>
<td></td>
<td>-3.58</td>
<td>13.390</td>
</tr>
<tr>
<td>A3</td>
<td>-0.03</td>
<td>11.796</td>
<td>A14</td>
<td>-0.03</td>
<td>11.484</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.796</td>
<td></td>
<td>-9.73</td>
<td>18.592</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>16.057</td>
<td></td>
<td>-6.41</td>
<td>15.877</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.012</td>
<td></td>
<td>-3.58</td>
<td>13.814</td>
</tr>
<tr>
<td>A4</td>
<td>-0.03</td>
<td>12.409</td>
<td>A15</td>
<td>-0.03</td>
<td>11.519</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>20.505</td>
<td></td>
<td>-9.73</td>
<td>18.738</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>17.556</td>
<td></td>
<td>-6.41</td>
<td>16.055</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>15.344</td>
<td></td>
<td>-3.58</td>
<td>14.069</td>
</tr>
<tr>
<td>A5</td>
<td>-0.03</td>
<td>11.723</td>
<td>A16</td>
<td>-0.03</td>
<td>11.254</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.238</td>
<td></td>
<td>-6.41</td>
<td>15.458</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>14.179</td>
<td></td>
<td>-3.58</td>
<td>13.505</td>
</tr>
<tr>
<td>A6</td>
<td>-0.03</td>
<td>11.955</td>
<td>A17</td>
<td>-0.03</td>
<td>11.599</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>19.632</td>
<td></td>
<td>-9.73</td>
<td>18.611</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>16.819</td>
<td></td>
<td>-6.41</td>
<td>15.924</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.720</td>
<td></td>
<td>-3.57</td>
<td>13.925</td>
</tr>
<tr>
<td>A7</td>
<td>-0.03</td>
<td>12.430</td>
<td>A18</td>
<td>-0.03</td>
<td>11.036</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>20.024</td>
<td></td>
<td>-9.73</td>
<td>17.545</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>17.100</td>
<td></td>
<td>-6.40</td>
<td>15.032</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.907</td>
<td></td>
<td>-3.58</td>
<td>13.164</td>
</tr>
<tr>
<td>A8</td>
<td>-0.03</td>
<td>11.670</td>
<td>A19</td>
<td>-0.03</td>
<td>10.737</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.624</td>
<td></td>
<td>-9.73</td>
<td>17.258</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.952</td>
<td></td>
<td>-6.41</td>
<td>14.787</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.983</td>
<td></td>
<td>-3.58</td>
<td>12.884</td>
</tr>
<tr>
<td>A9</td>
<td>-0.03</td>
<td>11.010</td>
<td>A20</td>
<td>-0.03</td>
<td>12.103</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.426</td>
<td></td>
<td>-9.73</td>
<td>19.912</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>14.936</td>
<td></td>
<td>-6.41</td>
<td>16.988</td>
</tr>
<tr>
<td>A10</td>
<td>-0.03</td>
<td>11.154</td>
<td>A21</td>
<td>-0.03</td>
<td>11.754</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.045</td>
<td></td>
<td>-9.73</td>
<td>18.634</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.408</td>
<td></td>
<td>-6.41</td>
<td>15.890</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.463</td>
<td></td>
<td>-3.59</td>
<td>13.877</td>
</tr>
<tr>
<td>A11</td>
<td>-0.03</td>
<td>10.810</td>
<td>A22</td>
<td>-0.03</td>
<td>10.921</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.239</td>
<td></td>
<td>-9.73</td>
<td>17.551</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>14.770</td>
<td></td>
<td>-6.41</td>
<td>14.998</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>12.923</td>
<td></td>
<td>-3.57</td>
<td>13.107</td>
</tr>
</tbody>
</table>
### THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>-0.03</td>
<td>10.726</td>
<td>B12</td>
<td>-0.03</td>
<td>10.857</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.146</td>
<td></td>
<td>-9.73</td>
<td>17.196</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>14.733</td>
<td></td>
<td>-6.46</td>
<td>14.580</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>12.884</td>
<td></td>
<td>-3.58</td>
<td>12.874</td>
</tr>
<tr>
<td>B2</td>
<td>-0.03</td>
<td>11.221</td>
<td>B13</td>
<td>-0.03</td>
<td>11.046</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.020</td>
<td></td>
<td>-9.73</td>
<td>17.487</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>15.376</td>
<td></td>
<td>-6.46</td>
<td>14.851</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.546</td>
<td></td>
<td>-3.59</td>
<td>13.126</td>
</tr>
<tr>
<td>B3</td>
<td>-0.03</td>
<td>12.056</td>
<td>B14</td>
<td>-0.03</td>
<td>11.124</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>19.135</td>
<td></td>
<td>-9.73</td>
<td>17.529</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>16.389</td>
<td></td>
<td>-6.46</td>
<td>14.988</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>14.326</td>
<td></td>
<td>-3.58</td>
<td>13.142</td>
</tr>
<tr>
<td>B4</td>
<td>-0.03</td>
<td>10.876</td>
<td>B15</td>
<td>-0.03</td>
<td>11.071</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.424</td>
<td></td>
<td>-9.73</td>
<td>17.557</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>14.925</td>
<td></td>
<td>-6.46</td>
<td>14.547</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.057</td>
<td></td>
<td>-3.59</td>
<td>13.163</td>
</tr>
<tr>
<td>B5</td>
<td>-0.03</td>
<td>12.021</td>
<td>B16</td>
<td>-0.03</td>
<td>11.709</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>19.238</td>
<td></td>
<td>-9.73</td>
<td>18.666</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>16.447</td>
<td></td>
<td>-6.46</td>
<td>15.704</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.488</td>
<td></td>
<td>-3.58</td>
<td>13.933</td>
</tr>
<tr>
<td>B6</td>
<td>-0.03</td>
<td>11.613</td>
<td>B17</td>
<td>-0.03</td>
<td>12.124</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.610</td>
<td></td>
<td>-9.73</td>
<td>19.361</td>
</tr>
<tr>
<td></td>
<td>-6.47</td>
<td>15.974</td>
<td></td>
<td>-6.46</td>
<td>19.361</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.036</td>
<td></td>
<td>-3.58</td>
<td>14.940</td>
</tr>
<tr>
<td>B7</td>
<td>-0.03</td>
<td>10.634</td>
<td>B18</td>
<td>-0.03</td>
<td>11.557</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.333</td>
<td></td>
<td>-9.73</td>
<td>18.701</td>
</tr>
<tr>
<td></td>
<td>-6.46</td>
<td>14.536</td>
<td></td>
<td>-6.46</td>
<td>15.740</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>13.247</td>
<td></td>
<td>-3.58</td>
<td>13.964</td>
</tr>
<tr>
<td>B8</td>
<td>-0.03</td>
<td>11.486</td>
<td>B19</td>
<td>-0.03</td>
<td>10.130</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.276</td>
<td></td>
<td>-9.73</td>
<td>16.225</td>
</tr>
<tr>
<td></td>
<td>-6.46</td>
<td>15.394</td>
<td></td>
<td>-6.47</td>
<td>13.631</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.771</td>
<td></td>
<td>-3.59</td>
<td>12.100</td>
</tr>
<tr>
<td>B9</td>
<td>-0.03</td>
<td>11.143</td>
<td>B20</td>
<td>-0.03</td>
<td>11.424</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.921</td>
<td></td>
<td>-9.73</td>
<td>18.262</td>
</tr>
<tr>
<td></td>
<td>-6.46</td>
<td>15.302</td>
<td></td>
<td>-6.47</td>
<td>15.373</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.531</td>
<td></td>
<td>-3.58</td>
<td>13.672</td>
</tr>
<tr>
<td>B10</td>
<td>-0.03</td>
<td>11.234</td>
<td>B21</td>
<td>-0.03</td>
<td>11.053</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>17.880</td>
<td></td>
<td>-9.73</td>
<td>17.721</td>
</tr>
<tr>
<td></td>
<td>-6.46</td>
<td>15.147</td>
<td></td>
<td>-6.46</td>
<td>15.025</td>
</tr>
<tr>
<td>B11</td>
<td>-0.03</td>
<td>12.195</td>
<td>B22</td>
<td>-0.03</td>
<td>11.660</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>19.349</td>
<td></td>
<td>-9.73</td>
<td>18.382</td>
</tr>
<tr>
<td></td>
<td>-6.46</td>
<td>16.385</td>
<td></td>
<td>-6.46</td>
<td>15.685</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>14.395</td>
<td></td>
<td>-3.58</td>
<td>13.783</td>
</tr>
</tbody>
</table>
## THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>-0.03</td>
<td>10.948</td>
<td>C12</td>
<td>-0.03</td>
<td>10.635</td>
</tr>
<tr>
<td></td>
<td>-9.75</td>
<td>17.476</td>
<td></td>
<td>-9.73</td>
<td>16.787</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.065</td>
<td></td>
<td>-6.41</td>
<td>14.454</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>13.164</td>
<td></td>
<td>-3.57</td>
<td>12.670</td>
</tr>
<tr>
<td>C2</td>
<td>-0.03</td>
<td>11.922</td>
<td>C13</td>
<td>-0.03</td>
<td>10.816</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.741</td>
<td></td>
<td>-9.73</td>
<td>17.204</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.189</td>
<td></td>
<td>-6.41</td>
<td>14.896</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>14.175</td>
<td></td>
<td>-3.58</td>
<td>13.050</td>
</tr>
<tr>
<td>C3</td>
<td>-0.03</td>
<td>12.198</td>
<td>C14</td>
<td>-0.03</td>
<td>11.433</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>19.624</td>
<td></td>
<td>-9.75</td>
<td>18.402</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>17.002</td>
<td></td>
<td>-6.41</td>
<td>15.843</td>
</tr>
<tr>
<td>C4</td>
<td>-0.03</td>
<td>11.155</td>
<td>C15</td>
<td>-0.03</td>
<td>11.648</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>17.424</td>
<td></td>
<td>-9.72</td>
<td>18.526</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.035</td>
<td></td>
<td>-6.41</td>
<td>15.926</td>
</tr>
<tr>
<td>C5</td>
<td>-0.03</td>
<td>11.439</td>
<td>C16</td>
<td>-0.03</td>
<td>12.254</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.150</td>
<td></td>
<td>-9.72</td>
<td>19.389</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.627</td>
<td></td>
<td>-6.40</td>
<td>16.856</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.718</td>
<td></td>
<td>-3.58</td>
<td>14.776</td>
</tr>
<tr>
<td>C6</td>
<td>-0.03</td>
<td>10.627</td>
<td>C17</td>
<td>-0.03</td>
<td>10.653</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>14.617</td>
<td></td>
<td>-6.41</td>
<td>14.659</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>12.835</td>
<td></td>
<td>-3.58</td>
<td>12.848</td>
</tr>
<tr>
<td>C7</td>
<td>-0.03</td>
<td>11.065</td>
<td>C18</td>
<td>-0.03</td>
<td>12.011</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>18.303</td>
<td></td>
<td>-9.72</td>
<td>19.224</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.715</td>
<td></td>
<td>-6.40</td>
<td>16.559</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.736</td>
<td></td>
<td>-3.58</td>
<td>14.484</td>
</tr>
<tr>
<td>C8</td>
<td>-0.03</td>
<td>12.195</td>
<td>C19</td>
<td>-0.04</td>
<td>11.126</td>
</tr>
<tr>
<td></td>
<td>-9.72</td>
<td>19.741</td>
<td></td>
<td>-9.73</td>
<td>17.673</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.986</td>
<td></td>
<td>-6.41</td>
<td>15.280</td>
</tr>
<tr>
<td></td>
<td>-3.59</td>
<td>14.849</td>
<td></td>
<td>-3.57</td>
<td>13.403</td>
</tr>
<tr>
<td>C9</td>
<td>-0.03</td>
<td>10.924</td>
<td>C20</td>
<td>-0.04</td>
<td>11.662</td>
</tr>
<tr>
<td></td>
<td>-9.74</td>
<td>17.913</td>
<td></td>
<td>-9.73</td>
<td>18.845</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.342</td>
<td></td>
<td>-6.40</td>
<td>16.289</td>
</tr>
<tr>
<td>C10</td>
<td>-0.03</td>
<td>10.992</td>
<td>C21</td>
<td>-0.04</td>
<td>10.477</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.184</td>
<td></td>
<td>-9.73</td>
<td>17.445</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.587</td>
<td></td>
<td>-6.41</td>
<td>15.081</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.627</td>
<td></td>
<td>-3.58</td>
<td>13.183</td>
</tr>
<tr>
<td>C11</td>
<td>-0.03</td>
<td>11.766</td>
<td>C22</td>
<td>-0.04</td>
<td>12.112</td>
</tr>
<tr>
<td></td>
<td>-9.73</td>
<td>18.827</td>
<td></td>
<td>-9.74</td>
<td>19.076</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.215</td>
<td></td>
<td>-6.41</td>
<td>16.513</td>
</tr>
</tbody>
</table>
## THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>-0.04</td>
<td>11.672</td>
<td>D12</td>
<td>-9.81</td>
<td>18.198</td>
</tr>
<tr>
<td></td>
<td>-8.83</td>
<td>18.253</td>
<td></td>
<td>-6.40</td>
<td>15.613</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.715</td>
<td></td>
<td>-3.57</td>
<td>13.601</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.765</td>
<td></td>
<td>-0.02</td>
<td>11.565</td>
</tr>
<tr>
<td>D2</td>
<td>-0.04</td>
<td>11.996</td>
<td>D13</td>
<td>-9.80</td>
<td>17.177</td>
</tr>
<tr>
<td></td>
<td>-9.84</td>
<td>18.973</td>
<td></td>
<td>-6.41</td>
<td>14.726</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.275</td>
<td></td>
<td>-3.57</td>
<td>12.886</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.225</td>
<td></td>
<td>-0.02</td>
<td>10.958</td>
</tr>
<tr>
<td>D3</td>
<td>-0.04</td>
<td>11.432</td>
<td>D14</td>
<td>-9.80</td>
<td>18.305</td>
</tr>
<tr>
<td></td>
<td>-9.84</td>
<td>18.630</td>
<td></td>
<td>-6.40</td>
<td>15.622</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.895</td>
<td></td>
<td>-3.57</td>
<td>13.617</td>
</tr>
<tr>
<td>D4</td>
<td>-0.04</td>
<td>12.028</td>
<td>D15</td>
<td>-9.87</td>
<td>19.218</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.536</td>
<td></td>
<td>-3.57</td>
<td>14.333</td>
</tr>
<tr>
<td>D5</td>
<td>-0.04</td>
<td>14.101</td>
<td>D16</td>
<td>-9.88</td>
<td>18.516</td>
</tr>
<tr>
<td></td>
<td>-9.81</td>
<td>17.602</td>
<td></td>
<td>-6.40</td>
<td>15.786</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>14.041</td>
<td></td>
<td>-3.57</td>
<td>13.655</td>
</tr>
<tr>
<td>D6</td>
<td>-0.04</td>
<td>11.053</td>
<td>D17</td>
<td>-9.88</td>
<td>18.363</td>
</tr>
<tr>
<td></td>
<td>-9.82</td>
<td>17.939</td>
<td></td>
<td>-6.40</td>
<td>15.638</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.243</td>
<td></td>
<td>-3.57</td>
<td>13.610</td>
</tr>
<tr>
<td>D7</td>
<td>-0.04</td>
<td>10.229</td>
<td>D18</td>
<td>-9.87</td>
<td>18.554</td>
</tr>
<tr>
<td></td>
<td>-9.81</td>
<td>16.671</td>
<td></td>
<td>-6.40</td>
<td>15.799</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>14.258</td>
<td></td>
<td>-3.57</td>
<td>13.709</td>
</tr>
<tr>
<td>D8</td>
<td>-9.81</td>
<td>20.055</td>
<td>D19</td>
<td>-9.87</td>
<td>19.271</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>17.144</td>
<td></td>
<td>-6.40</td>
<td>16.364</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.968</td>
<td></td>
<td>-3.56</td>
<td>14.250</td>
</tr>
<tr>
<td>D9</td>
<td>-9.81</td>
<td>17.789</td>
<td>D20</td>
<td>-9.87</td>
<td>17.182</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.149</td>
<td></td>
<td>-6.40</td>
<td>14.652</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.106</td>
<td></td>
<td>-3.57</td>
<td>12.815</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.040</td>
<td></td>
<td>-6.40</td>
<td>14.469</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.973</td>
<td></td>
<td>-3.56</td>
<td>12.671</td>
</tr>
<tr>
<td>D11</td>
<td>-9.80</td>
<td>17.557</td>
<td>D22</td>
<td>-9.86</td>
<td>15.521</td>
</tr>
<tr>
<td></td>
<td>-6.40</td>
<td>15.046</td>
<td></td>
<td>-6.40</td>
<td>13.217</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.111</td>
<td></td>
<td>-3.56</td>
<td>11.550</td>
</tr>
<tr>
<td></td>
<td>-0.02</td>
<td>11.160</td>
<td></td>
<td>-0.02</td>
<td>9.840</td>
</tr>
</tbody>
</table>
## THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>-9.76</td>
<td>18.156</td>
<td>E6</td>
<td>-9.76</td>
<td>18.136</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.652</td>
<td></td>
<td>-6.41</td>
<td>15.518</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.544</td>
<td></td>
<td>-3.58</td>
<td>13.533</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>11.625</td>
<td></td>
<td>0.02</td>
<td>11.607</td>
</tr>
<tr>
<td>E2</td>
<td>-9.77</td>
<td>18.001</td>
<td>E7</td>
<td>-9.76</td>
<td>18.540</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.327</td>
<td></td>
<td>-6.41</td>
<td>15.841</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.527</td>
<td></td>
<td>-3.58</td>
<td>13.864</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>11.468</td>
<td></td>
<td>0.02</td>
<td>11.792</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>14.181</td>
<td></td>
<td>-6.41</td>
<td>12.607</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>12.378</td>
<td></td>
<td>-3.58</td>
<td>11.000</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>10.357</td>
<td></td>
<td>0.02</td>
<td>9.405</td>
</tr>
<tr>
<td>E4</td>
<td>-9.77</td>
<td>17.910</td>
<td>E9</td>
<td>-9.79</td>
<td>16.637</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>15.449</td>
<td></td>
<td>-6.40</td>
<td>14.220</td>
</tr>
<tr>
<td></td>
<td>-3.58</td>
<td>13.444</td>
<td></td>
<td>-3.59</td>
<td>12.392</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>11.524</td>
<td></td>
<td>0.02</td>
<td>10.596</td>
</tr>
<tr>
<td></td>
<td>-6.41</td>
<td>16.424</td>
<td></td>
<td>-6.41</td>
<td>16.985</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>12.239</td>
<td></td>
<td>0.02</td>
<td>12.596</td>
</tr>
</tbody>
</table>
## THERMISTOR CALIBRATION DATA

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
<th>THERMISTOR</th>
<th>TEMP. (DEG C)</th>
<th>RES. (K-OHMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>-9.72</td>
<td>19.750</td>
<td>F12</td>
<td>-9.72</td>
<td>18.416</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>16.890</td>
<td></td>
<td>-6.48</td>
<td>15.788</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.754</td>
<td></td>
<td>-3.57</td>
<td>13.744</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>12.497</td>
<td></td>
<td>-0.03</td>
<td>11.641</td>
</tr>
<tr>
<td>F2</td>
<td>-9.72</td>
<td>16.216</td>
<td>F13</td>
<td>-9.72</td>
<td>18.948</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>13.900</td>
<td></td>
<td>-6.48</td>
<td>16.235</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>12.144</td>
<td></td>
<td>-3.57</td>
<td>14.197</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>10.336</td>
<td></td>
<td>-0.02</td>
<td>12.084</td>
</tr>
<tr>
<td>F3</td>
<td>-9.72</td>
<td>19.907</td>
<td>F14</td>
<td>-9.72</td>
<td>17.335</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>17.071</td>
<td></td>
<td>-6.48</td>
<td>14.871</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.899</td>
<td></td>
<td>-3.58</td>
<td>12.978</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>12.682</td>
<td></td>
<td>-0.02</td>
<td>10.987</td>
</tr>
<tr>
<td>F4</td>
<td>-9.72</td>
<td>18.312</td>
<td>F15</td>
<td>-9.72</td>
<td>18.491</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>15.697</td>
<td></td>
<td>-6.48</td>
<td>15.855</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.691</td>
<td></td>
<td>-3.57</td>
<td>13.857</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>11.572</td>
<td></td>
<td>-0.02</td>
<td>11.775</td>
</tr>
<tr>
<td>F5</td>
<td>-9.72</td>
<td>19.008</td>
<td>F16</td>
<td>-9.71</td>
<td>15.127</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>16.296</td>
<td></td>
<td>-6.48</td>
<td>12.973</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>14.236</td>
<td></td>
<td>-3.57</td>
<td>11.277</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>12.128</td>
<td></td>
<td>-0.02</td>
<td>9.561</td>
</tr>
<tr>
<td>F6</td>
<td>-9.72</td>
<td>20.508</td>
<td>F17</td>
<td>-9.72</td>
<td>18.488</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>17.581</td>
<td></td>
<td>-6.48</td>
<td>15.847</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>15.370</td>
<td></td>
<td>-3.57</td>
<td>13.757</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>13.014</td>
<td></td>
<td>-0.02</td>
<td>11.689</td>
</tr>
<tr>
<td>F7</td>
<td>-9.72</td>
<td>17.363</td>
<td>F18</td>
<td>-9.72</td>
<td>18.892</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>14.898</td>
<td></td>
<td>-6.48</td>
<td>16.199</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>12.974</td>
<td></td>
<td>-3.57</td>
<td>14.140</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>10.962</td>
<td></td>
<td>-0.02</td>
<td>11.998</td>
</tr>
<tr>
<td>F8</td>
<td>-9.72</td>
<td>18.643</td>
<td>F19</td>
<td>-9.72</td>
<td>20.404</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>15.982</td>
<td></td>
<td>-6.48</td>
<td>17.493</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.978</td>
<td></td>
<td>-3.57</td>
<td>15.195</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>11.892</td>
<td></td>
<td>-0.02</td>
<td>12.876</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>17.095</td>
<td></td>
<td>-6.48</td>
<td>15.028</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>12.638</td>
<td></td>
<td>-0.02</td>
<td>11.134</td>
</tr>
<tr>
<td>F10</td>
<td>-9.72</td>
<td>18.359</td>
<td>F21</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>15.736</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.742</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>11.664</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>F11</td>
<td>-9.72</td>
<td>18.091</td>
<td>F22</td>
<td>-9.72</td>
<td>17.902</td>
</tr>
<tr>
<td></td>
<td>-6.48</td>
<td>15.517</td>
<td></td>
<td>-6.48</td>
<td>15.351</td>
</tr>
<tr>
<td></td>
<td>-3.57</td>
<td>13.466</td>
<td></td>
<td>-3.57</td>
<td>13.394</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>11.406</td>
<td></td>
<td>-0.02</td>
<td>11.371</td>
</tr>
</tbody>
</table>


**TABLE II. THERMISTOR DISTRIBUTION**

**TRAPRIDGE GLACIER**

**HOLE #1 - CABLE 72T1**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A10</td>
<td>B-BLACK</td>
<td>6.1</td>
<td>A7</td>
<td>GREEN</td>
<td>56.7</td>
</tr>
<tr>
<td>A5</td>
<td>BLUE</td>
<td>21.7</td>
<td>A3</td>
<td>R-BLACK</td>
<td>66.7</td>
</tr>
<tr>
<td>A8</td>
<td>G-BLACK</td>
<td>41.7</td>
<td>A1</td>
<td>RED</td>
<td>71.7</td>
</tr>
</tbody>
</table>

**HOLE #2 - CABLE 72T2**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A17</td>
<td>WHITE</td>
<td>11.3</td>
<td>A11</td>
<td>GREEN</td>
<td>23.5</td>
</tr>
<tr>
<td>A16</td>
<td>B-BLACK</td>
<td>14.3</td>
<td>A9</td>
<td>R-BLACK</td>
<td>26.5</td>
</tr>
<tr>
<td>A14</td>
<td>BLUE</td>
<td>17.4</td>
<td>A13</td>
<td>RED</td>
<td>29.6</td>
</tr>
<tr>
<td>A12</td>
<td>G-BLACK</td>
<td>20.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**HOLE #2 - CABLE 72T3**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A21</td>
<td>GREEN</td>
<td>2.1</td>
<td>A18</td>
<td>RED</td>
<td>8.2</td>
</tr>
<tr>
<td>A19</td>
<td>R-BLACK</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**HOLE #3 - CABLE 72T4**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4</td>
<td>B-BLACK</td>
<td>7.6</td>
<td>D13</td>
<td>GREEN</td>
<td>49.5</td>
</tr>
<tr>
<td>D3</td>
<td>BLUE</td>
<td>9.5</td>
<td>D8</td>
<td>R-BLACK</td>
<td>59.5</td>
</tr>
<tr>
<td>D14</td>
<td>G-BLACK</td>
<td>34.5</td>
<td>D2</td>
<td>RED</td>
<td>64.5</td>
</tr>
</tbody>
</table>
## THERMISTOR DISTRIBUTION

### TRAPRIDGE GLACIER

#### HOLE #4 - CABLE 72T5

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D22</td>
<td>WHITE</td>
<td>8.9</td>
<td>D21</td>
<td>GREEN</td>
<td>72.5</td>
</tr>
<tr>
<td>D10</td>
<td>B-BLACK</td>
<td>12.5</td>
<td>D20</td>
<td>R-BLACK</td>
<td>82.5</td>
</tr>
<tr>
<td>D7</td>
<td>BLUE</td>
<td>37.5</td>
<td>D19</td>
<td>RED</td>
<td>87.5</td>
</tr>
<tr>
<td>D6</td>
<td>G-BLACK</td>
<td>57.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### HOLE #5 - CABLE 72T6

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D12</td>
<td>BLUE</td>
<td>10.3</td>
<td>C2</td>
<td>R-BLACK</td>
<td>45.3</td>
</tr>
<tr>
<td>D11</td>
<td>G-BLACK</td>
<td>25.3</td>
<td>C1</td>
<td>RED</td>
<td>50.3</td>
</tr>
<tr>
<td>C4</td>
<td>GREEN</td>
<td>35.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### HOLE #6 - CABLE 72T7

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>B-BLACK</td>
<td>11.6</td>
<td>C16</td>
<td>GREEN</td>
<td>35.6</td>
</tr>
<tr>
<td>C5</td>
<td>BLUE</td>
<td>21.6</td>
<td>C15</td>
<td>R-BLACK</td>
<td>41.6</td>
</tr>
<tr>
<td>C3</td>
<td>G-BLACK</td>
<td>29.6</td>
<td>C13</td>
<td>RED</td>
<td>43.6</td>
</tr>
</tbody>
</table>

#### HOLE #7 - CABLE 72T8

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8</td>
<td>R-BLACK</td>
<td>9.6</td>
<td>C12</td>
<td>RED</td>
<td>11.6</td>
</tr>
</tbody>
</table>
# THERMISTOR DISTRIBUTION

## TRAPRIDGE GLACIER

**HOLE #8 - CABLE 72T9**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E4</td>
<td>WHITE</td>
<td>5.5</td>
<td>E7</td>
<td>GREEN</td>
<td>29.4</td>
</tr>
<tr>
<td>E6</td>
<td>B-BLACK</td>
<td>5.4</td>
<td>E5</td>
<td>R-BLACK</td>
<td>35.4</td>
</tr>
<tr>
<td>E2</td>
<td>BLUE</td>
<td>15.4</td>
<td>E3</td>
<td>RED</td>
<td>37.4</td>
</tr>
<tr>
<td>E10</td>
<td>G-BLACK</td>
<td>23.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## STEELE GLACIER

**1972 - CABLE 72T10**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4</td>
<td>WHITE</td>
<td>70.3</td>
<td>C22</td>
<td>GREEN</td>
<td>106.3</td>
</tr>
<tr>
<td>B1</td>
<td>B-BLACK</td>
<td>82.3</td>
<td>C19</td>
<td>R-BLACK</td>
<td>112.3</td>
</tr>
<tr>
<td>B14</td>
<td>BLUE</td>
<td>92.3</td>
<td>C18</td>
<td>RED</td>
<td>114.3</td>
</tr>
<tr>
<td>B3</td>
<td>G-BLACK</td>
<td>100.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**1972 - CABLE 72T11**

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
<th>THERMISTOR</th>
<th>COLOUR</th>
<th>DEPTH (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>BLUE</td>
<td>26.0</td>
<td>E9</td>
<td>R-BLACK</td>
<td>47.0</td>
</tr>
<tr>
<td>C20</td>
<td>G-BLACK</td>
<td>33.0</td>
<td>D15</td>
<td>WHITE</td>
<td>54.0</td>
</tr>
<tr>
<td>B2</td>
<td>GREEN</td>
<td>40.0</td>
<td>E8</td>
<td>RED</td>
<td>61.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHM)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHM)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td><strong>JULY 3, 1972</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.61</td>
<td>-3.82</td>
<td>A7</td>
<td>12.84</td>
<td>-0.65</td>
</tr>
<tr>
<td>A5</td>
<td>14.16</td>
<td>-3.58</td>
<td>A3</td>
<td>11.98</td>
<td>-0.35</td>
</tr>
<tr>
<td>A8</td>
<td>12.94</td>
<td>-2.01</td>
<td>A1</td>
<td>12.12</td>
<td>-0.16</td>
</tr>
<tr>
<td><strong>P.M. JULY 7, 1972</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.45</td>
<td>-3.60</td>
<td>A7</td>
<td>13.03</td>
<td>-0.94</td>
</tr>
<tr>
<td>A5</td>
<td>14.16</td>
<td>-3.58</td>
<td>A3</td>
<td>11.98</td>
<td>-0.35</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.02</td>
<td>A1</td>
<td>12.14</td>
<td>-0.20</td>
</tr>
<tr>
<td><strong>A.M. JULY 9, 1972</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.40</td>
<td>-3.54</td>
<td>A7</td>
<td>13.08</td>
<td>-0.98</td>
</tr>
<tr>
<td>A5</td>
<td>14.16</td>
<td>-3.58</td>
<td>A3</td>
<td>11.98</td>
<td>-0.35</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.02</td>
<td>A1</td>
<td>12.15</td>
<td>-0.21</td>
</tr>
<tr>
<td><strong>16:30 JULY 11, 1972</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.35</td>
<td>-3.46</td>
<td>A7</td>
<td>13.09</td>
<td>-1.00</td>
</tr>
<tr>
<td>A5</td>
<td>14.17</td>
<td>-3.59</td>
<td>A3</td>
<td>11.99</td>
<td>-0.37</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.04</td>
<td>A1</td>
<td>12.18</td>
<td>-0.26</td>
</tr>
<tr>
<td><strong>12:15 JULY 14, 1972</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.29</td>
<td>-3.39</td>
<td>A7</td>
<td>13.11</td>
<td>-1.02</td>
</tr>
<tr>
<td>A5</td>
<td>14.19</td>
<td>-3.62</td>
<td>A3</td>
<td>11.99</td>
<td>-0.37</td>
</tr>
<tr>
<td>A8</td>
<td>12.96</td>
<td>-2.06</td>
<td>A1</td>
<td>12.18</td>
<td>-0.26</td>
</tr>
</tbody>
</table>
TRAPRIDGE GLACIER

HOLE #1

COMPLETED: 19:30 JUNE 18, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td><strong>A.M. JULY 17, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.20</td>
<td>-3.24</td>
<td>A7</td>
<td>13.10</td>
<td>-1.01</td>
</tr>
<tr>
<td>A5</td>
<td>14.18</td>
<td>-3.60</td>
<td>A3</td>
<td>11.97</td>
<td>-0.34</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.04</td>
<td>A1</td>
<td>12.17</td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>A.M. JULY 19, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.15</td>
<td>-3.17</td>
<td>A7</td>
<td>13.11</td>
<td>-1.03</td>
</tr>
<tr>
<td>A5</td>
<td>14.17</td>
<td>-3.58</td>
<td>A3</td>
<td>11.97</td>
<td>-0.34</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.03</td>
<td>A1</td>
<td>12.16</td>
<td>-0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>24:00 JULY 21, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>13.10</td>
<td>-3.12</td>
<td>A7</td>
<td>13.11</td>
<td>-1.03</td>
</tr>
<tr>
<td>A5</td>
<td>14.17</td>
<td>-3.58</td>
<td>A3</td>
<td>11.97</td>
<td>-0.34</td>
</tr>
<tr>
<td>A8</td>
<td>12.95</td>
<td>-2.03</td>
<td>A1</td>
<td>12.16</td>
<td>-0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>20:15 AUGUST 5, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>12.88</td>
<td>-2.76</td>
<td>A7</td>
<td>13.13</td>
<td>-1.07</td>
</tr>
<tr>
<td>A5</td>
<td>14.18</td>
<td>-3.60</td>
<td>A3</td>
<td>11.99</td>
<td>-0.37</td>
</tr>
<tr>
<td>A8</td>
<td>12.97</td>
<td>-2.03</td>
<td>A1</td>
<td>12.18</td>
<td>-0.26</td>
</tr>
</tbody>
</table>
### FIELD MEASUREMENTS

**TRAPRIDGE GLACIER**

**HOLE #2**
- **COMMENCED:** 16:45 JUNE 26, 1972.
- **COMPLETED:** 18:15 JUNE 27, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td><strong>JULY 3, 1972.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A21</td>
<td>11.87</td>
<td>-0.30</td>
</tr>
<tr>
<td>A19</td>
<td>12.48</td>
<td>-2.90</td>
</tr>
<tr>
<td>A18</td>
<td>13.64</td>
<td>-4.35</td>
</tr>
<tr>
<td>A17</td>
<td>14.12</td>
<td>-3.95</td>
</tr>
<tr>
<td>A16</td>
<td>13.60</td>
<td>-3.75</td>
</tr>
<tr>
<td>A14</td>
<td>13.86</td>
<td>-3.66</td>
</tr>
<tr>
<td>A12</td>
<td>11.98</td>
<td>-3.42</td>
</tr>
<tr>
<td>A11</td>
<td>12.78</td>
<td>-3.35</td>
</tr>
<tr>
<td>A9</td>
<td>12.82</td>
<td>-3.20</td>
</tr>
<tr>
<td>A13</td>
<td>12.91</td>
<td>-2.88</td>
</tr>
</tbody>
</table>

| **P.M. JULY 7, 1972.** |          |
| A21 | 11.86 | -0.26 |
| A19 | 12.38 | -2.76 |
| A18 | 13.62 | -4.30 |
| A17 | 14.14 | -3.94 |
| A16 | 13.61 | -3.79 |
| A14 | 13.89 | -3.72 |
| A12 | 12.01 | -3.52 |
| A11 | 12.80 | -3.40 |
| A9  | 12.85 | -3.24 |
| A13 | 13.00 | -3.01 |

| **A.M. JULY 9, 1972.** |          |
| A21 | 11.87 | -0.26 |
| A19 | 12.34 | -2.71 |
| A18 | 13.59 | -4.23 |
| A17 | 14.16 | -3.98 |
| A16 | 13.63 | -3.80 |
| A14 | 13.90 | -3.74 |
| A12 | 12.02 | -3.52 |
| A11 | 12.82 | -3.44 |
| A9  | 12.88 | -3.26 |
| A13 | 13.00 | -3.01 |

| **16:45 JULY 11, 1972.** |          |
| A21 | 11.86 | -0.28 |
| A19 | 12.30 | -2.62 |
| A18 | 13.57 | -4.20 |
| A17 | 14.16 | -3.98 |
| A16 | 13.63 | -3.80 |
| A14 | 13.90 | -3.74 |
| A12 | 12.02 | -3.52 |
| A11 | 12.82 | -3.44 |
| A9  | 12.86 | -3.24 |
| A13 | 13.00 | -3.01 |

| **12:30 JULY 14, 1972.** |          |
| A21 | 11.88 | -0.28 |
| A19 | 12.27 | -2.58 |
| A18 | 13.55 | -4.19 |
| A17 | 14.19 | -4.00 |
| A16 | 13.66 | -3.84 |
| A14 | 13.92 | -3.76 |
| A12 | 12.04 | -3.54 |
| A11 | 12.84 | -3.46 |
| A9  | 12.88 | -3.26 |
| A13 | 13.02 | -3.06 |
FIELD MEASUREMENTS

TRAPRIDGE GLACIER

HOLE #2


<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
</tbody>
</table>

**A.M. JULY 17, 1972.**

| A21 | 11.87 | -0.26 | A14 | 13.91 | -3.76 |
| A19 | 12.21 | -2.51 | A12 | 12.04 | -3.56 |
| A18 | 13.50 | -4.10 | A11 | 12.84 | -3.46 |
| A17 | 14.19 | -4.00 | A9  | 12.87 | -3.26 |
| A16 | 13.65 | -3.81 | A13 | 13.03 | -3.06 |

**P.M. JULY 18, 1972.**

| A21 | 11.88 | -0.28 | A14 | 13.91 | -3.77 |
| A19 | 12.19 | -2.45 | A12 | 12.04 | -3.54 |
| A17 | 14.18 | -3.99 | A9  | 12.87 | -3.26 |
| A16 | 13.65 | -3.81 | A13 | 13.03 | -3.08 |

**23:30 JULY 21, 1972.**

| A21 | 11.87 | -0.26 | A14 | 13.90 | -3.75 |
| A19 | 12.13 | -2.37 | A12 | 12.02 | -3.52 |
| A18 | 13.42 | -4.00 | A11 | 12.81 | -3.43 |
| A16 | 13.65 | -3.81 | A13 | 13.02 | -3.06 |

**20:30 AUGUST 5, 1972.**

| A21 | 11.86 | -0.23 | A14 | 13.92 | -3.77 |
| A19 | 11.98 | -1.30 | A12 | 12.03 | -3.54 |
| A18 | 13.24 | -3.70 | A11 | 12.82 | -3.45 |
| A17 | 14.17 | -3.99 | A9  | 12.87 | -3.25 |
| A16 | 13.67 | -3.83 | A13 | 13.03 | -3.08 |
FIELD MEASUREMENTS

TRAPRIDGE GLACIER

HOLE #3

COMPLETED: 04:20 JULY 6, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>17:10 JULY 10, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.86</td>
<td>-5.57</td>
<td>D13</td>
<td>11.17</td>
<td>-0.40</td>
</tr>
<tr>
<td>D3</td>
<td>13.86</td>
<td>-3.56</td>
<td>D8</td>
<td>12.89</td>
<td>-0.34</td>
</tr>
<tr>
<td>D14</td>
<td>12.37</td>
<td>-1.42</td>
<td>D2</td>
<td>12.29</td>
<td>-0.52</td>
</tr>
<tr>
<td>14:30 JULY 14, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.94</td>
<td>-5.66</td>
<td>D13</td>
<td>11.34</td>
<td>-0.70</td>
</tr>
<tr>
<td>D3</td>
<td>13.98</td>
<td>-3.72</td>
<td>D8</td>
<td>12.92</td>
<td>-0.40</td>
</tr>
<tr>
<td>D14</td>
<td>12.60</td>
<td>-1.80</td>
<td>D2</td>
<td>12.34</td>
<td>-0.60</td>
</tr>
<tr>
<td>P.M. JULY 16, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.96</td>
<td>-5.70</td>
<td>D13</td>
<td>11.56</td>
<td>-1.13</td>
</tr>
<tr>
<td>D3</td>
<td>14.00</td>
<td>-3.76</td>
<td>D8</td>
<td>12.94</td>
<td>-0.42</td>
</tr>
<tr>
<td>D14</td>
<td>12.63</td>
<td>-1.86</td>
<td>D2</td>
<td>12.44</td>
<td>-0.76</td>
</tr>
<tr>
<td>JULY 20, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.97</td>
<td>-5.70</td>
<td>D13</td>
<td>11.63</td>
<td>-0.62</td>
</tr>
<tr>
<td>D3</td>
<td>14.04</td>
<td>-3.80</td>
<td>D8</td>
<td>13.07</td>
<td>-0.62</td>
</tr>
<tr>
<td>D14</td>
<td>12.67</td>
<td>-1.23</td>
<td>D2</td>
<td>12.60</td>
<td>-1.02</td>
</tr>
<tr>
<td>22:00 JULY 21, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.95</td>
<td>-5.70</td>
<td>D13</td>
<td>11.62</td>
<td>-1.22</td>
</tr>
<tr>
<td>D3</td>
<td>14.03</td>
<td>-3.79</td>
<td>D8</td>
<td>13.15</td>
<td>-0.76</td>
</tr>
<tr>
<td>D14</td>
<td>12.66</td>
<td>-1.94</td>
<td>D2</td>
<td>12.60</td>
<td>-1.02</td>
</tr>
</tbody>
</table>
FIELD MEASUREMENTS

TRAPRIDGE GLACIER

HOLE #3

COMPLETED: 04:20 JULY 6, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>D4</td>
<td>15.96</td>
<td>-5.70</td>
<td>D13</td>
<td>11.63</td>
<td>-1.26</td>
</tr>
<tr>
<td>D3</td>
<td>14.05</td>
<td>-3.80</td>
<td>D8</td>
<td>13.26</td>
<td>-0.92</td>
</tr>
<tr>
<td>D14</td>
<td>12.67</td>
<td>-1.94</td>
<td>D2</td>
<td>12.62</td>
<td>-1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.96</td>
<td>-5.70</td>
<td>D13</td>
<td>11.65</td>
<td>-1.29</td>
</tr>
<tr>
<td>D3</td>
<td>14.07</td>
<td>-3.84</td>
<td>D8</td>
<td>13.30</td>
<td>-1.00</td>
</tr>
<tr>
<td>D14</td>
<td>12.69</td>
<td>-1.98</td>
<td>D2</td>
<td>12.63</td>
<td>-1.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20:00 JULY 28, 1972.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.94</td>
<td>-5.68</td>
<td>D13</td>
<td>11.66</td>
<td>-1.30</td>
</tr>
<tr>
<td>D3</td>
<td>14.07</td>
<td>-3.82</td>
<td>D8</td>
<td>13.30</td>
<td>-1.00</td>
</tr>
<tr>
<td>D14</td>
<td>12.70</td>
<td>-1.99</td>
<td>D2</td>
<td>12.64</td>
<td>-1.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>15.91</td>
<td>-5.63</td>
<td>D13</td>
<td>11.67</td>
<td>-1.32</td>
</tr>
<tr>
<td>D3</td>
<td>14.11</td>
<td>-3.89</td>
<td>D8</td>
<td>13.33</td>
<td>-1.03</td>
</tr>
<tr>
<td>D14</td>
<td>12.71</td>
<td>-2.01</td>
<td>D2</td>
<td>12.65</td>
<td>-1.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Trapridge Glacier

**Hole #4**

**Commenced:** 07:20 JULY 6, 1972.

**Completed:** 02:20 JULY 7, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>-------</td>
<td>-------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>D22</td>
<td>11.17</td>
<td>-2.79</td>
<td>D21</td>
<td>10.88</td>
<td>-0.20</td>
</tr>
<tr>
<td>D10</td>
<td>12.84</td>
<td>-1.66</td>
<td>D20</td>
<td>11.94</td>
<td>-0.60</td>
</tr>
<tr>
<td>D7</td>
<td>10.88</td>
<td>-1.14</td>
<td>D19</td>
<td>12.35</td>
<td>-0.46</td>
</tr>
<tr>
<td>D6</td>
<td>11.40</td>
<td>-0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17:50 JULY 10, 1972.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D22</td>
<td>11.31</td>
<td>-3.02</td>
<td>D21</td>
<td>10.88</td>
<td>-0.20</td>
</tr>
<tr>
<td>D10</td>
<td>13.42</td>
<td>-2.61</td>
<td>D20</td>
<td>11.01</td>
<td>-0.56</td>
</tr>
<tr>
<td>D7</td>
<td>11.35</td>
<td>-1.88</td>
<td>D19</td>
<td>12.29</td>
<td>-0.37</td>
</tr>
<tr>
<td>D6</td>
<td>11.38</td>
<td>-0.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15:00 JULY 14, 1972.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D22</td>
<td>11.38</td>
<td>-3.18</td>
<td>D21</td>
<td>10.88</td>
<td>-0.20</td>
</tr>
<tr>
<td>D10</td>
<td>13.54</td>
<td>-2.80</td>
<td>D20</td>
<td>11.01</td>
<td>-0.57</td>
</tr>
<tr>
<td>D7</td>
<td>11.41</td>
<td>-1.99</td>
<td>D19</td>
<td>12.35</td>
<td>-0.45</td>
</tr>
<tr>
<td>D6</td>
<td>11.39</td>
<td>-0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JULY 16, 1972.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D22</td>
<td>11.42</td>
<td>-3.23</td>
<td>D21</td>
<td>10.88</td>
<td>-0.20</td>
</tr>
<tr>
<td>D10</td>
<td>13.60</td>
<td>-2.90</td>
<td>D20</td>
<td>11.01</td>
<td>-0.57</td>
</tr>
<tr>
<td>D7</td>
<td>11.42</td>
<td>-2.00</td>
<td>D19</td>
<td>12.36</td>
<td>-0.45</td>
</tr>
<tr>
<td>D6</td>
<td>11.40</td>
<td>-0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JULY 20, 1972.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D22</td>
<td>11.46</td>
<td>-3.33</td>
<td>D21</td>
<td>10.88</td>
<td>-0.20</td>
</tr>
<tr>
<td>D10</td>
<td>13.66</td>
<td>-3.00</td>
<td>D20</td>
<td>10.95</td>
<td>-0.42</td>
</tr>
<tr>
<td>D7</td>
<td>11.47</td>
<td>-2.09</td>
<td>D19</td>
<td>12.34</td>
<td>-0.44</td>
</tr>
<tr>
<td>D6</td>
<td>11.49</td>
<td>-0.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Thermistor 1</td>
<td>Res. (K-Ohms)</td>
<td>Temp. (Deg C)</td>
<td>Thermistor 2</td>
<td>Res. (K-Ohms)</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------</td>
<td>---------------</td>
<td>---------------</td>
<td>--------------</td>
<td>---------------</td>
</tr>
<tr>
<td>21:45 JULY 21, 1972</td>
<td>D22 11.45 3.30</td>
<td>D21 10.86 -0.17</td>
<td>D10 13.65 2.97</td>
<td>D20 11.01 -0.54</td>
<td>D7 11.46 2.03</td>
</tr>
<tr>
<td>19:00 JULY 23, 1972</td>
<td>D22 11.47 3.34</td>
<td>D21 10.86 -0.18</td>
<td>D10 13.67 3.00</td>
<td>D20 11.01 -0.56</td>
<td>D7 11.47 2.10</td>
</tr>
<tr>
<td>15:20 JULY 24, 1972</td>
<td>D22 11.48 3.37</td>
<td>D21 10.87 -0.20</td>
<td>D10 13.69 3.00</td>
<td>D20 11.03 -0.58</td>
<td>D7 11.48 2.10</td>
</tr>
<tr>
<td>19:30 JULY 28, 1972</td>
<td>D22 11.48 3.36</td>
<td>D21 10.86 -0.17</td>
<td>D10 13.70 3.02</td>
<td>D20 11.00 -0.52</td>
<td>D7 11.48 2.08</td>
</tr>
<tr>
<td>16:25 AUGUST 5, 1972</td>
<td>D22 11.49 3.37</td>
<td>D21 10.88 -0.20</td>
<td>D10 13.74 3.10</td>
<td>D20 11.02 -0.56</td>
<td>D7 11.50 2.14</td>
</tr>
</tbody>
</table>
**FIELD MEASUREMENTS**

**TRAPRIDGE GLACIER**

**HOLE #5**

**COMMENCED:** 15:10 JULY 10, 1972.  
**COMPLETED:** 24:00 JULY 10, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>-------</td>
<td>-------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td><strong>16:20 JULY 11, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>16.15</td>
<td>-7.20</td>
<td>C2</td>
<td>12.36</td>
<td>-0.70</td>
</tr>
<tr>
<td>D11</td>
<td>11.38</td>
<td>-0.39</td>
<td>C1</td>
<td>11.30</td>
<td>-0.60</td>
</tr>
<tr>
<td>C4</td>
<td>11.66</td>
<td>-0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>13:00 JULY 14, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>16.95</td>
<td>-8.21</td>
<td>C2</td>
<td>13.78</td>
<td>-2.92</td>
</tr>
<tr>
<td>D11</td>
<td>13.81</td>
<td>-4.60</td>
<td>C1</td>
<td>11.31</td>
<td>-0.61</td>
</tr>
<tr>
<td>C4</td>
<td>13.24</td>
<td>-3.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>JULY 17, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>17.07</td>
<td>-8.38</td>
<td>C2</td>
<td>13.91</td>
<td>-3.15</td>
</tr>
<tr>
<td>D11</td>
<td>13.91</td>
<td>-4.78</td>
<td>C1</td>
<td>11.29</td>
<td>-0.59</td>
</tr>
<tr>
<td>C4</td>
<td>13.35</td>
<td>-3.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>JULY 19, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>17.09</td>
<td>-8.39</td>
<td>C2</td>
<td>13.92</td>
<td>-3.16</td>
</tr>
<tr>
<td>D11</td>
<td>13.92</td>
<td>-4.79</td>
<td>C1</td>
<td>11.28</td>
<td>-0.59</td>
</tr>
<tr>
<td>C4</td>
<td>13.35</td>
<td>-3.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>19:00 JULY 21, 1972.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D12</td>
<td>17.09</td>
<td>-8.39</td>
<td>C2</td>
<td>13.91</td>
<td>-3.16</td>
</tr>
<tr>
<td>D11</td>
<td>13.92</td>
<td>-4.79</td>
<td>C1</td>
<td>11.32</td>
<td>-0.04</td>
</tr>
<tr>
<td>C4</td>
<td>13.34</td>
<td>-3.84</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TRAPRIDGE GLACIER

#### HOLE #5

| THERMISTOR | RES. | TEMP. | THERMISTOR | RES. | TEMP. |
|-------------|--|-----|--|-------------|--|-----|
|             | (K-OHMS) | (DEG C) |             | (K-OHMS) | (DEG C) |
| 16:30 JULY 24, 1972. | | | | | |
| D12 | 17.13 | -8.42 | C2 | 13.96 | -3.19 |
| D11 | 13.96 | -4.82 | C1 | 11.32 | -0.63 |
| C4 | 13.39 | -3.90 | | | |
| | | | | | |
| 18:00 JULY 28, 1972. | | | | | |
| D12 | 17.14 | -8.43 | C2 | 13.96 | -3.18 |
| D11 | 13.96 | -4.81 | C1 | 11.32 | -0.63 |
| C4 | 13.39 | -3.91 | | | |
| | | | | | |
| D11 | 13.98 | -4.86 | C1 | 11.37 | -0.72 |
| C4 | 13.40 | -3.94 | | | |

### TRAPRIDGE GLACIER

#### HOLE #6

| THERMISTOR | RES. | TEMP. | THERMISTOR | RES. | TEMP. |
|-------------|--|-----|--|-------------|--|-----|
|             | (K-OHMS) | (DEG C) |             | (K-OHMS) | (DEG C) |
| JULY 14, 1972. | | | | | |
| C6 | 14.02 | -5.48 | C16 | 12.71 | -0.70 |
| C5 | 13.71 | -3.59 | C15 | 12.00 | -0.60 |
| C3 | 13.52 | -1.83 | C13 | 11.22 | -0.64 |
FIELD MEASUREMENTS

TRAPRIDGE GLACIER

HOLE #6
COMPLETED:  11:00 JULY 13, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C6</td>
<td>14.29</td>
<td>-5.85</td>
<td>C16</td>
<td>13.83</td>
<td>-2.28</td>
</tr>
<tr>
<td>C5</td>
<td>14.06</td>
<td>-4.14</td>
<td>C15</td>
<td>12.01</td>
<td>-0.60</td>
</tr>
<tr>
<td>C3</td>
<td>14.59</td>
<td>-3.24</td>
<td>C13</td>
<td>11.22</td>
<td>-0.64</td>
</tr>
<tr>
<td>C6</td>
<td>14.37</td>
<td>-6.00</td>
<td>C16</td>
<td>13.99</td>
<td>-2.50</td>
</tr>
<tr>
<td>C5</td>
<td>14.14</td>
<td>-4.24</td>
<td>C15</td>
<td>11.99</td>
<td>-0.58</td>
</tr>
<tr>
<td>C3</td>
<td>14.68</td>
<td>-3.37</td>
<td>C13</td>
<td>11.24</td>
<td>-0.70</td>
</tr>
<tr>
<td>C6</td>
<td>14.43</td>
<td>-6.10</td>
<td>C16</td>
<td>14.08</td>
<td>-2.64</td>
</tr>
<tr>
<td>C5</td>
<td>14.20</td>
<td>-4.35</td>
<td>C15</td>
<td>11.98</td>
<td>-0.58</td>
</tr>
<tr>
<td>C3</td>
<td>14.74</td>
<td>-3.44</td>
<td>C13</td>
<td>11.22</td>
<td>-0.66</td>
</tr>
<tr>
<td>C6</td>
<td>14.44</td>
<td>-6.10</td>
<td>C16</td>
<td>14.08</td>
<td>-2.63</td>
</tr>
<tr>
<td>C5</td>
<td>14.21</td>
<td>-4.36</td>
<td>C15</td>
<td>11.96</td>
<td>-0.54</td>
</tr>
<tr>
<td>C3</td>
<td>14.74</td>
<td>-3.46</td>
<td>C13</td>
<td>11.20</td>
<td>-0.61</td>
</tr>
<tr>
<td>C6</td>
<td>14.50</td>
<td>-6.20</td>
<td>C16</td>
<td>14.14</td>
<td>-2.73</td>
</tr>
<tr>
<td>C5</td>
<td>14.26</td>
<td>-4.40</td>
<td>C15</td>
<td>11.99</td>
<td>-0.58</td>
</tr>
<tr>
<td>C3</td>
<td>14.79</td>
<td>-3.54</td>
<td>C13</td>
<td>11.22</td>
<td>-0.65</td>
</tr>
</tbody>
</table>
TRAPRIDGE GLACIER

HOLE #6
COMPLETED: 11:00 JULY 13, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C6</td>
<td>14.54</td>
<td>-6.23</td>
</tr>
<tr>
<td>C5</td>
<td>14.29</td>
<td>-4.43</td>
</tr>
<tr>
<td>C3</td>
<td>14.81</td>
<td>-3.56</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C6</td>
<td>14.16</td>
<td>-2.76</td>
</tr>
<tr>
<td>C5</td>
<td>12.01</td>
<td>-0.60</td>
</tr>
<tr>
<td>C3</td>
<td>11.23</td>
<td>-0.69</td>
</tr>
</tbody>
</table>

17:45 AUGUST 5, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C6</td>
<td>14.57</td>
<td>-6.28</td>
</tr>
<tr>
<td>C5</td>
<td>14.29</td>
<td>-4.45</td>
</tr>
<tr>
<td>C3</td>
<td>14.83</td>
<td>-3.57</td>
</tr>
</tbody>
</table>

TRAPRIDGE GLACIER

HOLE #7
COMPLETED: 18:00 JULY 15, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C8</td>
<td>12.76</td>
<td>-0.78</td>
</tr>
<tr>
<td>C12</td>
<td>10.90</td>
<td>-0.50</td>
</tr>
</tbody>
</table>

JULY 16, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C8</td>
<td>13.06</td>
<td>-1.20</td>
</tr>
<tr>
<td>C12</td>
<td>11.18</td>
<td>-1.00</td>
</tr>
</tbody>
</table>

JULY 17, 1972.

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>C8</td>
<td>14.22</td>
<td>-2.80</td>
</tr>
<tr>
<td>C12</td>
<td>11.82</td>
<td>-2.15</td>
</tr>
</tbody>
</table>
TRAPRIDGE GLACIER

HOLE #7

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>18:45 JULY 28, 1972.</td>
<td>15.20</td>
<td>-4.10</td>
<td>C12</td>
<td>12.49</td>
<td>-3.27</td>
</tr>
<tr>
<td>18:00 AUGUST 5, 1972.</td>
<td>15.28</td>
<td>-4.20</td>
<td>C12</td>
<td>12.55</td>
<td>-3.37</td>
</tr>
</tbody>
</table>

STEELE GLACIER

1972 DRILL HOLE

<table>
<thead>
<tr>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
<th>THERMISTOR</th>
<th>RES.</th>
<th>TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
<td></td>
<td>(K-OHMS)</td>
<td>(DEG C)</td>
</tr>
<tr>
<td>16:30 AUGUST 10, 1972.</td>
<td>12.55</td>
<td>-1.54</td>
<td>B1</td>
<td>13.63</td>
<td>-4.77</td>
</tr>
<tr>
<td></td>
<td>12.32</td>
<td>-0.96</td>
<td>B14</td>
<td>14.31</td>
<td>-5.43</td>
</tr>
<tr>
<td></td>
<td>11.90</td>
<td>-1.14</td>
<td>B3</td>
<td>15.96</td>
<td>-5.88</td>
</tr>
<tr>
<td></td>
<td>10.84</td>
<td>-0.54</td>
<td>C22</td>
<td>16.31</td>
<td>-6.13</td>
</tr>
<tr>
<td></td>
<td>12.98</td>
<td>-1.38</td>
<td>C19</td>
<td>15.32</td>
<td>-6.41</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
<td>-2.14</td>
<td>C18</td>
<td>16.64</td>
<td>-6.46</td>
</tr>
<tr>
<td></td>
<td>13.23</td>
<td>-3.90</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>