CRREL
EPORT 86-11

US Army Corps
of Engineers

Cold Regions Research &
Engineering Laboratory

Morphology, hydraulics and sediment transport of an ice-covered river
Field techniques and initial data

CRREL

CRREL Report 86-11

October 1986

Morphology, hydraulics and sediment transport of an ice-covered river

Field techniques and initial data

D.E. Lawson, E.F. Chacho, Jr., B.E. Brockett, J.L. Wuebben,
C.M. Collins, S.A. Arcone and A.J. Delaney

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188 Exp. Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): CRREL Report 86-11	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: U.S. Army Cold Regions Research and Engineering Laboratory; 6b. OFFICE SYMBOL (If applicable): CRREL	7a. NAME OF MONITORING ORGANIZATION: Office of the Chief of Engineers
6c. ADDRESS (City, State, and ZIP Code): Hanover, N.H. 03755-1290	7b. ADDRESS (City, State, and ZIP Code): Washington, D.C. 20314-1000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
CWIS 31722 CWIS 31568			

11. TITLE (Include Security Classification)

Morphology, hydraulics and sediment transport of an ice-covered river. Field techniques and initial data.

12. PERSONAL AUTHOR(S)

Lawson, D.E.; Chacho, E.F. Jr.; Brockett, B.E.; Wuebben, J.L.; Collins, C.M.; Arcone, S.A. and Delaney, A.J.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	October 1986	49

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Alaska	Frazil ice	Tanana River
			Braided rivers	Ice-covered rivers	
			Field tests	River currents	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This initial study of the ice-covered Tanana River, near Fairbanks, Alaska, attempted to 1) establish field methods for systematic and repetitive quantitative analyses of an ice-covered river's regime, 2) evaluate the instruments and equipment for sampling, and 3) obtain the initial data of a long-term study of ice cover effects on the morphology, hydraulics and sediment transport of a braided river. A methodology was established, and detailed measurements and samplings, including profiling by geophysical techniques, were conducted along cross sections of the river. A small, portable rotary drill rig equipped with a 356-mm (14-in.) ice auger was used to cut large diameter holes in the ice cover for through-the-ice measurements. Portable heat sources and a heated shelter were required to continuously thaw and dry equipment for the repetitive measurements. Measurements included ice cover thickness, water level, water depth, temperature, flow velocity, suspended load and bed load, frazil ice distribution and bed material composition. Remotely gathered data included apparent resistivity and subsurface radar profiling. The various techniques, sampling gear and problems encountered during use in the subfreezing cold are described in detail in this report. Preliminary results indicate that water flow below the ice cover occurs in distinct channels that

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: D. E. Lawson	22b. TELEPHONE (Include Area Code): 603 646-4344; 22c. OFFICE SYMBOL: CRREL-RE

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. Abstract (cont'd)

are generally separated from each other by stagnant deposits of frazil ice. These deposits generally extend from the bottom of the ice cover to the river bed, acting as lateral channel walls for the subice flow. Of the total area beneath the ice cover of each cross section, 35 to 50% consists of stagnant frazil ice deposits. Dimensions, hydraulic parameters and sediment transport rates vary among the subice channels. A new form of frazil ice aggregate—called frazil ice pebble—is described. Its shape is reminiscent of water-worn stream pebbles with dimensions ranging up to 15 cm on the longest axis. Each frazil pebble consists of individual frazil ice particles or small aggregates of particles that are bound together by ice. They appear to develop from irregular aggregates of frazil that are eroded from frazil deposits and then transported downstream by the current. Their smooth and rounded form develops from bounding and rolling of the rough aggregates along the bottom of the ice cover during transport.

PREFACE

This report was prepared by Dr. Daniel E. Lawson, Research Physical Scientist, Edward F. Chacho Jr., Research Civil Engineer, Bruce E. Brockett, Physical Science Technician, all of the Geological Sciences Branch, Research Division; James L. Wuebben, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division; Charles M. Collins, Research Physical Scientist, Geological Sciences Branch, Research Division; Dr. Steven A. Arcone, Research Geophysicist, and Allan J. Delaney, Physical Science Technician, Snow and Ice Branch, both of the Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The funding for this research was provided by the Office of the Chief of Engineers under Civil Works Work Units CWIS 31722, *Geomorphic Factors Affecting Sediment Transport and Deposition in Northern Rivers*, and CWIS 31568, *Erosion Potential of Inland Shorelines and Embankments in Regions Subject to Freezing and Thawing*.

A primary intent of the field work described in this report was to evaluate techniques for examining the winter regime of an ice-covered river under extreme cold. This would then serve as guidance for future work of this type, as well as for modifying or developing equipment to better meet the needs of research or the general collection of river data during the winter. The field work also initiated data collection on sediment transport, hydraulics and morphology of an ice-covered river.

The authors thank SGT Charles Newhouse for his assistance in the field, Stephen Perkins for computer programming used in reduction and plotting of data, and Patricia Butler for analyzing sediment concentrations of the ice and water. They also thank Dr. George Ashton, Michael Ferrick and Edward Foltyn of CRREL for their critical review of this report.

CONTENTS

ILLUSTRATIONS

Figure

Figure | Page

TABLES

Table

Morphology, Hydraulics and Sediment Transport of an Ice-Covered River
Field Techniques and Initial Data

D.E. LAWSON, E.F. CHACHO, JR., B.E. BROCKETT,
J.L. WUEBBEN, C.M. COLLINS, S.A. ARCONE AND A.J. DELANEY

INTRODUCTION

An ice cover can significantly alter the characteristics and morphological processes of rivers in cold regions. Hydraulic and sediment transport processes under ice cover conditions, for example, are more complex than open channel conditions and not well understood (Michel 1971, Ashton 1980). Certain changes in river flow from the summer to winter regime have been identified mainly by theoretical and laboratory analyses. These analyses have indicated that an ice cover generally increases the normal flow depth and decreases the average flow velocity as the result of the increased resistance of the upper, solid ice boundary (Larsen 1969, 1973; Uzuner 1975; Shen and Hardin 1978; Sayre and Song 1979). The resistance or hydraulic roughness of the ice cover varies over time, with the underside being smoother during its formation and growth, but becoming rippled (Carey 1966, 1967; Larsen 1969) as ambient air temperatures rise, heat transfer through the ice is reduced, and water at temperatures above freezing melts the base of the ice cover (Ashton 1971, 1972; Ashton and Kennedy 1972). The hydraulic roughness attains its maximum value when the bottom of the ice cover is modified during spring breakup, or when large deposits of frazil ice accumulate there. In addition, formation of ice floe jams during freezeup can produce a very rough bottom configuration.

Similarly, an ice cover modifies the velocity and shear stress distributions, although the precise form of these distributions remains in question (Shen and Hardin 1978, Sayre and Song 1979, Lau and Krishnappen 1981). For the same discharge, shear stress at the bed is, in general, less under the winter regime than under the summer regime. The configuration and thus the hydraulic roughness of the bed may also vary as the ice cover forms and grows, and as the hydraulic roughness of the underside of the ice cover progressively changes during winter. A reduction in velocity and bed shear stress results in a decrease in both the suspended sediment load and bedload (Tywoniuk and Fowler 1972, Sayre and Song 1979).

Systematic, quantitative field studies of ice-covered rivers, including examination of their morphology, sediment transport and hydraulics, are lacking. The few published field studies of river behavior in winter (e.g., Michel 1971) have in general examined only certain physical characteristics, such as ice cover thickness, frazil ice distribution and bed configuration or, less often, hydraulic parameters. The U.S. Geological Survey and foreign and domestic government agencies have sporadically, but not routinely, monitored flow and discharge in selected rivers during winter, but the basic research on ice-covered river behavior has not been done.

There are perhaps several reasons why such systematic field studies and basic data are lacking: the general logistical problems inherent to working on an ice cover during low temperatures, a lack of suitable methods and sampling equipment for use in winter, or perhaps an underlying assumption that sediment and water discharge are severely reduced during the ice-covered period and therefore of less interest than during the open water period. In general, air temperatures below 0°C coupled with river water near 0°C can lead to rapid icing and freezeup of equipment, thus making it difficult to obtain measurements or samples repetitively. The accuracy of measurements may also be in doubt, particularly since standard equipment used during summer months has not been tested adequately under subfreezing conditions to define its limitations.

In this report, we discuss the initial results of a field study of the morphology, hydraulics and sediment transport of the ice-covered Tanana River in central Alaska. In addition, we discuss in some detail the methods and equipment used to overcome the basic logistical problems associated with working in the extreme cold.

STUDY OBJECTIVES AND FIELD LOCALE

Our objectives in this initial study were: 1) to establish the field methods for analyzing flow and sediment transport beneath an ice cover, 2) to evaluate the instruments and equipment used for sampling, and 3) to obtain initial data on the physical characteristics and hydraulics of a river with an ice cover.

This study was conducted in late February and March 1984 on the Tanana River near Fairbanks, Alaska (Fig. 1). We chose the Tanana River because an extensive data set exists on river morphology and hydraulics during the summer season. These data constitute one of the largest data sets available on an alluvial gravel-bed river and were compiled or measured for the Tanana River Monitoring and Research Program (Neill et al. 1984). Cross sections established during this program were also reasonably accessible for the winter work. In addition, the winter climate of Fairbanks could provide extremely low, subfreezing temperatures and a thick ice cover for testing and evaluating methodology and sampling gear.

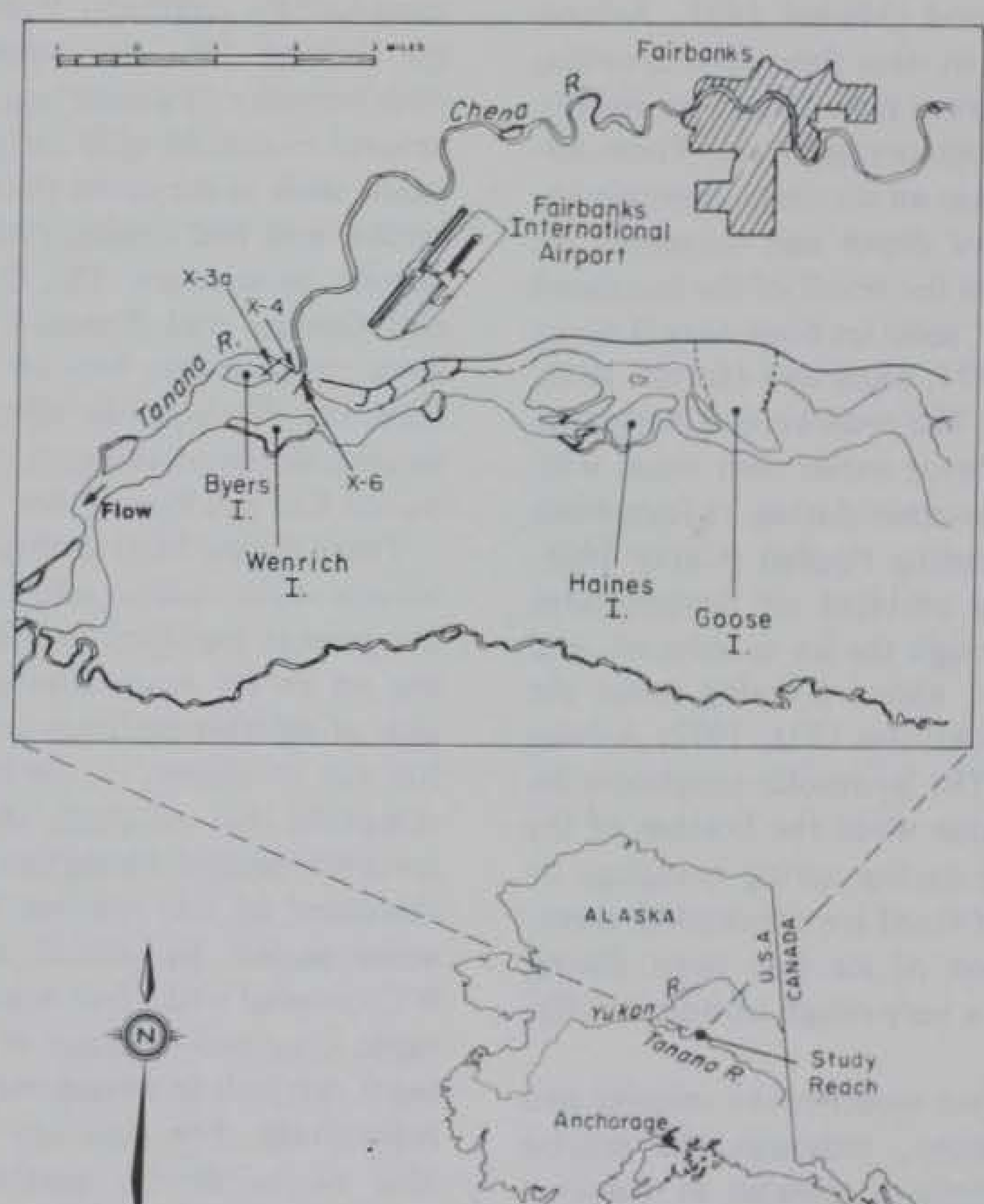


Figure 1. Location of the study reach on the Tanana River near Fairbanks, Alaska.

Figure 2. Aerial photograph of the Tanana River near its confluence with the Chena River in late summer of 1983. Detailed measurements and sampling were done from 22 February to 5 March on cross section X4. Geophysical surveys were made along cross sections X4 and X6. Morphological characteristics of cross sections X6 and X4 were also measured on 30 March.

STUDY SITE

The specific reach investigated for this study is a well-defined bend in the Tanana River near its confluence with the Chena River (Fig. 2). Channel patterns within this section of the river might best be described as transitional between braided and meandering (Neill et al. 1984), with the outermost banks of the active channel exhibiting a meandering pattern within a wide active floodplain (Fig. 2). Flow within this active floodplain is characterized by a braided pattern during periods of low discharge but nearly bankfull conditions during spring flooding and during the peak period of summer runoff from glaciers and mountain snowpacks. (The Tanana River near Fairbanks, Alaska, is described in detail by Neill et al. [1984].)

The physical and hydraulic parameters were measured in detail along a previously established cross section (X4) located just downstream of the mouth of the Chena River (Fig. 2). In previous years, periodic summer and sporadic winter measurements were made on this cross section (Neill et al. 1984, Chacho et al., in press). Physical parameters were also remotely monitored along cross section X4 as well as along another previously established cross section (X6) located just upstream of the confluence, and at specified distances up or downstream of cross section X4 (Fig. 2). Cross section X6 was also measured to determine ground truth for the geophysical measurements.

EQUIPMENT

The equipment used in this study is available through commercial or governmental sources; we hope that this will ensure that anyone wishing to follow procedures discussed in this report can readily obtain duplicate sampling and drilling equipment.

Vehicles

Because of the location of this study, vehicles were used to tow equipment and supplies to and from the site daily and to position it along the transect under investigation. A Bombardier tracked vehicle towed the equipment train, which consisted of a drill rig and a tent mounted on a metal frame with skis (Fig. 3). In our work, the Bombardier was helpful in packing the snow beneath its tracks, providing paths for moving sleds by snowmobile, for walking between access holes along the transect and for using the geophysical instruments. Two snowmobiles towed sleds carrying a portable generator (Fig. 4), delicate instruments and additional personnel.

Figure 3. Bombardier tracked vehicle towing drill and tent mounted on metal frame with skis. Equipment and supplies were also carried on the Bombardier and the platform of the drill.

Figure 4. Snowmobiles transported personnel and towed sleds carrying delicate instruments and the generator.

Drilling equipment

We used a rotary drill (Fig. 5) developed at CRREL for augering and core sampling permafrost (Brockett and Lawson 1985) to obtain undisturbed core samples of the ice cover, and to auger access holes through it. The CRREL drill is trailer-mounted and can be towed off-road on either skis or all-terrain tires. This drill is a modified version of the General Dig-R-Mobile Model 550 (Fig. 5). (Modifications are described in detail by Brockett and Lawson [1985]). The unmodified Dig-R-Mobile, with adapters fabricated for use of an ice auger and a CRREL ice-coring auger, would also be suitable for the ice cover work. The CRREL drill was initially selected because it could provide control for augering multiple holes next to one another, and sufficient power to cut any debris-rich ice that might be encountered.

We used the 7.6-mm (3-in.) diameter CRREL ice-coring auger, with tungsten carbide cutters (Ueda et al. 1975), to obtain the continuous cores of the ice cover (Fig. 6). Core samples from this ice-coring auger are essentially undisturbed and can be used for both physical and chemical analyses.

A 356-mm (14-in.) diameter, double flight auger designed by Dr. Malcolm Mellor of CRREL (Fig. 7) was used to cut access holes. This auger was also equipped with tungsten carbide cutters and

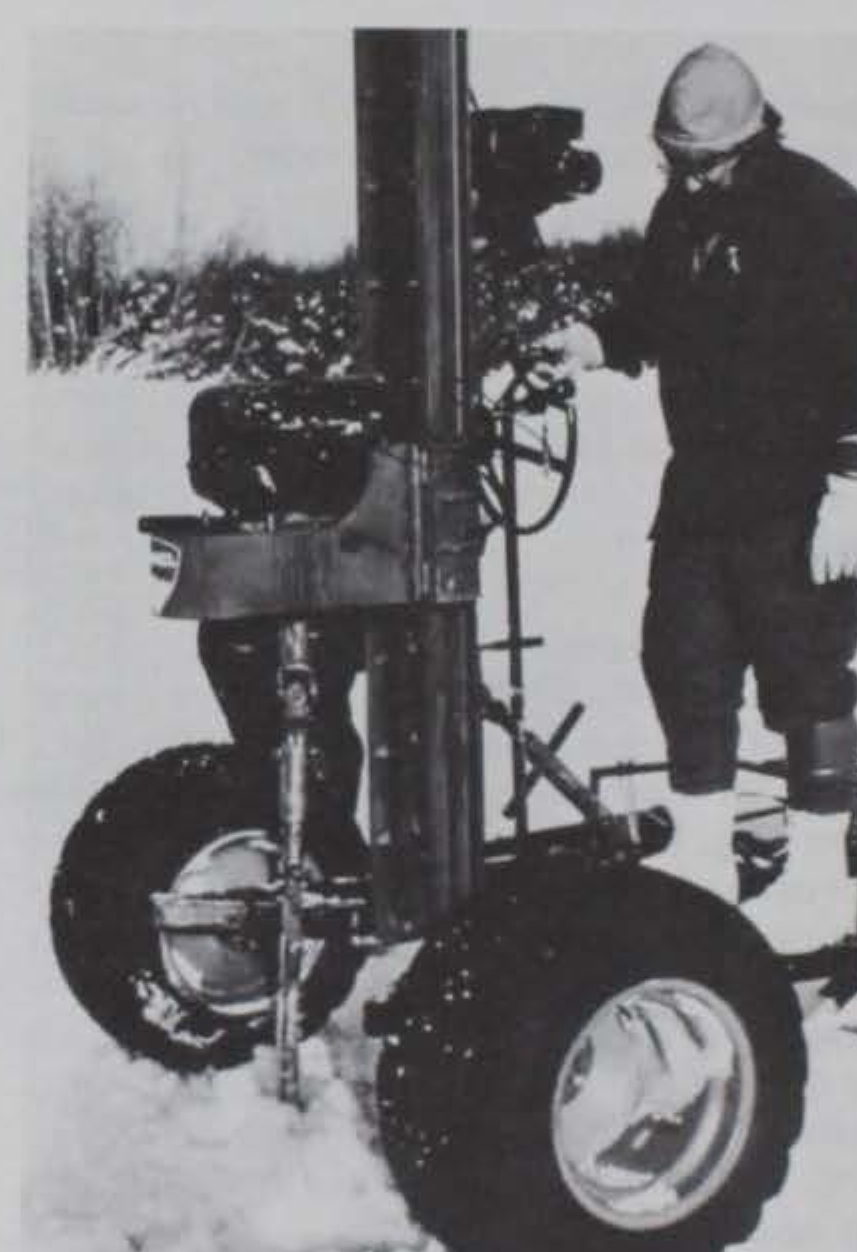


Figure 5. Portable drill augering an access hole in the ice cover.

Figure 6. CRREL ice-coring auger; used for undisturbed core sampling of the ice cover.

Figure 7. Double flight auger of 14 in. (35.6 cm) diameter was used for cutting access holes in the ice cover. Partially frozen slush adheres to auger after encountering wet, partly consolidated frazil ice near the bottom of the ice cover.

was selected because we anticipated having to auger through ice containing sediment. This item is not commercially available, however; we recommend that a 305-mm (12-in.), or larger, diameter ice auger with a single flight and steel cutters be substituted for it.

Sampling equipment

We measured current velocities, both magnitude and direction, with a Marsh McBirney, Inc., Model 511 Electromagnetic (EM) Water Current Meter (Fig. 8). It consists of a transducer probe with cable and a signal processor housed in a portable case. Velocity components along the Y-axis and X-axis of the electromagnetic sensor are displayed, with a full-scale output range of 3.05 m/s (10 ft/s). The current meter was calibrated by the manufacturer for an operating range of -20° to 40°C, and was subsequently tested by CRREL in a test basin to verify its accuracy.

In addition, we used a U.S. Geological Survey ice vane current meter (Fig. 9), following standard procedures, to measure the magnitude of water velocity and compare it with the electromagnetic current meter. The ice vane meter does not indicate direction of flow. Each unit is calibrated by the USGS and is supplied with data to convert signal output to current velocity; we did not test the accuracy of this unit ourselves.

We measured suspended sediment transport using a hand-held, freeze-resistant, depth-integrating sampler (Model US DH-75) (Fig. 10), which is available from the Federal Inter-Agency Sedimentation Project (St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota). This sampler uses a 4.76-mm-i.d. nozzle and a 1-L plastic bottle. It is calibrated to maximum velocities of 2.0 m/s (6.6 ft/s) and samples to within 10 cm (4.0 in.) of the bed.

A hand-held version of the Helley-Smith type bedload sampler (Emmett 1980) was used to collect bedload samples for determining sediment transport rate and grain size. This sampler has a

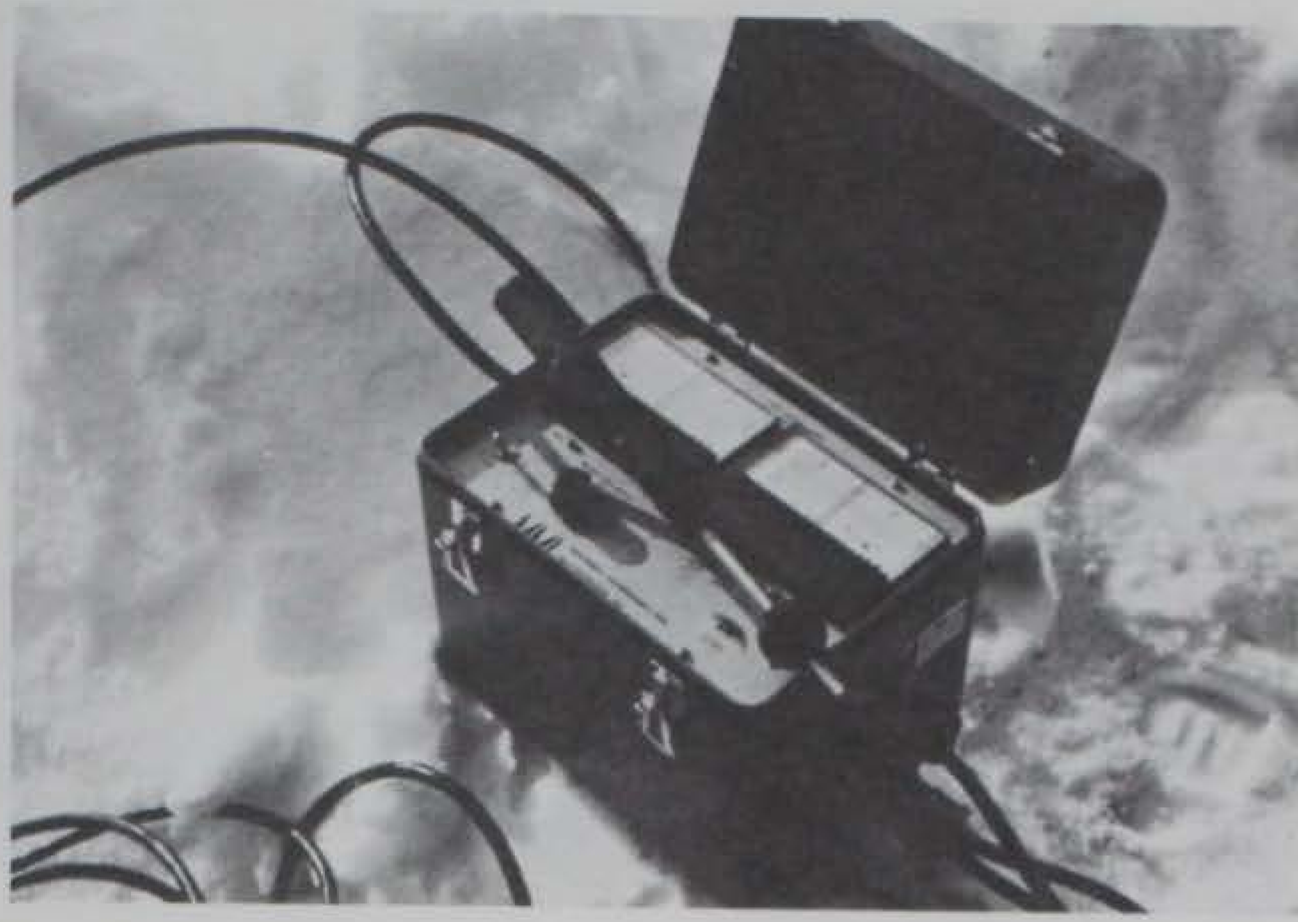


Figure 8. Electromagnetic current meter, manufactured by Marsh McBirney, Inc.; used for measuring magnitude and direction of flow.

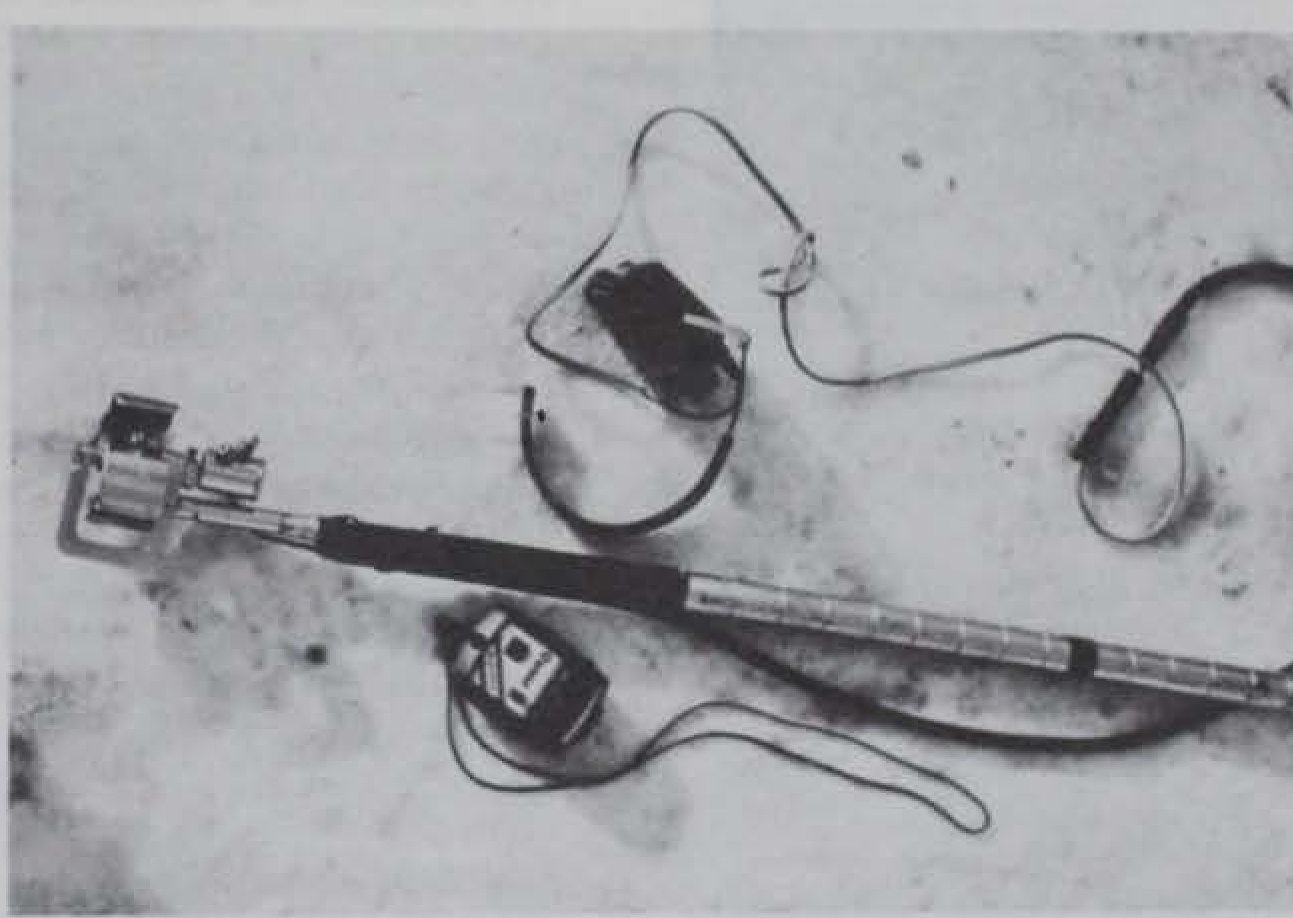


Figure 9. U.S. Geological Survey ice vane current meter; it measures the velocity magnitude, but not direction.

Figure 10. Freeze-resistant suspended sediment sampler attached to sectional aluminum rod with Hartwell pin. Plastic sample bottle is 1 L in volume.

Figure 11. Hand-held version of Helley-Smith type bedload sampler with standard sampling bag attached. Rear of bag has been modified by removing stitching and securing it with a metal clip.

760- by 760-mm² orifice and uses standard monofilament polyester sampling bags with a 250-μm mesh (ASTM 7-60-250) (Fig. 11). It was manufactured by GBC, Inc., of Denver, Colorado.

An adaptor was fabricated for attaching the suspended sediment sampler, bedload sampler and EM current meter to 1-m-long sections of lightweight aluminum rod. Sections of rod were held together by Hartwell pins (Fig. 12). Pressure-sensitive measuring tape that is waterproof and shrink resistant was glued to each section of rod, and each section was sequentially numbered for measuring sampling depths.

We sampled bed material with a Wildco-Peterson grab dredge (Fig. 13). This sampler is normally suspended by cable and released for free fall to the river bed; once it penetrates the bottom, the sampler is slowly pulled up from the bed, which allows the jaws to close and sample a 0.09-m² area of the river bed. Its heaviness (39 kg) and dimensions permit sampling of gravel beds.

Geophysical equipment

We used two electromagnetic methods of geophysical exploration to profile the Tanana River. Each method uses the transmission of radio waves between fixed transmit and receive antennas to define geologic detail to depths of about 10 m. The first technique, known as magnetic induction, uses steady state, single frequency radio waves. The

Figure 12. Lightweight aluminum rod in 1-m-long sections connected by Hartwell pins. Pressure-sensitive tape was used for depth measurements.

Figure 13. Wildco-Peterson grab dredge for bottom sampling. Sampler was emptied into metal pan after being pulled from bed.

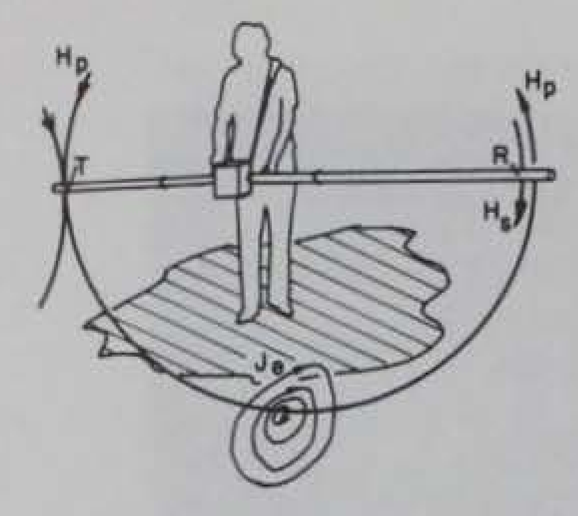


Figure 14. Magnetic induction instrument (Geonics EM-31) for measuring ground resistivity. The transmitting loop T *produces a primary magnetic field* H_p *that induces eddy currents* J_e *within the ground.* J_e *then produces a secondary magnetic field* H_s*, which is received out of phase with* H_p *at the receiver* R. *The quadrature phase component of* H_s/H_p *is calibrated in mhos/m of conductivity.*

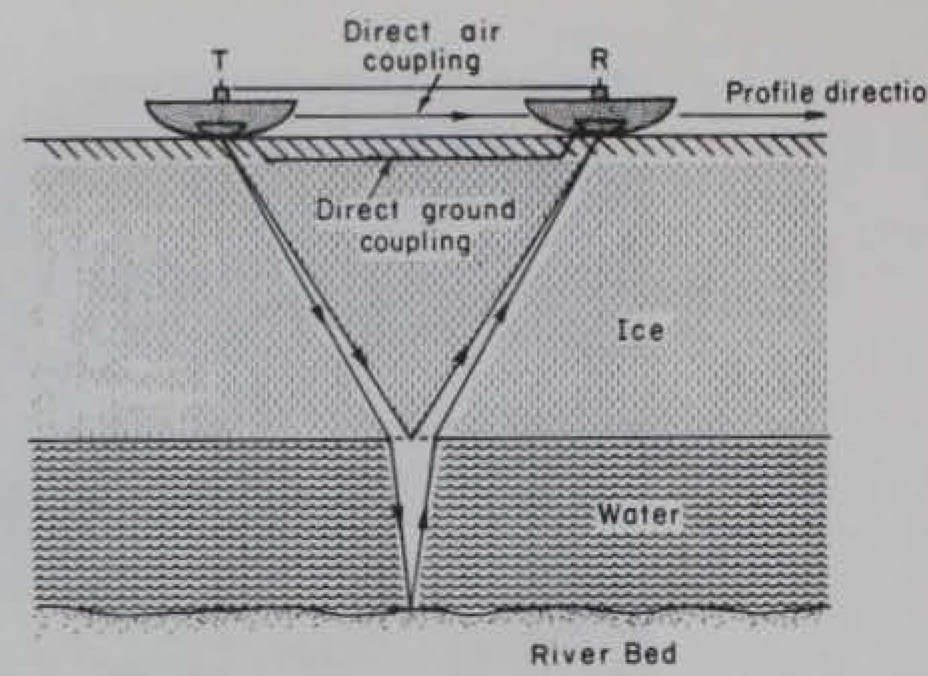


Figure 15. Idealized sketch of the radar antenna setup and ray paths of some potential propagation paths on an ice-covered river. Antennas are towed in tandem across the ice surface.

second technique, radar, uses short pulses of radio waves. Magnetic induction discriminates geologic features by seeking changes in ground conductivity through changes in the induced magnetic field. Radar seeks changes in dielectric properties through echo times.

Resistivity profiling (magnetic induction) derives ground conductivity from the amount of magnetic field coupling between two loop antennas located slightly above the earth's surface (Fig. 14). One loop, the transmitter antenna, generates a primary magnetic field of fixed frequency that couples directly with the receiver loop, but also induces electrical currents (sometimes referred to as "eddy" currents) within the ground. These currents then generate a secondary magnetic field that also couples with the receiver loop. The primary and secondary coupling depend on loop orientation and separation, but the secondary coupling depends on ground conductivity as well. The ratio of secondary to primary coupling is calibrated against conductivity for an assumed homogeneous earth, but interpretation schemes are available for discriminating layer parameters. Additional information on theory and calibration is presented by Arcone et al. (1979).

The instrument that we used for magnetic induction or resistivity profiling was the EM-31 manufactured by Geonics Ltd., of Toronto, Canada (Fig. 14). The instrument operates at 39.2 kHz with a loop to loop separation of 3.66 m. In its normal position, the loops are oriented horizontally (axis vertical) and they are fixed in a coplanar position. The instrument was held about 1 m above the ice surface, which results in about a 12% decrease in conductivity values from what would be obtained on the ground surface. The approximate depth to which conductivity information can be obtained in this mode is 7 m.

The subsurface radar system was manufactured by the Xadar Corporation and is similar to other commercially available systems. It has been shown useful for profiling ice depth and bathymetry of lakes and rivers (Annan and Davis 1977, Kovacs 1978, Arcone et al. 1982). This ground-based impulse radar employs separate transmit and receive antennas that were towed in tandem over the ice surface (Fig. 15). The antennas are specially designed dipoles that were horizontally polarized perpendicular to the profile direction and were separated 1.5 m. The transmit antenna radiates pulses of 10–20 ns duration at a repetition rate of 50 kHz. Several thousand of the pulses are then regularly sampled to convert the echoes into a lower frequency facsimile for graphic representation. Our system outputs eight scans per second, with each scan covering any one of several ranges between 50 and 2000 ns. A time range of 500 ns was found adequate for profiles of the river transects. Time and amplitude of the return are plotted and graphically display an apparent profile of the subsurface interfaces (Fig. 16).

The horizontal axis of the radar graphic record is calibrated to antenna position by event markers artificially recorded during the survey. The ver-

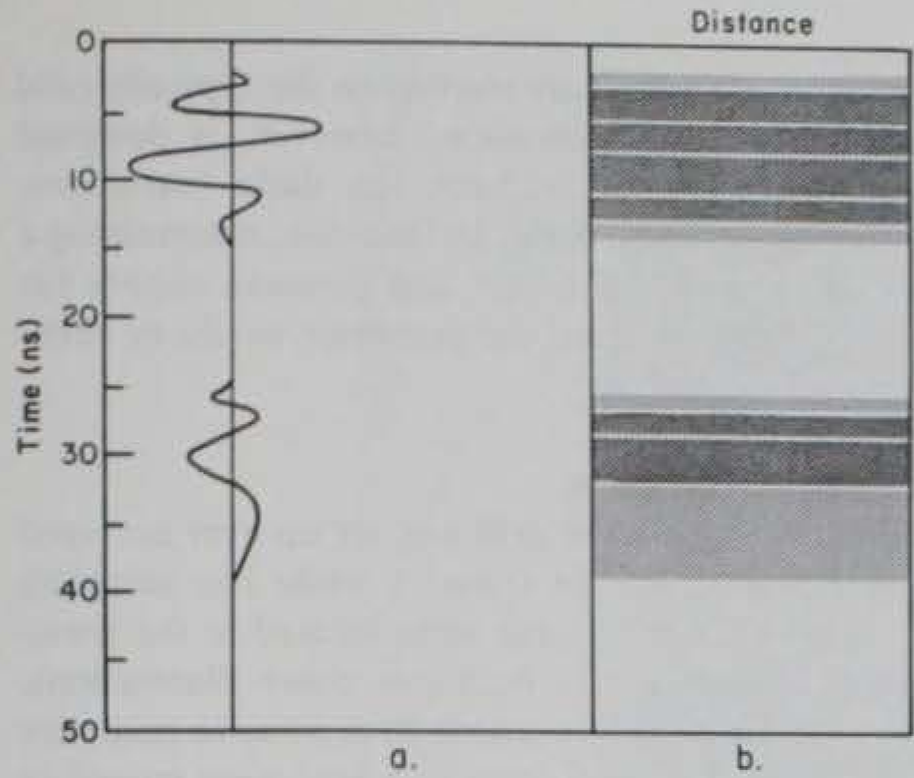


Figure 16. Idealized radar pulse returns (a) and an equivalent graphic display (b), should these returns remain constant with distance.

tical axis is echo return time in nanoseconds and represents the round trip from antenna to target and back. Interpreting a record means converting echo time into distance, a procedure that requires knowledge of radio wave velocity in the materials being investigated. Radio wave velocity in air is 30 cm/ns, in ice it is about 16.7 cm/ns, and in cold water near 0°C, it is about 3.3 cm/ns. Since frazil ice is a combination of ice and water, its radio wave velocity can cover almost 45% of the range of velocity available for electromagnetic waves and can cause substantial difficulty in interpretation. Our pulse spectrum was centered near 130 MHz, which is fairly well out of the dispersive range for water near 0°C and precluded the possibility of pulse waveform distortion.

A single pulse wavelet emitted during the Tanana River survey lasted approximately two cycles or 16 ns. We can therefore calculate the minimum detectable water depth for a given ice thickness. Such a calculation is necessary because the leading edge of the river bottom echo may overlap with the trailing edge of the ice bottom echo and thus produce a radar record falsely indicating no open water beneath the ice cover. Referring to Figure 15, we assume rays refract nearly vertically into the water because of the large contrast in velocity between ice and water. If the depth of the water is d, then the travel time in the water t_w is

$$t_w = 2d/V_w \qquad (1)$$

where V_w is the velocity in the water. This delay must be about 16 ns to allow the ice bottom reflection to separate from the water bottom reflection. The value d = 26 cm or roughly 1 ft is about the minimum discernible depth for this study.

Shelter and icing control

Standard kerosene-fueled shop heaters of 50,000 Btu (53×10^6 J) and 100,000 Btu (106×10^6J) were used to control icing of equipment and warm up engines before starting. The 100,000-Btu unit was used for rapid thawing of items that would not readily be damaged by excessive heat. The smaller 50,000-Btu unit was used for the more heat sensitive items as well as for drying gloves and warming hands. Electrical power for the heaters and other electrical equipment such as the current meter was supplied by a portable, 4-kW, 120-V, single-phase electric generator manufactured by Power Guard. It has a 23-A output at 1800 rpm and is powered by a Briggs and Stratton 4-cycle engine of 8 hp (6000 W). The unit weighs 63.5 kg.

An insulated tent (2.5 by 3 by 2 m high), manufactured by Weatherport, was assembled atop a specially fabricated metal framework with skis (see cover illustration). The dimensions, portability and light weight were particularly suitable for this project, allowing it to be easily towed behind the Bombardier and located over each access hole for sampling. The tent was heated to prevent icing of sampling equipment.

Surveying equipment

The ice surface and water level elevations along the transect were surveyed using a self-leveling level and a collapsible fiberglass rod. Hole distances from benchmarks located on the northern bank were measured using a 100-m metal tape.

Miscellaneous equipment

Other pieces of equipment included a calibrated thermistor and portable Kiethley meter for measuring water temperature, and a portable YSI meter for measuring water conductivity and salinity. We also used a frazil ice sampler developed for frazil deposits beneath sea ice (Rand 1982) in an attempt to obtain undisturbed samples of frazil ice.

FIELD TECHNIQUES AND METHODOLOGY

In this section, we describe how the program was actually conducted under field conditions, including the logistics of movement, drilling and sampling techniques, and any limitations or problems with the sampling scheme or equipment that were identified during field work.

To be as efficient as possible and effectively use available personnel, field procedures were designed around the concept of a work train. All major pieces of equipment and the tent were towed on-site, in the order of their use, from hole to hole. Personnel worked on either drilling and coring the ice cover, or measuring and sampling through each access hole. Although six people were often available, the entire operation was most effectively conducted using five. Two worked on drilling and related activities; three worked on sampling and related activities. Geophysical monitoring was conducted separately after the cross-section measurements were completed.

Logistics

Because of security reasons, all equipment and supplies were moved to and from the site daily and stored at a location about 3.2 km from the field site. This required about 1½ hours daily for setup and breakdown. Equipment was loaded onto sleds and the Bombardier, and the drill and tent were towed behind the Bombardier (Fig. 3). Field personnel traveled on snow machines towing sleds containing sampling gear and the generator (Fig. 4). Several key pieces of gear, such as the snow machines and heaters, were stored in a warm place each evening for easy startup on the typically cold mornings. Our operation, however, is designed for work on ice without the daily tear-down, where this can be done. In that case, maintaining a portable infrared heater and propane supply for daily warming up of the generator would be sufficient.

Drilling procedures

Once on site, the drill was set up over surveyed positions along the transect while the sampling tent and sampling gear were located at the previously drilled access hole (see cover illustration). We set the generator about 30 m away to minimize the noise. The drill, tent and gear were moved in tandem as each new access hole was drilled and sampling through the previous hole was completed. Holes were spaced along the transect at a 10-m interval.

On very cold days, below about -18°C, it was customary practice to warm up the drill motor with the kerosene heaters, and subsequently the tent and equipment before work began.

Following warmup, the snow was removed from the hole site and drilling begun. Each site was first cored continuously using the CRREL ice-coring auger. This core was then logged and stored frozen in plastic tubing for laboratory analyses of its debris content, grain size and other characteris-

Figure 17. A typical undisturbed core of the ice cover obtained with the CRREL ice-coring auger, with plastic tubing and other items for packaging core for cold storage.

Figure 18. Access hole produced by augering four 14-in. (35.6-cm) diameter holes side-by-side in a cloverleaf pattern. Frazil ice of various types and water fill the hole just below the top of the ice cover.

tics (Fig. 17). We did not encounter any problems in coring the ice cover.

Next, the access hole was augered. Because of the dimensions of the bed material sampler, we had to auger four holes side-by-side in a cloverleaf pattern to produce a hole with dimensions of about 60 cm^2 (Fig. 18). Our other samplers could have been used with only two holes augered side-by-side. The average time to cut a single hole was about 10 minutes, so cutting the four holes required about 40 minutes.

The rate of penetration by the auger varied, depending upon the amount of congealed frazil slush that was encountered. Cutting rates were rapid where columnar black ice was encountered, typically where open water underlay the ice cover. Very slow rates were caused by thick layers of porous, wet, congealed frazil ice or slush that occurred within the lowermost part of the ice cover. Stagnant water and frazil deposits were typically located beneath the ice at these locations. Frozen slush adhered to the auger flights and cutters, essentially stopping its advance through the ice (Fig. 7).

In addition, some difficulties resulted from locating the four holes next to each other. Once a single hole was cut and water rose into the hole, centering and then maintaining the location of the auger was often difficult. Typically, incomplete cutting of the ice that near the base of three of the four holes resulted in a lip of ice that had to be removed with an ice chisel. We found that the best procedure was to drill each hole, in succession, to within several centimetres of the base of the ice cover, and then complete them in succession. These problems could be eliminated by using a single auger of about 60-cm diameter.

Data collection

Before measurements could be taken, any drill cuttings or frazil ice that filled the hole had to be removed. This ice was scooped from the hole using a skimmer (Fig. 19a); however, in the large holes, the process of clearing was too slow. Holes of 3-mm diameter were therefore drilled through a coal shovel to produce a much larger version of the skimmer (Fig. 19b). At locations with currents, frazil in transport often continually moved into the access hole and had to be removed between each sampling. At locations where frazil deposits extended below the ice cover, access holes could not be cleared.

After measuring ice thickness, water depth and water level relative to the ice cover height, current velocity was measured. The magnitude and direction of the current velocity were determined with the electromagnetic (EM) current meter, beginning at 15 cm above the bed and then at each suc-

a. Commercially available skimmer used for ice fishing.

b. A more efficient skimmer—a coal shovel with holes drilled through it.

Figure 19. "Skimmers" for removing frazil ice from access holes.

cessive 30-cm interval. Meter readouts were observed for between 20 and 60 seconds to account for natural variability in the flow and the range and average velocity were recorded. We found no significant problems with use of this current meter and found it useful in delineating the locations of stagnant frazil ice deposits without flow, while clearly delineating the movement of water at the base of such deposits.

Velocities measured with the ice vane meter were compared to EM meter readings in selected holes. Standard procedure for this instrument was followed, with a 45-second interval typically used for counts. Measurements by the EM and ice vane meters were comparable at the higher velocities but differed significantly at low velocities (below ≈ 0.3 m/s). Since the USGS recommends not using this current meter at low velocities and since the EM meter was found accurate during calibration at these velocities, we assume the EM meter readings to be correct. We do not, however, have any comparative calibration tests of each instrument.

Although the EM meter measured velocities when moving frazil ice was present, we are not certain of its accuracy because frazil particles hitting the probe can produce readouts of an apparent velocity. Similarly, in partly consolidated and apparently porous frazil ice deposits, measurements suggested water movement through the porous media but, again, because of boundary effects, these values are probably not accurate. Some flow within the frazil bodies probably takes place, and a possible method to measure this flow would be to insert the EM sensor in a section of plastic well screen within the frazil deposit. This would eliminate contact of the sensor and ice particles, while not obstructing water flow.

Sampling the suspended sediment load followed the velocity measurements. After mounting the sampler on the sectioned rod, we lowered it to the river bed and raised it to the bottom of the ice cover at a constant rate. Normally, one or two descents and ascents were needed to fill the 1-L bottle to about two thirds full in water depths of about 3.0 m. Sampling within the heated tent prevented problems with freezeup of either the sampler's nozzle or vent hole.

The suspended sediment sampler did not obtain a representative sample in slow moving frazil or frazil deposits because of clogging of the nozzle with frazil particles. Holes with stagnant ice to the bed were not sampled for suspended sediment, while those with frazil deposits to a limited depth beneath the ice cover were sampled only below the deposit.

It is also clear that use of the standard depth-integrating sampler is not completely appropriate for through-the-ice measurements. The reason is that raising and lowering the sampler through the water within the access hole, which at locations on the Tanana River exceeded 1.2 m in depth, or through the water-saturated frazil ice deposits, introduces an error by sampling this water. A sampler is therefore needed that can be opened just below the ice cover or base of the frazil deposits, and then closed before it is pulled from beneath the ice or frazil to the surface. In this way, only those sections of the water column below the ice cover would be sampled.

Bedload was sampled next, the sampler being lowered and raised on the sectioned rod with its orifice facing downstream, and then positioned with the orifice upstream and parallel with the river bed. The sampler was held in this position for 30 seconds, pulled vertically upward away from the bed about 30 cm and then tilted back, in order to limit the amount of frazil or other material that might enter the sample bag during ascent. Nonetheless, when thick frazil deposits were present below the ice cover, it still entered the bag. Because fine- to coarse-grained sand is present within the frazil ice, this may introduce an error in the bedload calculations. One modification that would solve this problem might be the addition of a spring-mounted, messenger activated trapdoor. This door would be opened at the bed and then shut after sampling was completed before the sampler is pulled away from the bed. This modification would require testing to define what changes may alter the sampler's hydraulic efficiency, so that winter data would be comparable to data gathered using a standard sampler during summer.

An additional requirement found necessary in the field was the reuse of the bedload sampler bags. Detaching and reattaching the bags is time consuming and, when cold, very difficult. Instead, we found that by removing the seam at the downstream (bottom end) of the bag and sealing it with a removable clamp (Fig. 11), we could wash the entire sample out of the bag into a cloth sample bag. We used cloth sample bags to allow the excess water to drain through them and to minimize loss of sample while trying to wash it out of the bag through the sampler's orifice. We found the seams of the bag and its attachment with the metal frame poorly designed for extraction of the sample by washing, however, because they trapped sand that could not be removed. The warm environment of the tent kept the mesh of the bag free of ice for repetitive use.

Bed material was the last sediment sample taken because this sampling disturbs the water column and bed configuration. The Peterson dredge was suspended from a hand-held rope, after it was slowly lowered to just below the ice cover. The rope was then released and the dredge allowed to free fall to the bed. Impact with the bed releases a latch clamp that allows the clam shell to close as it

Figure 20. Sled-mounted tripod with portable winch. Tripod can be positioned over access hole and various samplers raised or lowered with the winch cable.

is pulled away from the bed. After pulling it back to the surface, we opened it over a large metal pan (Fig. 13). The sample was then washed from the pan into a cloth bag.

In practice, two to three drops of the dredge might be required because of the coarse composition of the bed. Gravel-size particles can become wedged between the jaws, allowing finer material to be washed from the sample as it is raised. In such cases we attempted to sample a different part of the bed in each drop by repositioning the sampler beneath the hole. Also, wherever stagnant frazil ice extended some depth below the ice cover, the sampler did not close properly because the drag exerted on the sampler as it fell through the frazil was sufficient to release the latch clamp and allow it to close before its impact with the bed. This was especially a problem in water of 2.4 m or less depth. Similarly, the bed material could not be sampled with the dredge when frazil deposits extended to the bed.

After using this heavy sampler by hand, we recommend that a sled-mounted tripod with a portable winch (Fig. 20) be used to lower and raise this or any other heavy sampler. Its use would make it easier to position the sampler over the hole center, to lower it beneath the ice for release, and particularly to retrieve it after it is full. The tripod sled could be towed behind the sampling tent and readily positioned over the hole whenever needed. Similarly, a standard bedload sampler or point-integrating suspended sampler could be raised and lowered with the cable and winch. The large diameter of the hole and the slipperyness of the ice or snow cover, once wet, make the use of a hand-line a bit perilous and thus for safety reasons, a tripod system is recommended.

Once the sampling and measurements were completed, we covered the hole with a sheet of plywood. This procedure is highly recommended since the 60-cm hole is large enough for a person to fall through. Usually by the next morning, an ice cover had formed that would support the weight of a person and the plywood could be removed.

Geophysical analyses

Geophysical profiling was conducted independently of the down-hole data collection. The apparent resistivity meter can be run by one person, while the subsurface radar unit requires two people. In both cases, standard procedures as outlined by the manufacturers were followed.

The apparent resistivity meter is fairly straightforward to use. After calibration to the conductivity of the river water, transects were established and marked at a 2-m interval. Cross section X4 was examined first, followed by transects located up or downstream of its location, including cross section X6. Measurements were made at 2-m intervals and recorded for full interpretation in the office.

Trends in conductivity values from the EM-31 can, however, be identified while conducting the survey. These trends indicate the presence of open water or frazil ice deposits beneath the ice cover. Identifying these locations would be useful, for example, when drill holes were needed only where open water areas were to be sampled. We found no problems with this technique and believe it to be very useful for rapidly identifying the basic distribution of open water and frazil ice deposits beneath an ice cover.

The subsurface radar unit continuously profiles each transect as it is towed over the ice surface. The graphic record that is produced must then be interpreted in the office after comparison to detailed physical measurements. Morey (1974), Annan and Davis (1976), and Arcone et al. (1982) describe data interpretation in more detail.

Experiences summary

This field study has identified certain limitations on sampling equipment that affect the accuracy of data, as well as techniques or methods that appear to work adequately on ice-covered rivers for obtaining data systematically, yet effectively, under conditions of extreme cold.

There are several critical elements of the field program:

1. *Heat.* In order to be able to repetitively and systematically sample under extremely cold conditions, portable heat sources are essential. These heat sources are needed for startup of mechanical equipment, for thawing and drying sampling and analytical equipment, and for personal safety. Without a heat source, rapid ice formation would quickly immobilize samplers, tools and analytical instruments. At a minimum a 100,000-Btu (106×10^6 J) heater is recommended for rapid thawing and drying of equipment not affected by intense heat.

2. *Insulated tent on skis.* An insulated shelter is essential to repetitive and systematic sampling under extremely cold conditions. Personnel as well as equipment function better under dry, warm conditions when the wind-chill factor is eliminated. We suggest that full zipper door openings be used for ease of movement of people and equipment into or out of the tent. A partial floor, shelving and racks with reliable tie downs for equipment storage in the tent are also important additions. For an extensive program in which sample processing and analysis on the river is required, a second tent with a complete floor and infrared heater would be necessary. All equipment should be organized and securely stored to prevent accidental loss down the access hole. The tent does cause one sampling problem. The rod sections have to be assembled and broken down as a sampler is used; for the suspended sediment sampler, in particular, this requires a well coordinated team.

3. *Electrical source.* There are several advantages to having electrical power on site. In our case, it was required for operating the drill winch and kerosene heaters. It was also needed for running the EM current meter because the low ambient temperatures ($< -20°C$) could rapidly reduce battery power below the minimum required to operate the instrument. Similarly, if complete sample processing and analytical chemistry ability is desired, electricity would be required. Further, we also found that without power for the heaters, it was very difficult to pull start gasoline powered engines (drill and generator) below about -20°C. If equipment is left on-site overnight, rather than removed daily as was required for our work, a small portable generator could be carried by hand to the site daily in order to start a portable heater which, in turn, could warm up the larger generator.

We identified several pieces of sampling gear and instrumentation that require design modification. In particular:

1. Remote control of the opening and closing of the nozzle on the depth-integrating suspended sediment sampler is needed to allow selective sampling of only the open water areas beneath the ice cover. A point integrating sampler could be used if more detailed data are required.

2. Remote control doors on the bedload sampler are needed to prevent infilling of the sample bag with frazil ice. The bag configuration and closure should be redesigned for rapid and complete removal of the sediment sample. The external support rod on the bag needs to be modified or excluded.

3. The bed material sampler needs to be reconsidered, particularly for use where thick frazil ice lies between the ice cover and river bed. A smaller sampler would decrease the size needed for the access hole, although a large volume of sample is still required to ensure that grain size analyses are representative. A remotely controlled closing mechanism would also prove useful on this sampler.

We also found that several new pieces of equipment are needed, which are not now available:

1. A sampler is needed for frazil ice in transport. This sampler might be similar in design to a bedload sampler, which could be suspended in the flow and have an orifice door that could be opened and closed remotely.

2. A tripod-mounted winch and cable should be mounted on a small sled and located over the hole center at each site for raising and lowering sediment sampling equipment.

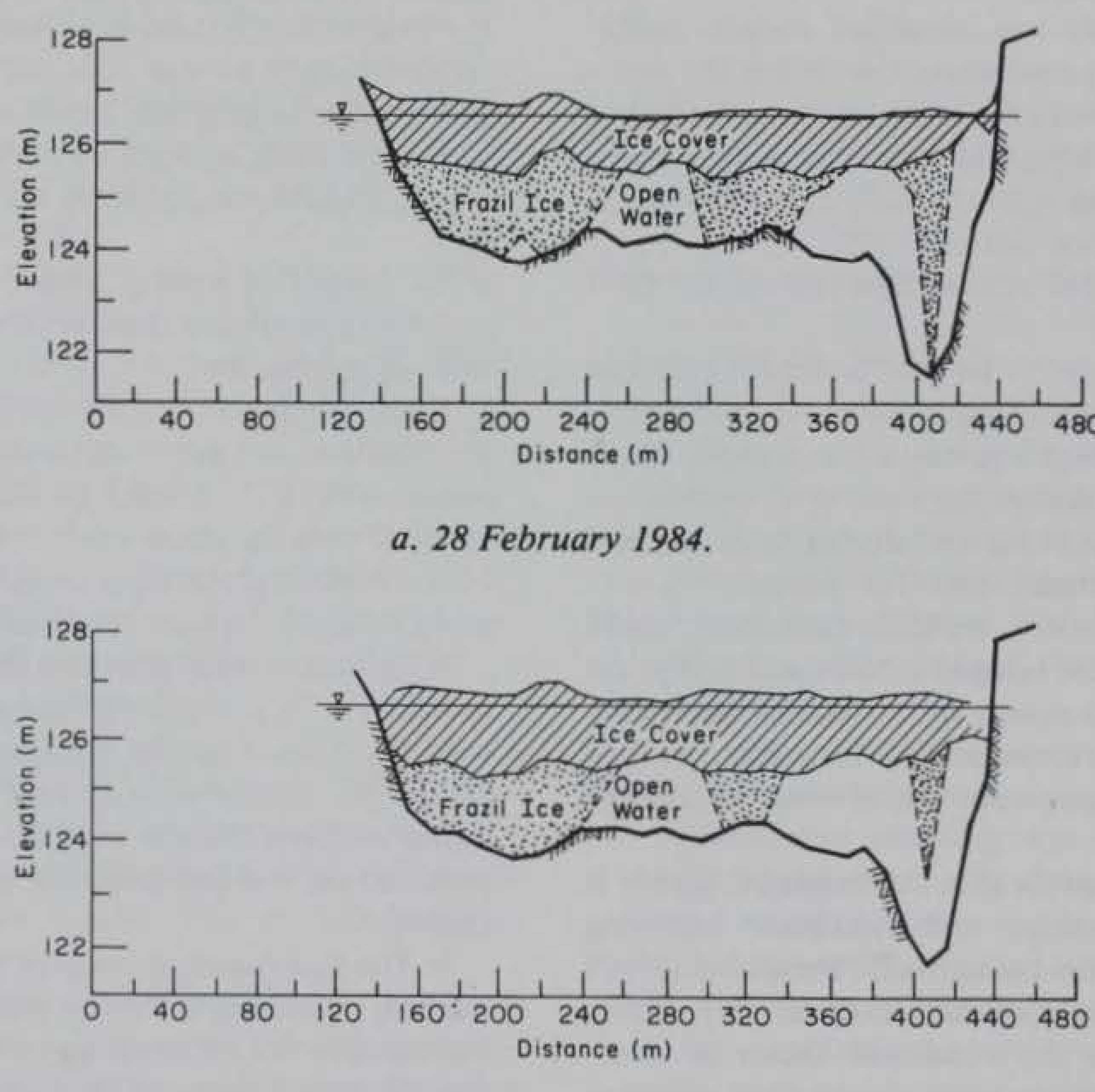
3. Frazil ice that is stationary beneath the ice cover, whether unconsolidated or partly consolidated, cannot now be sampled without disturbing its structure and distribution. The frazil ice sampler for sea ice (Rand 1982) did not usually retain a sample, and when it did, the ice structure was disturbed. Probing through frazil deposits indicated differences in the character of the frazil ice at different depths. These properties may affect river behavior and need to be defined.

MORPHOLOGY, TRANSPORT AND HYDRAULIC DATA

In this section, we present data from the detailed study of cross section X4 and morphological data from cross section X6, as well as data from the geophysical measurements. In addition, the winter 1984 data are compared to similar data gathered in previous years.

Mid-winter physical characteristics

The fluvial parameters defined by the detailed measurements of 28 February–5 March 1984 on cross section X4 included ice cover thickness and elevation, water depth, water temperature, loca-



a. 28 February 1984.

b. 30 March 1984.

Figure 21. Composite cross sections of transect X4 as defined by measurements. Ice cover thickness and configuration, river bed profile, and distribution of open flowing water, stagnant deposits of frazil ice and water level are shown. Northern bank on right. Distance from benchmark on south bank area.

tion and thickness of stagnant frazil ice, water velocity distribution and sediment transport data, including suspended sediment, bedload and bed material samples (Table 1).

A composite cross section, based upon these access hole data and surveying of cross section X4 (Fig. 21), illustrates the overall configuration of the upper and lower surfaces of the ice cover, the profile of the river bed, and the spatial distribution of open, flowing water and of stagnant deposits of frazil ice. The average water level is also indicated.

The ice cover surface was fairly rough, apparently resulting from jamming of frazil ice floes and pans at this location during ice cover formation in the fall.* The ice cover was frozen to the bed only adjacent to each bank and its thickness varied between 0.9 and 1.2 m, except along the north bank where it thinned to about 0.03 m. The reason for this thin ice along the north bank is not clear.

Debris, mostly clay- to sand-size sediment and minor amounts of organic material, was usually disseminated within the lower 0.6 to 0.9 m of the ice cover with quantities ranging from 0.3 to 60.5 g/L (mean 9.75 g/L, σ = 15.1) in 25 samples from cores at four locations. This ice was typically composed of congealed frazil, formed by freezing of frazil slush.

Typically, frazil ice deposits were partly consolidated and offered some resistance to penetration by the sampling rod and EM probe. This resistance was not uniform with depth and suggested a layered structure. Characteristics of the frazil crystals varied within these apparent layers from fine-grained, loose slush composed of individual disks, to individual small round grains, to well-defined aggregates of variable size and shape. Our attempts to sample the frazil ice deposits without disturbing them were fruitless, the frazil ice sampler being unable to retrieve any samples without remolding and mixing them in the process of sampling. Larger frazil particles also clogged the sampling tube.

The relationship between the ice surface elevation and the water level elevation is directly related to the location of the frazil ice deposits. In all cases (Fig. 21), the ice surface elevation above the stagnant frazil deposits exceeded the ice surface elevation above the flowing water. The areas of the apparent isostatic anomolies near mid-channel can be attributed to the additional buoyant forces exerted on the solid ice cover by the thick, partially consolidated frazil ice deposits. Preliminary com-

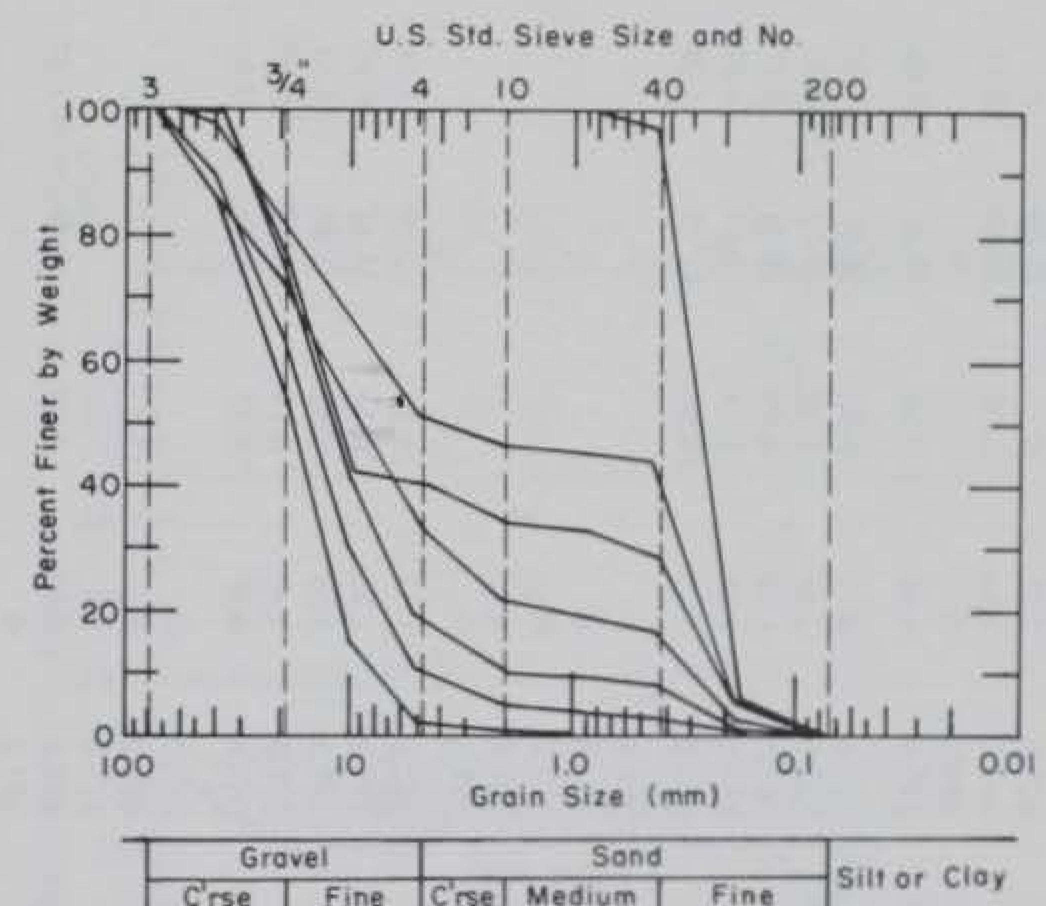


Figure 22. Representative cumulative curves of the grain size of bedload and bed material samples of cross section X4.

* Personal communication with D. Dinwoodie of CRREL-AK, 1984.

Table 1. Data summary for cross section at X4, Tanana River, 28 February–5 March 1984.

Hole no.	Station (m)	Effective depth (m)	Average velocity (m/s)	Area (m^2)	Q (m^3/s)	SS (mg/L)	SS (Mg/day)	Unit bedload rate (kg/m s)	Bedload (Mg/day)	D_{50} bedload (mm)	DM bedload (mm)	Flow direction* (deg.)
	439.7	0										
1	435.2	1.08	0	6.76	0	—	—	0	0	—	—	—
2	427.2	2.12	0	19.05	0	—	—	0	0	—	—	—
3	417.2	3.84	0.26	38.63	10.13	112.8	98.7	0.0002	0.15	—	—	287
4	407.2	0		0								
5	397.2	4.02	0.59	40.47	23.68	59.3	121.3	0.0003	0.26	—	—	336
6	387.2	2.19	1.05	22.07	23.28	189.6	381.4	0.0421	36.6	0.37	2.60	360
7	377.2	1.66	1.33	16.71	22.25	71.1	136.7	0.0594	51.6	5.09	7.21	339
8	367.2	1.89	0.49	19.01	9.27	65.3	52.3	0.0361	31.4	2.28	3.21	329
9	357.2	1.36	0.33	13.65	4.49	288.4	111.9	0.0271	23.6	0.28	0.70	340
10	347.2	1.11	0.36	11.19	3.99	92.6	31.9	0.0003	0.26	—		334
11	337.2	0										
12	327.2	0										
13	317.2	0										
14	307.2	0										
15	297.2	0										
16	287.2	1.57	0.23	15.79	3.66	98.5	31.1	0.0297	25.8	0.29	0.68	304
17	277.2	1.43	0.74	14.41	10.67	121.6	112.1	0.0741	64.4	0.31	0.38	339
18	267.2	1.28	0.90	12.88	11.54	69.5	69.3	0.0024	2.1	0.28	0.34	330
19	257.2	1.45	0.75	14.57	10.87	48.1	45.2	0.0228	19.8	3.09	3.68	338
20	247.2	0.67	0.52	6.74	3.51	48.1†	14.6	0.0001	0.09	0.27	0.31	332
21	237.2	0										
22	227.2	0										
23	217.2	0										
24	207.2	0.53	0.27	5.37	1.47	48.1†	6.1	0.0001	0.09	0.17	0.21	304
25	197.2	0										
Total or average				257.30	138.81	101.1	1212.6	0.0227	256.2	0.37	2.75	
Subtotal 439.7–347.2 (holes 1–10)				187.54	97.09	111.4	934.2	0.0237	143.9	1.00	4.08	
Subtotal 287.2–197.2 (holes 16–24)				69.76	41.72	77.2	278.4	0.0215	112.3	0.32	1.04	

* Relative to north.

† The concentration in these holes was not measured and assumed equal to adjacent hole (no. 19).

putations indicate that the increased ice surface elevation would result if the frazil deposits had a density of 60–70% ice by volume. Density measurements were not made in this study; however, densities of frazil ice deposits have been reported in the 50–70% range (Beltaos and Dean 1981).

Three separate, distinct, open and flowing areas of water beneath the ice cover were defined by drilling (Fig. 21). Each subice channel was characterized by different current velocities, discharges and sediment transport rates. The subice channels were separated by the deposits of frazil ice that extended from the bottom of the ice cover to the river bed. In addition, a small subice channel surrounded by stagnant frazil ice was observed on the south side of the cross section (Fig. 21).

Bed material samples ranged in texture from silty sand to sandy gravel (Fig. 22). The difference in texture among most samples resulted from a different proportion in the sand-size particle range. Coarsest samples were obtained beneath flowing water, as expected, while sandy materials were located beneath the stagnant frazil ice deposits (Fig. 21). The exception occurred within the channel on the north bank, where silty sand mixed with organic litter covered the bed beneath the deepest, but slowest flowing water. The bed was also apparently armored by gravel-size particles in some areas of high velocity. In locations on the edge of frazil deposits where velocities were less, probing and drag sampling suggested that the bed was mostly sand but had pebble-size stones lying on or partially embedded in it.

Hydraulic characteristics

Velocity, magnitude and direction were measured at each access hole in which open water was encountered. Average velocity in the water column ranged from 0 to 1.33 m/s (Table 1), with the maximum velocities occurring near the center of each subice channel and decreasing laterally toward the frazil deposits (Fig. 23). A significant difference in the velocity distributions occurred at stations 347.2–367.2 m where relatively low velocities were observed. This was an area in which we also observed a thick layer of frazil ice pebbles (described in detail later in this report) in transport. The decreased velocities may be attributed to an increase in roughness, as compared to a solid ice cover, which results from either the grain roughness of the pebbles at rest or their interaction during transport in this upper, mobile boundary layer. The average flow direction was relatively uniform except near the north (right edge) of the two major subice channels (Fig. 24).

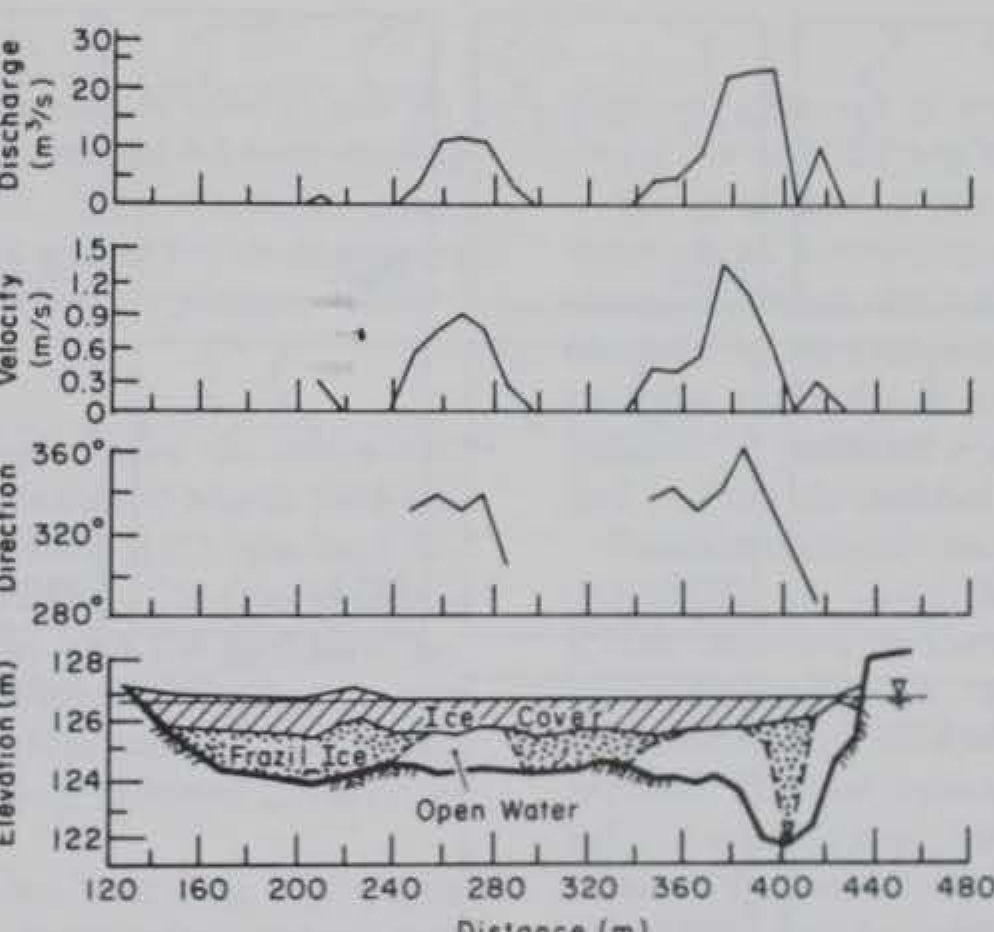


Figure 23. Velocity direction, magnitude and calculated discharge for cross section X4 on 28 February 1984. Northern bank on right.

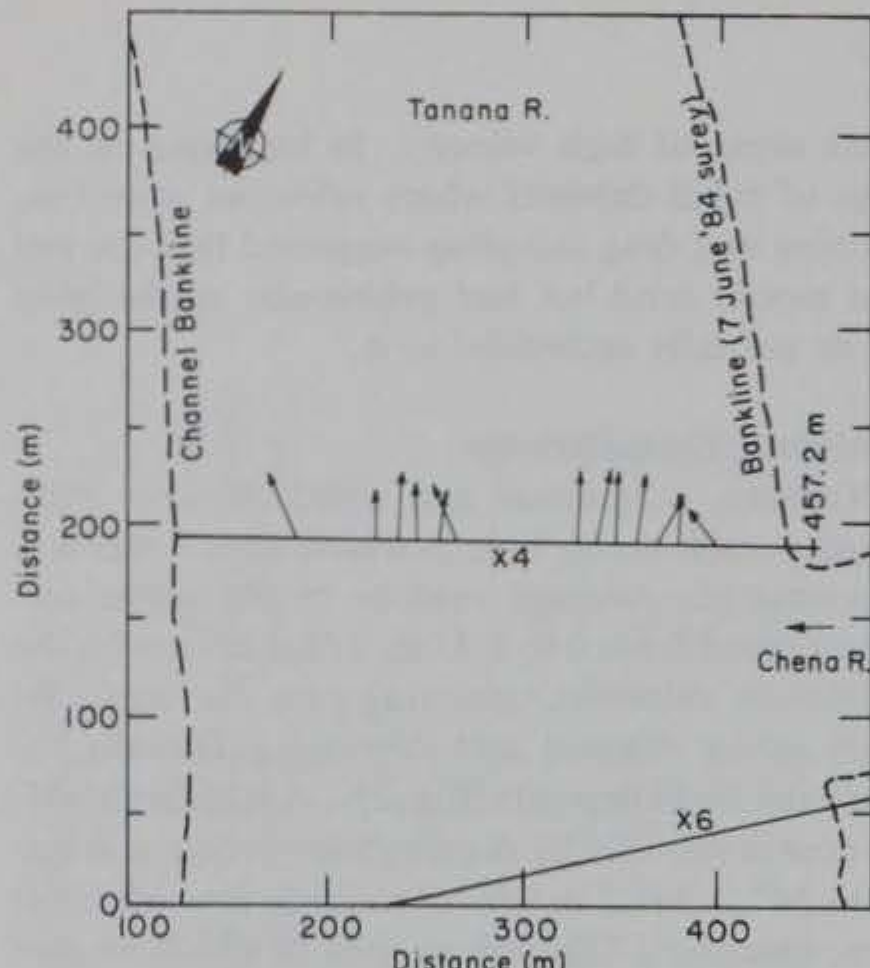
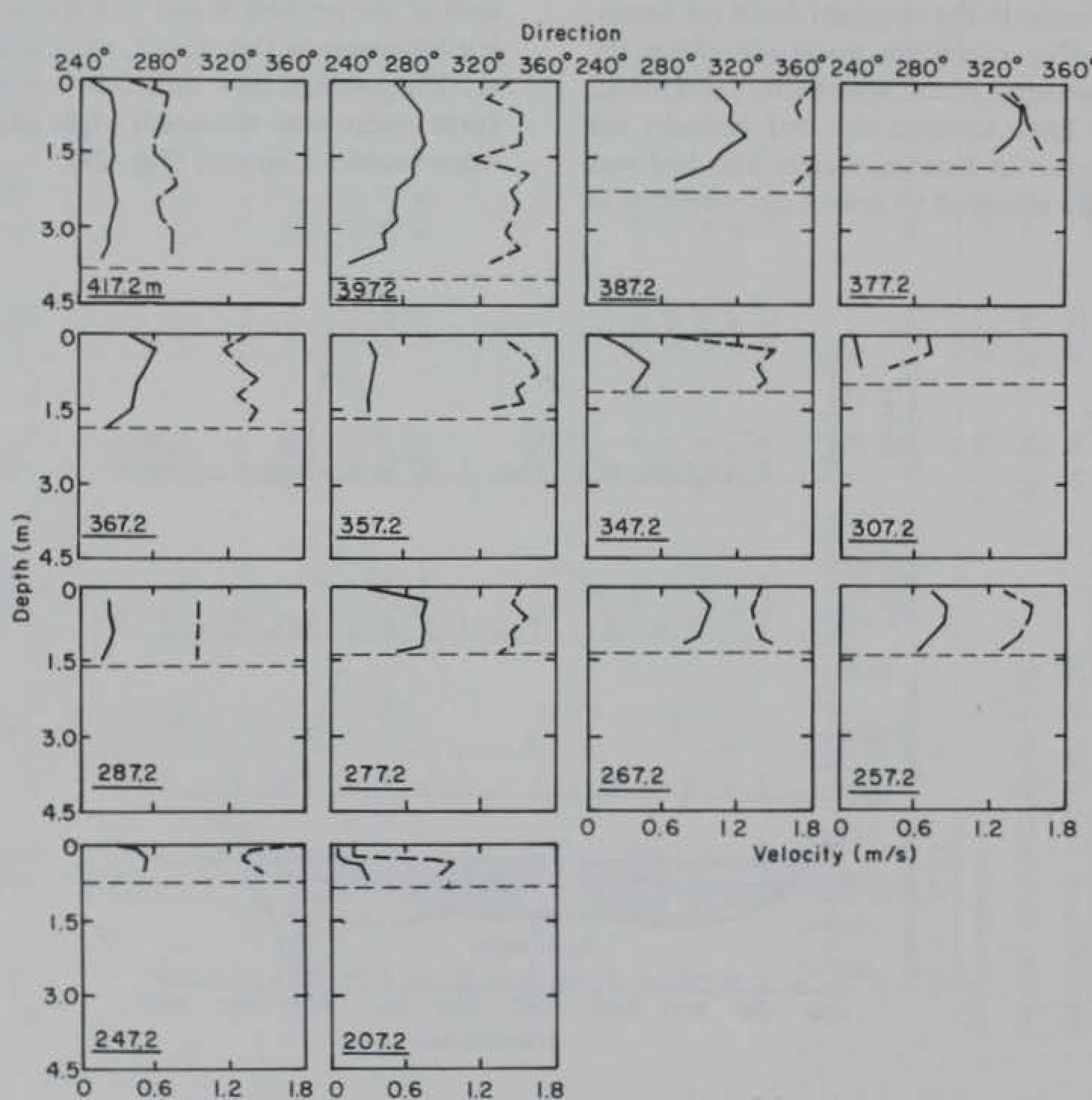


Figure 24. Plan view of Tanana River with direction of flow measured on X4 illustrated by vectors for average velocity.

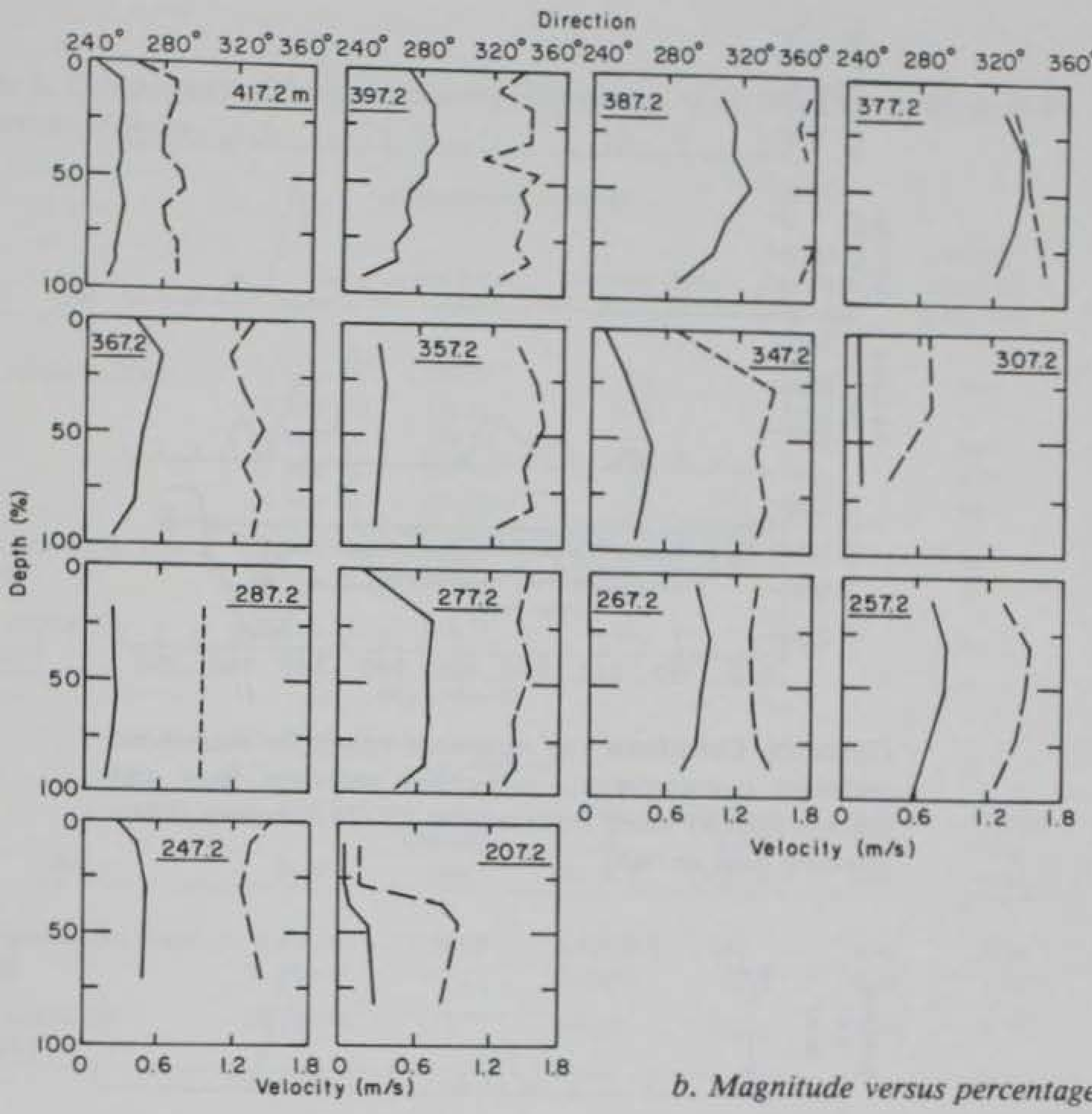
The vertical profiles of velocity and direction of flow at each access hole show considerable variability over the cross section (Fig. 25). The velocity profiles ranged from the commonly assumed double logarithmic distribution (e.g., station 397.2 m, Fig. 25) to a very flat vertical distribution through most of the water column (e.g., station 417.2 m, Fig. 25). The measured profiles indicate no distinct lateral pattern to the vertical velocity distributions, although there is generally a trend toward a logarithmic distribution in the north (right) subice channel and generally a flat distribution in the south (left) subice channel. Because of the apparent variability of velocity distributions, the computation of boundary roughness parameters and shear stress based on profile analysis (i.e., Larsen 1969, Calkins et al. 1982) has been postponed until multiple cross-section surveys and water surface slopes can be attained.

Calculations of the cross-section area and the velocity distribution within partitioned sections of each subice channel (Table 1) indicate that the discharge was not evenly distributed among the three



a. Magnitude versus depth.

Figure 25. Vertical velocity distribution in access holes (distance in metres from southern bank). Solid line for magnitude; dashed line for direction.



b. Magnitude versus percentage of depth.

Figure 25 (cont'd).

primary channels. The maximum velocity and discharge was in the central channel between stations 397 and 377 m (Fig. 23). Total discharge calculated at cross section X4 was 139 m^3/s during the sampling period of 28 February–5 March 1984.

Sediment transport

The total sediment load during the mid-winter sampling period of 28 February–5 March 1984 was 1469 Mg/day of which 83% (1213 Mg/day) occurred as suspended load and 17% (256 Mg/day) as bedload (Table 1). As with the hydraulic parameters, the sediment transport parameters also differed within each subice channel. Locations with frazil ice deposits were assumed to carry no sediment load.

The suspended sediment load (Fig. 26) closely followed the velocity distribution within each subice channel. The distribution of the suspended sediment concentration followed a similar pattern, with the exception that the maximum concentration was observed at station 357 m where a relatively low velocity was measured.

The grain size of this material typically ranged from silt to a very fine sand (Table 1), the maximum size being the same as the finest material sampled in the bedload. The clarity of the water and this similarity in grain size suggest that the sediment is probably transported mainly near the bed and not throughout the entire water column.

Bedload transport was observed only in the two central subice channels beneath the ice cover where, contrary to the hydraulic and suspended sediment parameters, the total rates were nearly the same in each channel (56–44%, Table 1). The bedload material typically ranged in size from sand to sandy gravel (Table 1). In the north central channel (station 347–397 m), the rate of transport and the size of the transported material (Fig. 27) were well correlated. In the south central channel (station 247–287 m), the material size and transport rate were not well correlated; in fact, a very

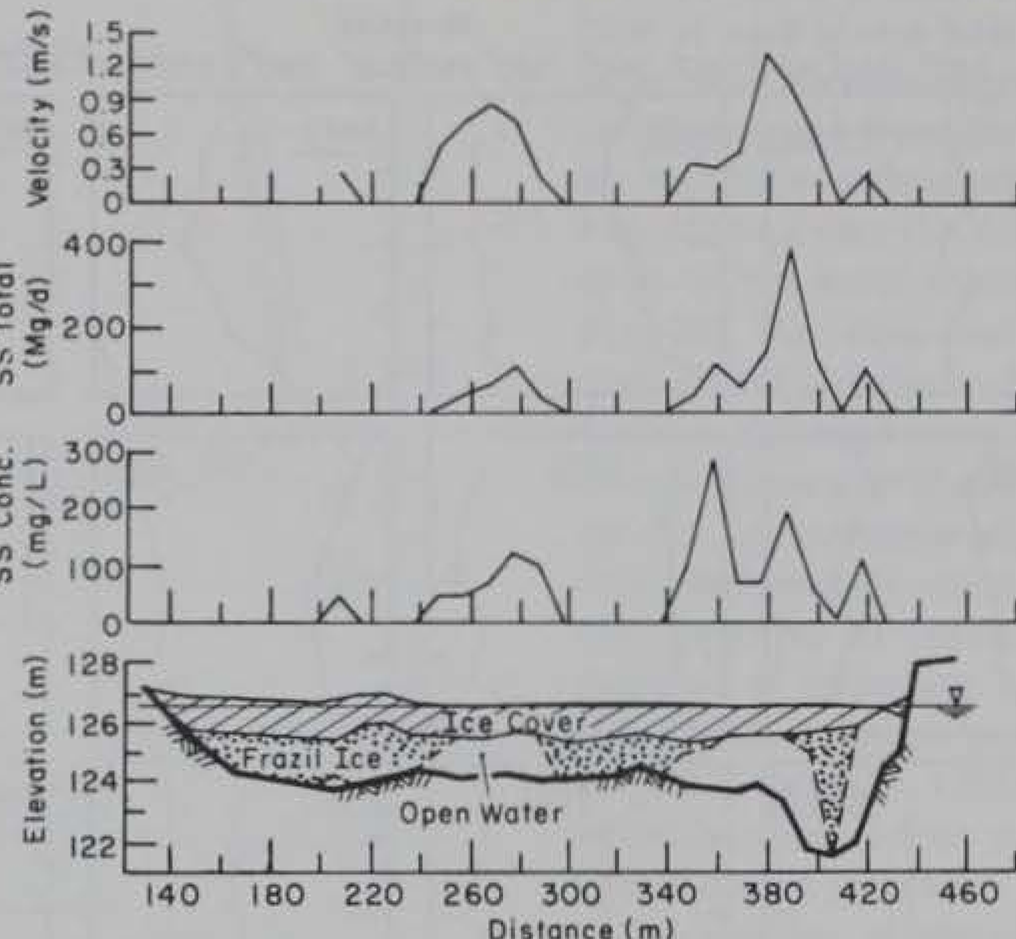


Figure 26. Calculated and measured values for suspended sediment concentration, suspended sediment load and average velocity along cross section X4 (28 February 1984). Northern bank on right.

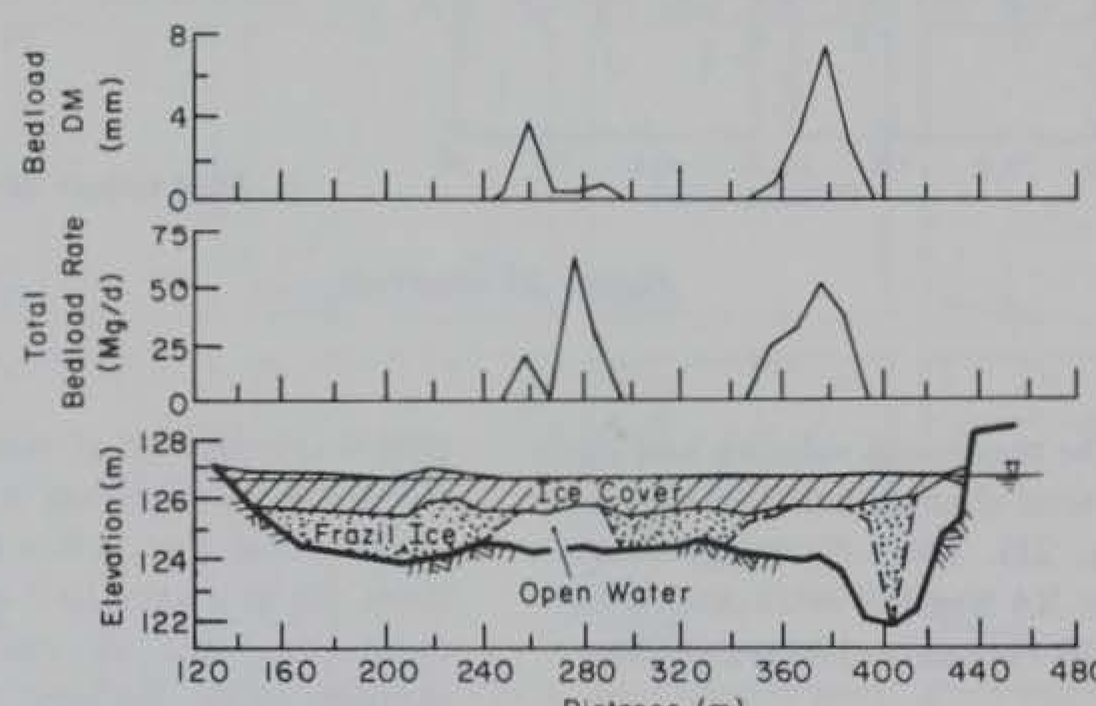


Figure 27. Measured bedload transport rates and mean particle size of bedload along cross section X4 (28 February 1984). Northern bank on right.

fine material (*DM* = 0.38 mm) accounted for the maximum bedload rate measured on the entire cross section (64.4 Mg/day, Table 1, Fig. 27).

Both suspended and bedload transport rates are similar in range to the transport rates measured by the U.S. Geological Survey during winter 1981 on cross sections located just downstream of cross section X4 at Byers Island and several miles upstream at Goose Island (Table 2, Fig. 1) (Burrows and Harold 1983).

The proportion of suspended sediment and bedload in the total sediment load undergoes a seasonal change. During summer, suspended load is about 100 times as large as bedload in this reach of the river (Burrows and Harrold 1983, Harrold and Burrows 1983). In contrast, the winter data indicate that the suspended load is 2–30 times as large as the bedload. The seasonal reduction in suspended load or "clearing" of the water column has been generally noted (e.g., Osterkamp 1975) but

Table 2. Comparison of winter sediment transport data on the Tanana River near Fairbanks, Alaska.

a. Suspended sediment

Site	*Date*	*Discharge (cm)*	*Concentration (mg/L)*	*Sediment (Mg/day)*	*Percent less than 0.062 mm*
Byers Island (USGS)	3 Mar 81	156.03	72	970	52
	5 Mar 81	156.03	152	2050	77
	11 Mar 81	159.14	127	1740	55
	17 Mar 81	159.14	65	893	41
	25 Mar 81	161.12	119	1660	65
Upper end Goose Island (USGS)	6 Mar 81	156.03	47	633	41
	24 Mar 81	161.12	51	709	51
Cross section X4 (CRREL)	28 Feb 84	138.75	101	1213	—

b. Bedload

Site	*Date*	*Discharge (cm)*	*Unit rate (kg/m s)*	*Sediment load (Mg/day)*	*Median size (mm)*	*Average size (mm)*
Upper end Goose Island (USGS)	6 Mar 81	156.03	0.03650	337	0.39	3.16
	24 Mar 81	161.12	0.00252	23.3	0.40	1.81
Cross section X4 (CRREL)	28 Feb 84	138.75	0.0227	256	0.37	2.75

the reason for this reduction has not yet been fully explained. Glaciers provide a portion of the water and sediment transported by the Tanana River; reduced melting and discharge of both water and sediment from glaciers during fall and winter may be the significant factor in this reduction.

Late winter physical characteristics

The morphological characteristics of cross sections X4 and X6 measured on 30 March 1984 included ice cover thickness and elevation, water depth, and location and thickness of stagnant frazil ice deposits.

The two sets of morphological measurements on cross section X4 show that in general the changes that have taken place over the course of one month near the end of the winter season are all related to the frazil ice deposits (Fig. 21). Although the deposits of stagnant frazil ice remained in the same general locations, the deposits were reduced in size in two ways. The central and north deposits appear to have been scoured by flow in the subice channels (no discharge or velocity measurements are available for verification). In addition, deposits were reduced in thickness by solidification of the frazil deposit and ice cover growth. These changes reduced the area of frazil ice below the solid ice cover from 51 to 40% (Table 3).

Other alterations include the disappearance of the small subice channel previously located in the southernmost frazil deposit near station 200 m because of filling with frazil. In addition, there was no ice cover growth in the flowing subice channels, except near the north bank where an unusually thin ice cover was observed on 28 February 1984. The net effect of ice cover growth over the frazil deposits and maintaining the ice cover over subice channels was a slight reduction (5%) of the total cross-sectional area beneath the solid ice cover (Table 3).

The morphological characteristics of cross section X6 measured on 30 March 1984 are generally similar to those of cross section X4, with the exception of the presence of two sand bars between stations 410 and 420 m and between 310 and 370 m (Fig. 28). The ice cover lies directly upon the bar surfaces. Because of these bars, the channel bed

Table 3. Calculated areas for cross sections X4 and X6.

Date	*Water surface elevation (m)*	*Area below solid ice (m²)*	*Open water area below frazil ice (m²)*	*(%)*	*Area of frazil ice (m²)*	*(%)*
		Cross section X4				
28 Feb 84	126.55	508.6	249.6	49	259.0	51
30 Mar 84	126.61	482.4	290.3	60	192.0	40
		Cross section X6				
30 Mar 84	126.67	360.4	239.7	67	120.7	33

has more relief than at cross section X4. Excluding the bar surfaces, the river bed is relatively flat with a maximum relief of less than 1 m.

Four distinct subice channels with flowing water were observed, two created by the sand bars, and the largest two created by a large frazil ice deposit (Fig. 28). Frazil ice made up 33% of the total area beneath the solid ice cover (Table 3). Although no velocity measurements were made on 30 March 1984, observations on that date indicated that the subice channels in cross section X6 are characterized by different velocities and discharges.

A comparison of cross sections X4 and X6 (Table 3) indicate that the total area below the solid ice cover is 34% larger at X4 and includes both more open water and frazil ice. Without velocity measurements at both sites, we cannot determine precisely why the percentage of area of open water versus stagnant frazil ice deposits differs within the short reach of river between the two sites.

We can, however, cite two factors that account for most of the difference in areas of open water. The first and most important factor is that what appears as a deep channel on the right bank of cross section X4 (Fig. 21) is actually a scour hole formed at the confluence of the Chena and Tanana Rivers just upstream of the cross section (Chacho et al., in press). The water velocities in the vicinity of the scour hole are very low during the winter (Table 1), resulting in very little discharge within a large proportion of the cross section. Further, the discharge at cross section X4 is larger than at X6 because of the additional flow from the

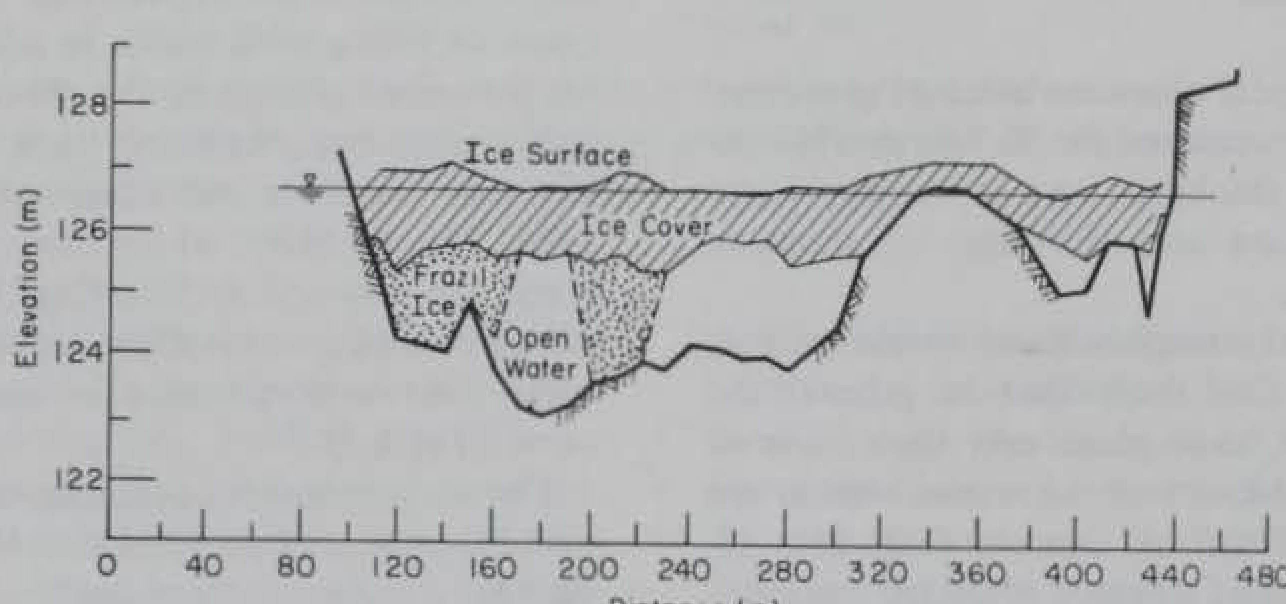
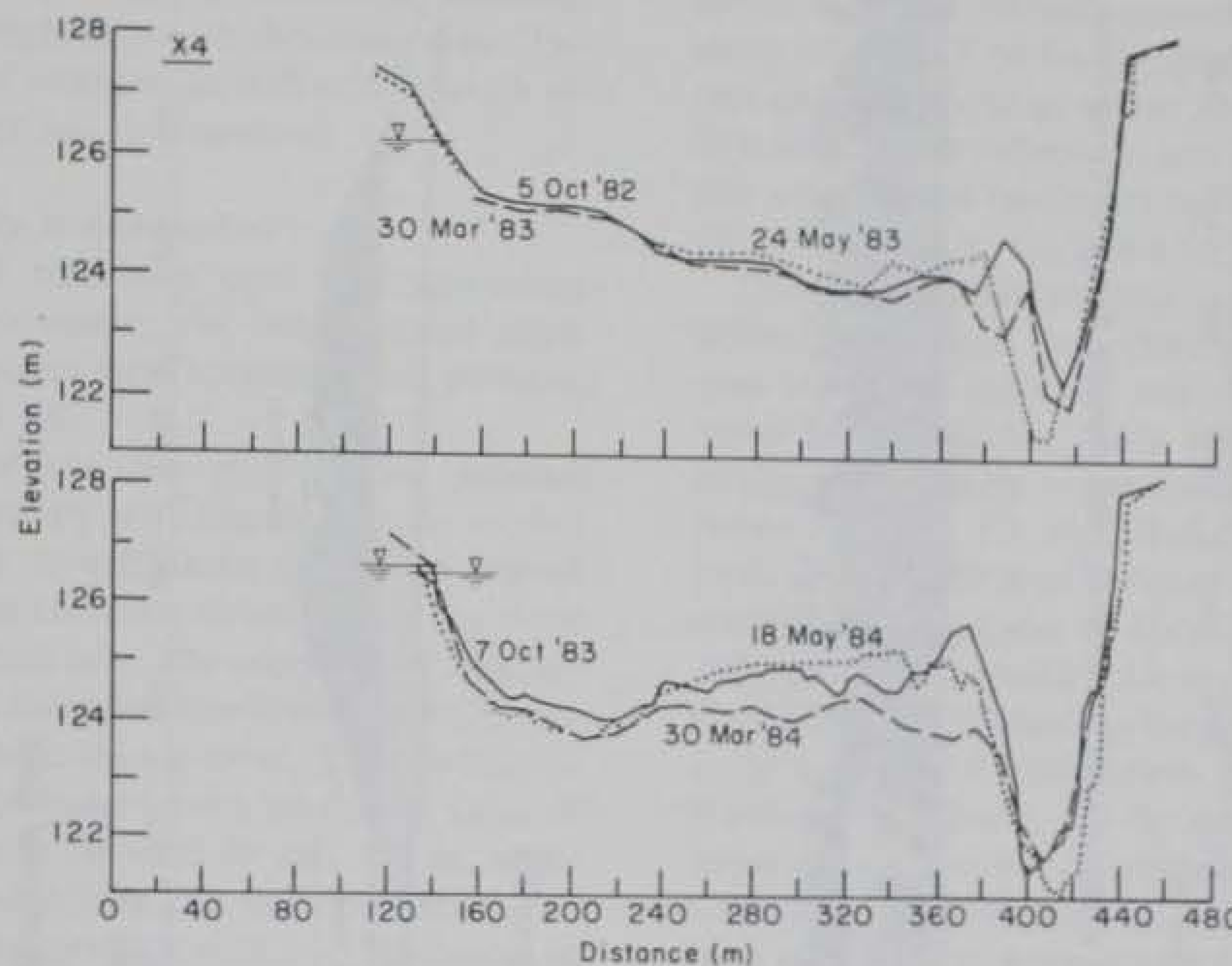


Figure 28. Composite cross section X6 as defined by measurements. Northern bank on right.

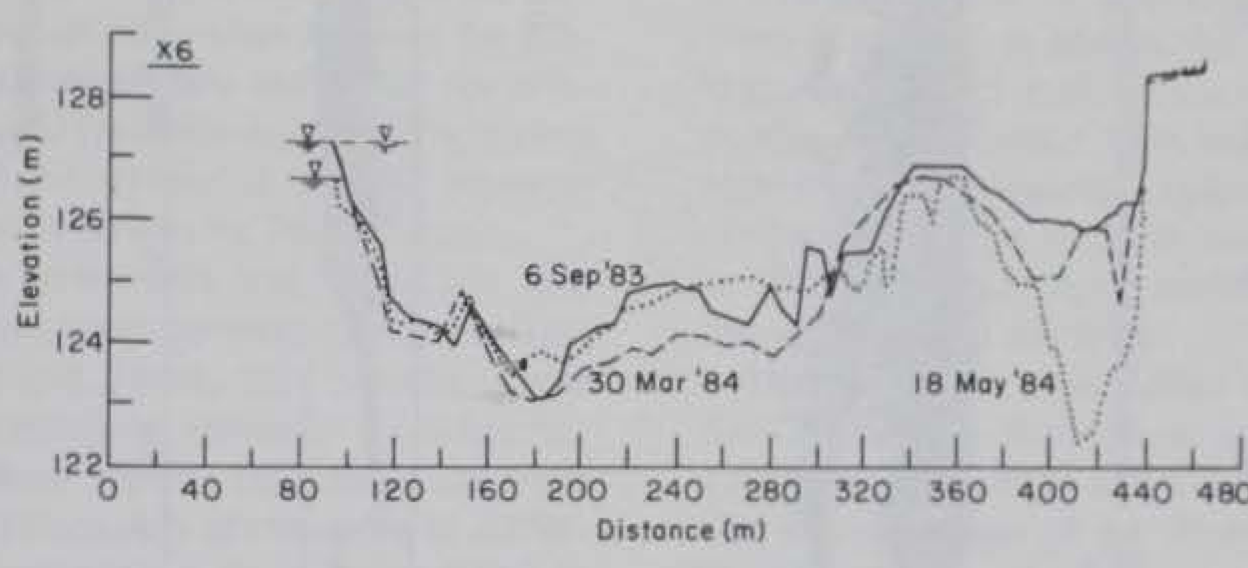
Chena River. On 30 March 1984, the Chena River flow was 8.5 m^3/s, while the Tanana River above the confluence was 139 m /s.*

Seasonal morphology

We examined changes in channel cross-section configuration by comparing the winter data with the bed profile data measured just prior to freeze-up and just after breakup (Chacho et al., in press). The bed profile sequences at cross sections X4 and X6 are compared in Figure 29. These comparisons suggest that seasonal changes in various parameters result in seasonal fluctuations in the bed profile. The bed profile beneath the ice cover is



a. Cross section X4.

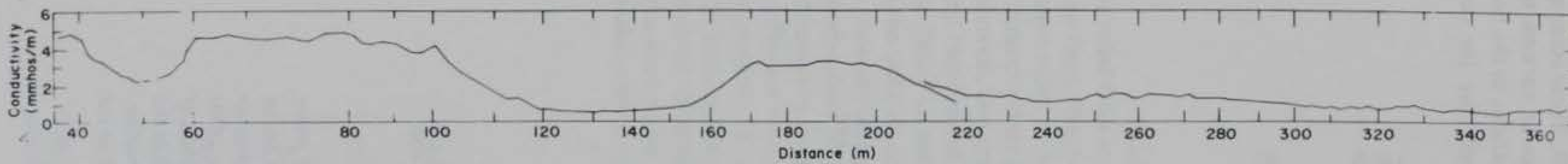


b. Cross section X6.

Figure 29. Comparison of bed profiles of cross sections X4 and X6 from 1982 to 1984 with the data of this study. Significant changes in the river bed at cross section X4 during the formation and presence of an ice cover are suggested by comparison between the final profile of the open water season (7 October 1983) with the bed profile on 18 February 1984. Aggradation of the bed and formation of the bar at the mouth of the Chena River took place during each summer, while the winter bed profile is flatter, with less relief and lower average profile elevation. Changes at cross section X6 from summer to winter and during winter with an ice cover present are similar to those at X4. North bank on right.

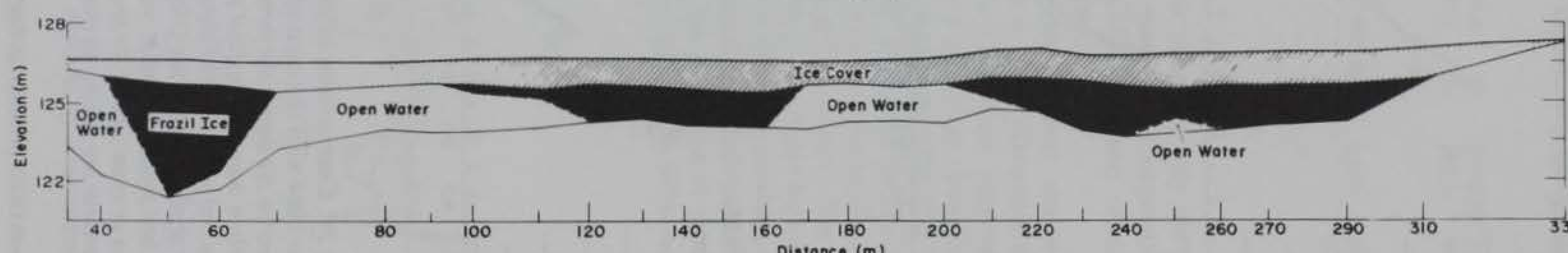
---

* Personal communication with USGS personnel in Fairbanks, Alaska, 1985.



a. Conductivity profile. Conductivity values differ significantly in areas of open water and frazil deposits beneath the ice cover.

b. Radar profile.



c. Measured cross-sectional data.

Figure 30. Geophysical data compared to measured data along cross section X4; looking upstream; north bank on left; distances from north bank benchmark. (Lower scale varies with the rate at which the antenna was pulled across the ice.)

typically of lower relief and flatter than during summer months. Average channel elevation is similarly less. The data suggest that decreasing discharge in fall, coupled with eventual ice cover formation, are important variables affecting bed degradation. In contrast, rising discharge during and following breakup leads to increased sediment transport and aggradation in the study area. The precise timing of changes, as well as how much effect the ice cover has, is unknown.

Geophysical data interpretation

The apparent resistivity data and subsurface radar profiles compare well with ground truth data from the access hole measurements on cross sections X4 and X6.

Figure 30a shows the conductivity profiles based upon resistivity profiling along cross section X4. The profile reveals three regions of higher conductivity that correlate directly with the three flowing subice channels. The areas of low conductivity separating them are locations where deposits of frazil ice underlie the ice cover. The conductivity values for open water have a maximum value of about 4.5 mhos/m between 60 and 100 m, while between 160 and 210 m, its value is about 2.8. These differences correlate with the differences in the texture of the bed sediments, which are more conductive or fine-grained near the confluences of the Chena and Tanana Rivers than within the central channel. Conductivity values between the subice channels are extremely low and reflect the presence of consolidated frazil ice deposits. Slight rises ($\approx$ 0.5 mhos/m) are correlated with the presence of subice channels overlain by frazil deposits.

Data for cross section X6 (Fig. 31a) show two strongly conductive zones between 160 and 210 m, and between 230 and 270 m, thus locating subice channels. The conductivity values ($\approx$ 5.0 mhos/m) peak higher in these regions than those on cross section X4 and are possibly attributable to differences in bottom material. A third region between 130 and 160 m had lower values comparable to one of the channels on cross section X4, indicating flowing water, but possibly significant transport of frazil ice also. Near the north bank, conductivity values peaked near 3.5 mhos/m above open water.

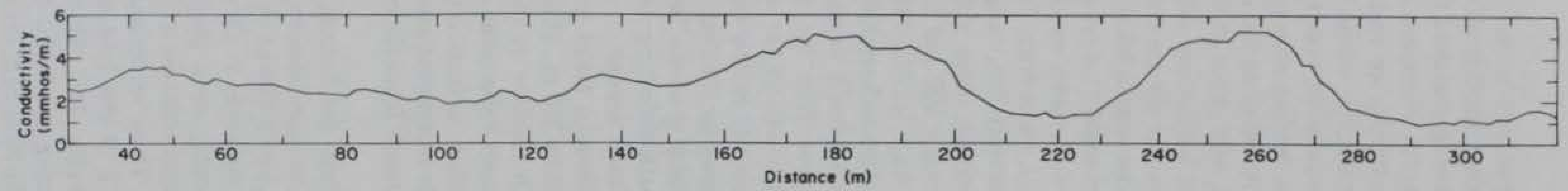
Figures 30b and 31b are the radar profiles from cross sections X4 and X6 respectively. The very first returns are two to three dark bands that do not change in form or time delay across the entire record. They represent direct coupling in the air between antennas and first arrive at 5 ns delay because of the 1.5 m antenna separation. Overlapping this band and extending another 40 to 60 ns throughout both records are several dark bands of varying shape. These returns represent a direct ground wave coupling under the ice surface and reflections (single and multiple) within the ice cover. A 1.5-m antenna separation would cause a delay of about 9 ns for the leading edge of the direct ground coupling, about 30 ns to the end of a first ice bottom reflection, and about 45 ns to the end of a second (multiple) ice bottom reflection, assuming a 1.2 m thickness for the ice cover.

The radar profile for cross section X4 (Fig. 30b) defines the deepest river channel (5.4 m) as being near the north bank, as was shown on the measured bed profile (Fig. 30c), while from 75 to 290 m the river bottom is relatively flat, ranging between 2.2 and 3.1 m. Strong radar reflections from the bed are seen between 100 and 150 ns in areas where there was no frazil ice (70–115 m and 160–210 m). No strong bottom reflection is seen in the deep open channel on the north bank, apparently because of diffraction from the complex frazil-water deposit. At the side of the channel, however, the bottom reflections briefly occur before they are diffracted away by the frazil ice. A faint echo at 50 m does appear at about 245 ns but this may be a multiple path reflection from the sides of the channel and frazil deposit.

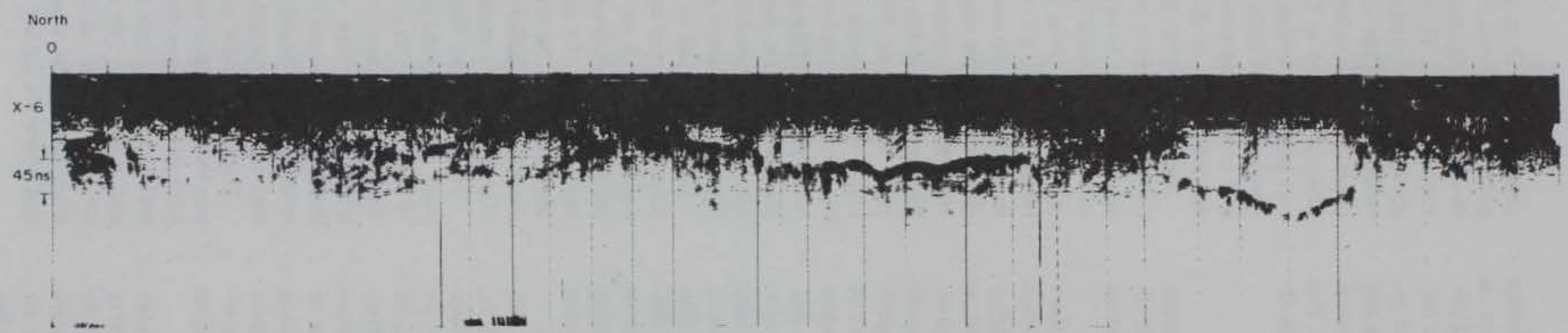
Extensive areas of continuous frazil ice occur from 115 to 160 m and 210 to 310 m. These locations correspond well with sections of the radar profile where distinct bottom reflections are absent. The small channel within the frazil is not well distinguished. The multiple incoherent returns recorded in the frazil zones result from the complex character of this material.

The maximum time delays for bottom reflections in the two channels on cross section X4 are about 133 ns at 90 m and about 104 ns at 190 m. The known values of ice thickness at these locations coupled with the radar data predict the depths of the channel bottoms from the ice surface to be about 2.8 and 2.4 m. These values agree well with the known depths of 2.79 and 2.34 m.

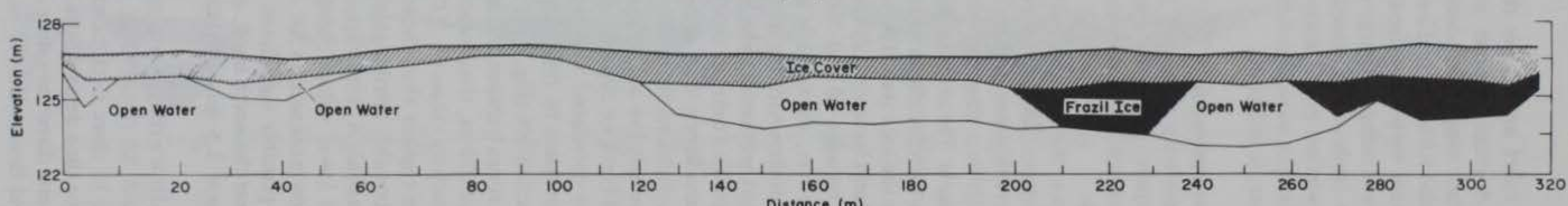
The second radar profile (Fig. 31b), 320 m long, was located along cross section X6. Radar data exhibit strong echoes from the river bed, correlating with the two distinct subice channels between 130 and 205 m and 240 and 275 m on the transect. Strong, but less distinct, echoes were returned from the smaller channels near the north bank, and where the ice lay on the bars in the river bed.



a. Conductivity profile—two zones of open water are indicated.



b. Radar profile.



c. Measured cross-section profile.

Figure 31. Geophysical data compared to measured data along cross section X6; looking upstream; north bank on left; distances from north bank benchmark. (Lower scale varies with the rate at which the antenna was pulled across the ice).

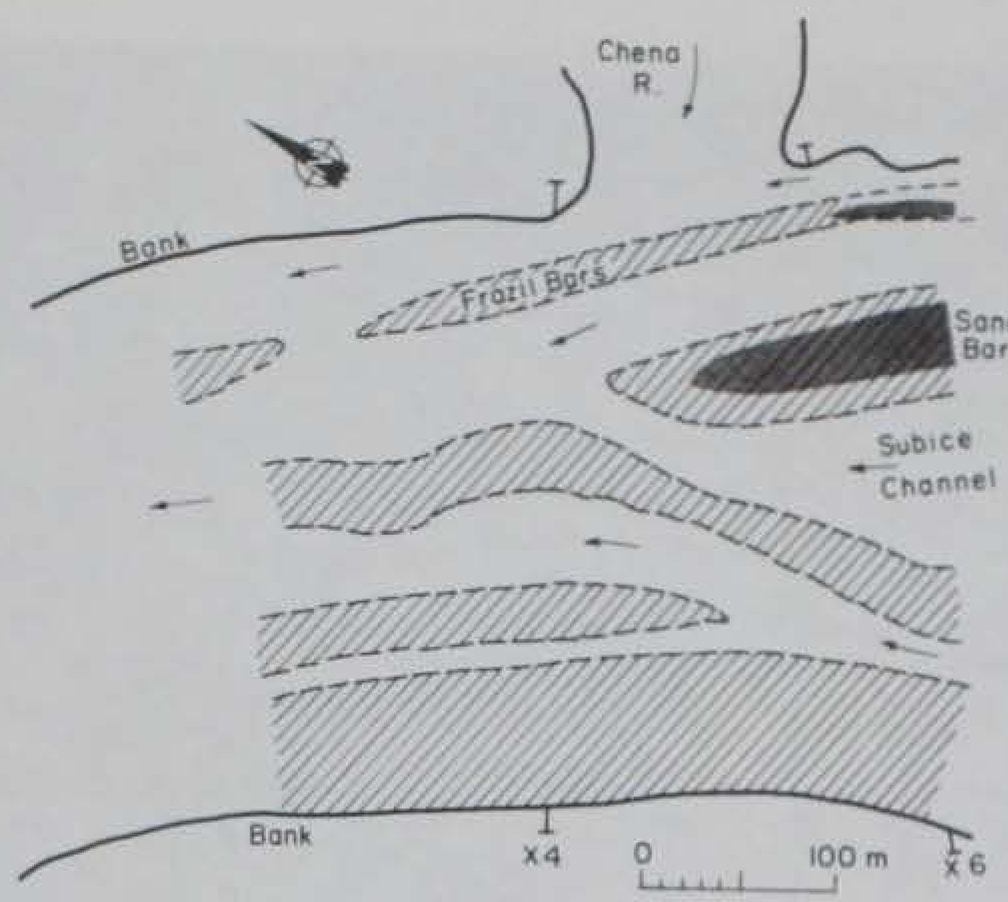


Figure 32. Spatial distribution of frazil ice deposits and open water (subice channels) beneath the ice cover within the study reach. Distribution at cross sections X4 and X6 are based upon measured data, while distribution elsewhere is based upon geophysical data interpreted using comparisons with ground-truth data on cross sections X4 and X6.

Spatial morphology

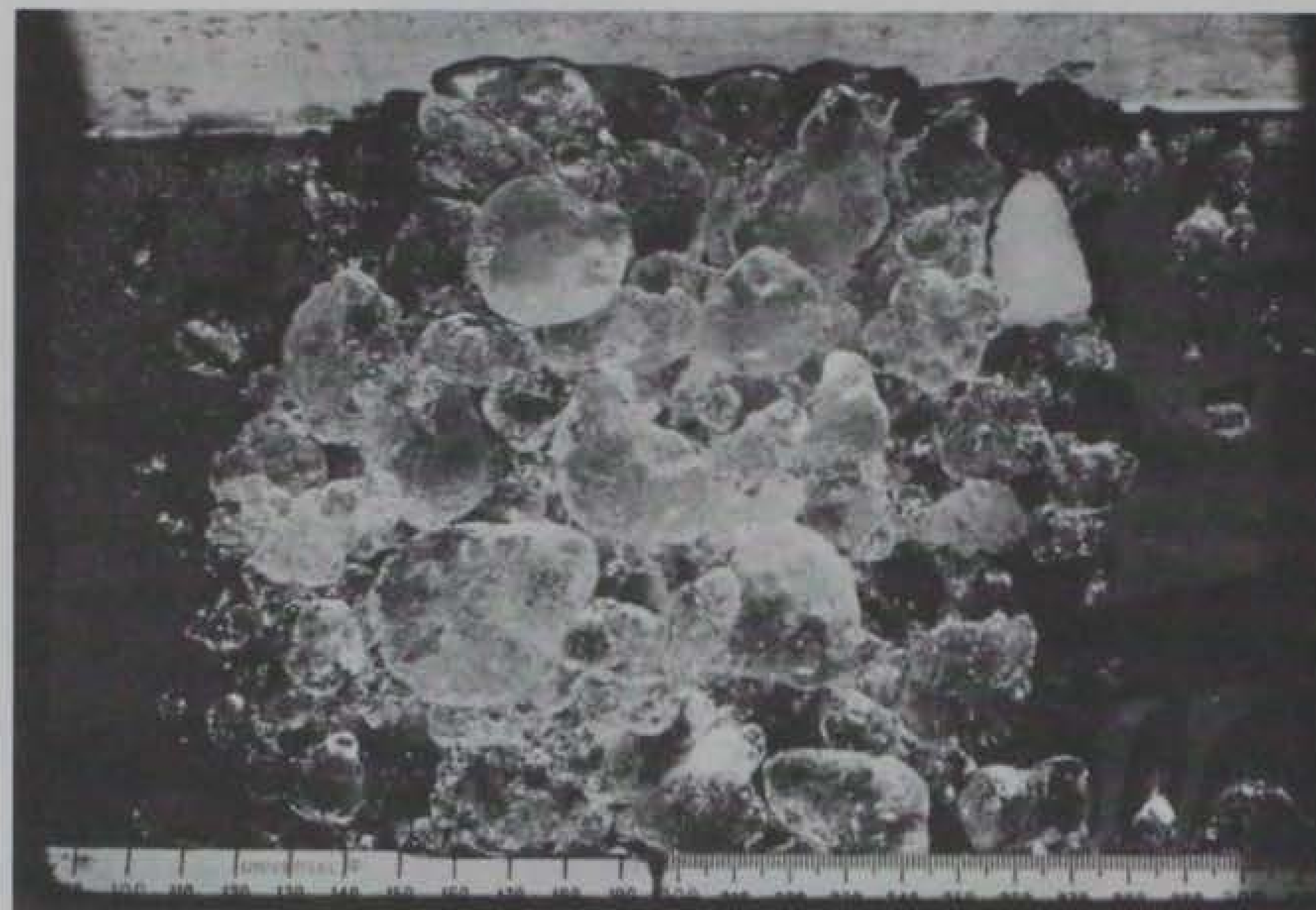
The ground truth data, the apparent resistivity profiles and the radar profiles (Fig. 30 and 31), suggest the spatial distribution of the subice channels and the stagnant frazil ice deposits within this reach of the river (Fig. 32). Conductivity profiles at 50 m upstream and parallel to X4, and at intervals along, but perpendicular to, X4 indicated that the frazil deposits extended longitudinally upstream and downstream. These longitudinal deposits, here referred to as *frazil bars*, appear responsible for maintaining the distinct hydraulics of each subice channel by acting as lateral channel walls or boundaries for the flowing water. The pattern of subice channels is not straight—they appear to meander as well as to converge into single channels where frazil bars terminate, exhibiting an anastomosing pattern on a larger scale (Fig. 32).

Frazil ice characteristics

The size and shape of frazil ice, both individual disks and aggregates of particles, varied widely within flowing water and stagnant deposits. Types of frazil ice ranged from recently formed small disks, flocs and rounded, aged grains, to partly consolidated slush or aggregates (e.g., Michel 1971, Osterkamp 1978, Martin 1981), and to a unique, previously unreported form of frazil aggregate we have termed a *frazil ice pebble* (Fig. 33). The dimensions and morphology of the frazil ice encountered in transport in the river and in the stagnant frazil deposits, excluding the frazil ice pebbles, are similar to those reported in the literature.

Frazil ice pebbles are unique in terms of both size and shape (Fig. 33). They range from less than 5 mm to greater than 150 mm along their longest axis. Their shape is reminiscent of water-worn stream pebbles with smooth surfaces and corners exhibiting rounded edges. They are composed of individual frazil disks and rounded grains, which appear to be welded or sintered together (Fig. 34). Occasionally, several aggregates of frazil particles may be welded together to form a single frazil pebble. Thin-sections cut from frazil pebbles indicate that the optical c-axes of the frazil disks are not aligned in a preferred orientation (Fig. 35).

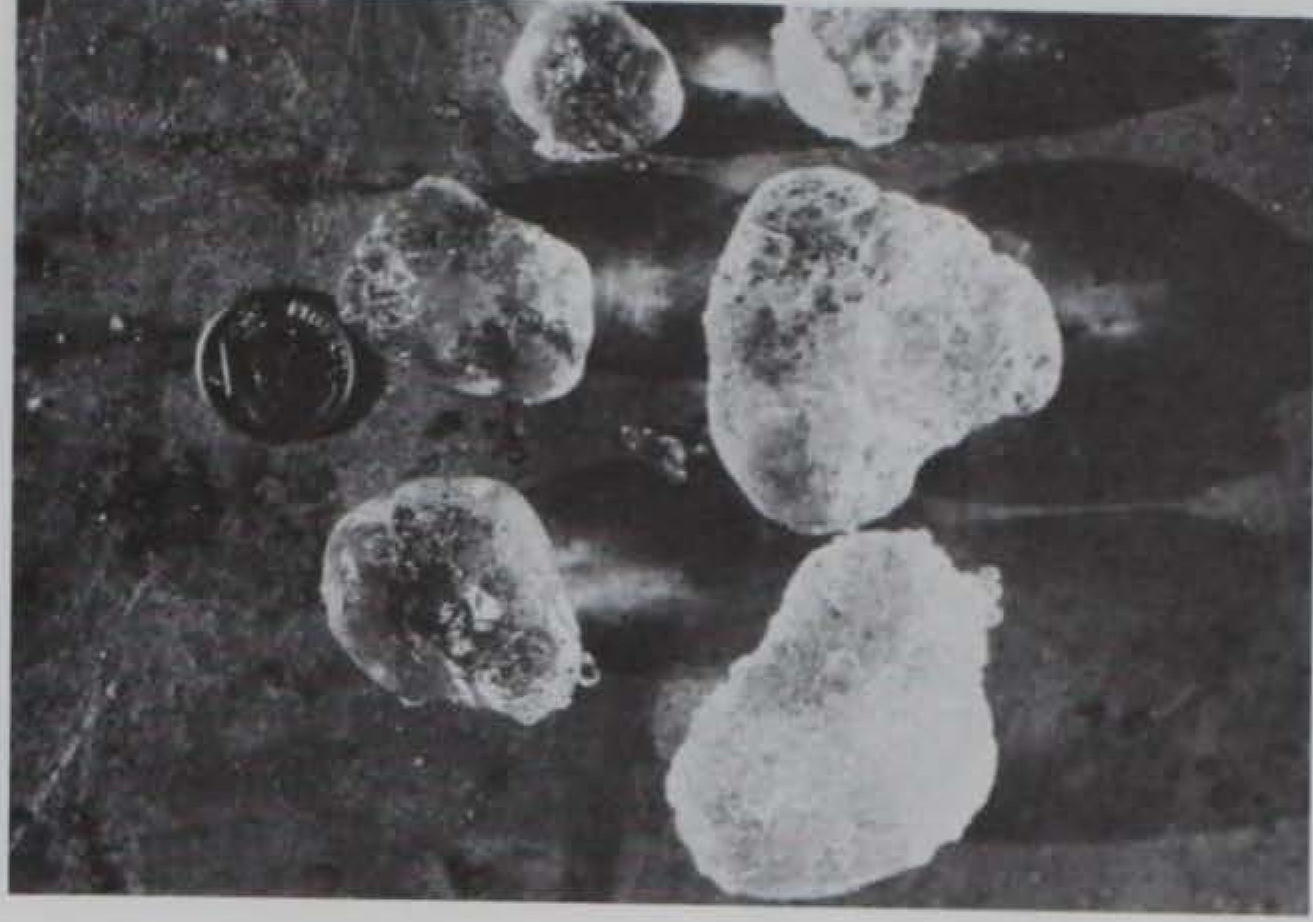
Frazil ice pebbles are found in transport in the subice channels as well as deposited in the frazil bars. Their characteristics suggest they originate as partially congealed aggregates that are eroded from the stagnant frazil deposits that bound the subice channels. As this aggregate is transported by the current, it is rolled or bounced along the bottom of the ice cover. This further compresses



a. Typical mixture of frazil pebbles in transport.

b. Closeup of (a).

Figure 33. Examples of frazil ice pebbles.

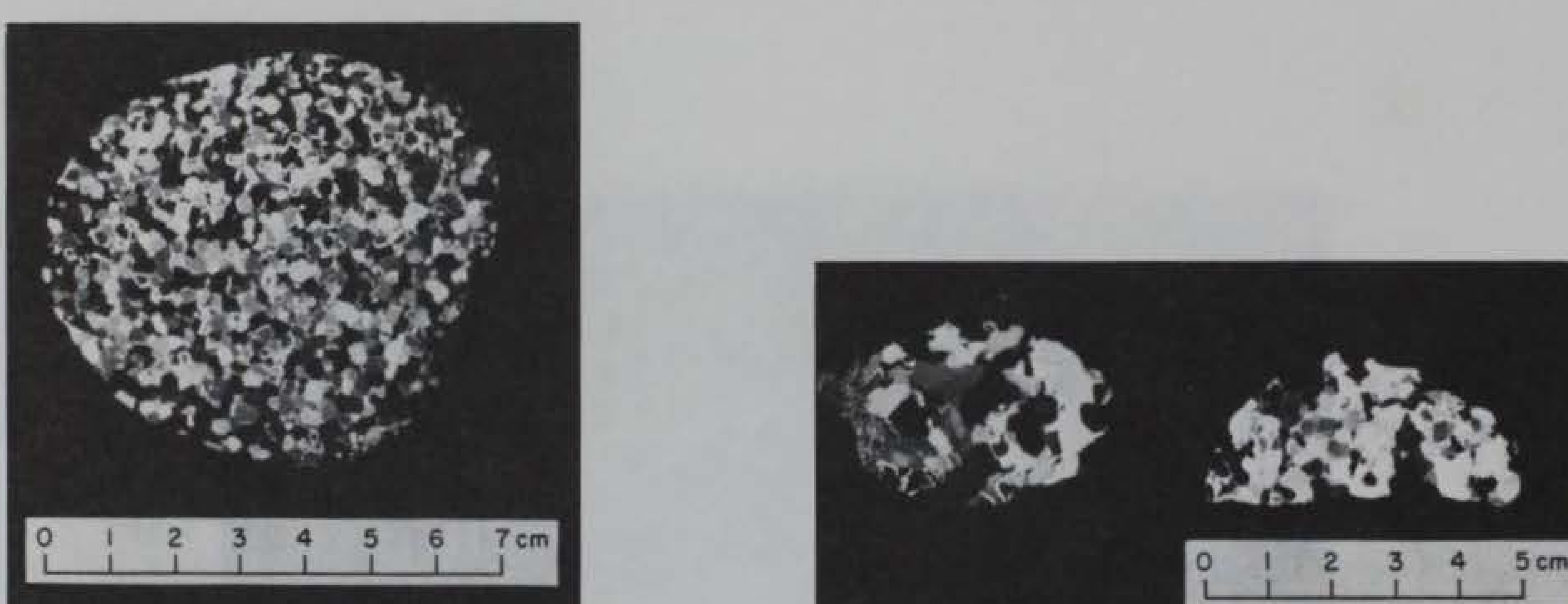


c. Small frazil ice pebbles, with composing grains exposed by melting along grain boundaries.

d. Large frazil ice pebble nearly 15 cm on long axis.

Figure 33 (cont'd).

Figure 34. Closeup showing the individual frazil particles that compose a frazil pebble. Rounded edges and overall shape of frazil pebbles are reminiscent of water-worn stream pebbles.



a. *b.*

Figure 35. Thin sections cut through individual frazil pebbles (under cross polarized light). Individual grains are not aligned with a preferred orientation. Grain sizes are mostly smaller in pebble (a); thin sections in (b) were cut perpendicular to one another.

and consolidates the particles, as well as causing thermal and mechanical abrasion and thus rounding. This process would maintain clearly identifiable frazil disks or other particle shapes while developing the pebble's configuration. The dimensions of the individual pebbles will therefore depend to a large extent on the velocity of the current eroding and then transporting the original frazil aggregate, while the internal composition will be determined by that of the frazil deposit from which it was eroded.

DISCUSSION AND CONCLUSIONS

The results of this initial study indicate that ice cover is an important factor affecting the flow and morphology of the Tanana River. Water flow occurs within distinct, subice channels separated by stagnant frazil ice. Each channel has its own transport and hydraulic characteristics. Meandering and possibly anastomosing of these channels is suggested by our data.

Our preliminary data also indicate that significant quantities of sediment are transported as suspended sediment and bedload in subice channels. Material in the bedload ranges from sand to sandy gravel. Bed material shows a similar range in size beneath the subice channels, but is typically a fine to medium sand beneath frazil deposits, and a coarse or pebbly sand near the edge of these deposits.

Flow within each subice channel differs in velocity magnitude, but less so in direction. Frazil ice deposits act as lateral boundaries or channel walls for each subice flow. Velocity decreases laterally toward these bars as well as within about 0.3 m (20–25%) of the underside of the ice cover and of the river bed. Of the total area of the cross sections, frazil ice deposits occupied between 35 and 50%, and thus discharge area was limited to 50 to 65% of the river channel cross section.

Comparison of cross-sectional profiles suggests that the river bed is generally lower and its relief generally less with an ice cover present than without it. When this change in configuration occurs is not clear from our data, and thus further analysis of the ice cover effect is needed. Similarly, the control over where frazil deposits accumulate has not been identified.

A unique form of frazil ice discovered in this study, referred to here as a *frazil ice pebble*, appears to be a thermally or mechanically eroded aggregate of consolidated frazil particles. They appear to develop their smooth and rounded pebble shape during transport in subice channels by rolling and bounding along the underside of the ice cover.

Finally, our study indicates that a reasonably systematic and repetitive analysis of the physical characteristics, hydraulics and sediment transport rates of rivers with an ice cover can be undertaken, but that existing techniques and equipment can be improved with certain modifications. Shelter and heat sources to thaw and dry equipment and sampling gear rapidly are essential to performing these analyses during winter. The spatial variability in certain physical characteristics between measured transects can be defined using apparent resistivity and subsurface radar profiling after they are compared to the ground truth data measured along a single transect.

RECOMMENDATIONS

Equipment

Various modifications or fabrications are possible to improve data collection and reduce the time required for sampling, including:

1. A frazil ice sampler for use on partially or fully consolidated frazil of differing sizes and shapes, and a device for sampling frazil in transport.
2. A modified bedload sampler with seamless bags and an opening for sample extraction at the rear (downstream) end, and with trapdoors that can be opened once on the bed and closed after the sample is taken.
3. A freeze-resistant suspended load sampler that can likewise be activated only within open water areas beneath the ice cover.
4. A bed material sampler for gravel-size sediment that, once lying on the bed, can be manually or automatically activated to pick up the sample. This feature would eliminate problems with clogging and not attaining sufficient fall velocity through thick frazil ice or shallow water. It must be capable of obtaining a representative sample of gravel. Dimensions that are smaller than the Peterson grab dredge would reduce the size required for access holes and reduce the time necessary to auger each hole.

Research

A program should be undertaken to analyze in detail the morphology, hydraulics and sediment transport of a reach of an ice-covered river throughout the winter. Results of the winter observations should then be compared to similar data for the ice-free summer season. This work should then be extended for a number of reaches representing a range of river channel morphologies.

This research would require establishing multiple transects at fixed intervals across the particular reach of the river. Access holes in the Tanana River spaced at a 10-m interval seems workable under extreme winter conditions. Measurements of physical characteristics should be repeated each month of the period when the river is ice-covered, perhaps more often if data indicate rapid changes or variations in river morphology and hydraulics. Based on our experience, down-the-hole sampling and measurements average about ¼ to ½ hour. The apparent resistivity meter can be used to identify areas of thick frazil deposits or of open water, and thus the locations where large access holes are needed for detailed measurements of hydraulics and sediment transport.

Data on ice-covered rivers that are now lacking and should be analyzed include 1) seasonal and monthly changes in bed configuration ascribable to scour or deposition and their relationship to ice cover formation and growth, 2) effects of variations in discharge and water level, 3) factors controlling the distribution of frazil ice deposits and analyses of their effects on river regime, and 4) basic hydraulic parameters as they vary with time and from cross section to cross section within a river reach.

Further research on the spatial and temporal distribution of frazil ice deposits and the subice channels of flowing water should especially be undertaken. The existence of subice channels has important fundamental implications for the winter regime of rivers that need to be defined. For example, questions such as when and how do longitudinally oriented frazil bars form, what is their linear extent and how long do they exist, and how does the confinement of water flow between them affect sediment aggradation or degradation, need to be answered. Flow of water through porous frazil deposits may have important effects.

In addition, the characteristics of frazil ice pebbles need to be analyzed to define their origin precisely. Their transport also needs further verification since they could clearly be a problem for hydraulic structures with water intakes, such as turbines. Further observations of their presence or absence in other northern rivers are also needed to determine if the Tanana River observations are typical.

LITERATURE CITED

Annan, A.P. and J.L. Davis (1976) Impulse radar sounding in permafrost. *Radio Science,* **11**(4): 383–394.

Annan, A.P. and J.L. Davis (1977) Impulse radar applied to ice thickness measurement and fresh water bathymetry. Geological Survey of Canada, Report of Activities, Pt. B, Paper 77-1B.

Arcone, S.A., Delaney, A.J. and P.V. Sellmann (1979) Detection of arctic water supplies with geophysical techniques. USA Cold Regions Research and Engineering Laboratory, Special Report 79-15.

Arcone, S.A., P.V. Sellmann and A.J. Delaney (1982) Radar detection of ice wedges in Alaska. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-43.

Ashton, G.D. (1971) The formation of ice ripples on the underside of river ice covers. Ph.D. Dissertation (unpub.). Iowa City: University of Iowa.

Ashton, G.D. (1972) Turbulent heat transfer to wavy boundaries. In *Proceedings, 1972 Heat Transfer and Fluid Mechanics Institute,* pp. 200–213.

Ashton, G.D. (1980) Freshwater ice growth, motion, and decay. In *Dynamics of Snow and Ice Masses* (S.C. Colbeck, Ed.). New York: Academic Press, Inc., pp. 261–304.

Ashton, G.D. and J.F. Kennedy (1972) Ripples on the underside of river ice covers. *Journal of Hydraulics Division, American Society of Civil Engineers,* **98**(HY9): 1603–1624.

Beltaos, S. and A.M. Dean, Jr. (1981) Field investigations of a hanging ice dam. In *Proceedings, International Association for Hydraulic Research, Symposium on Ice, Laval University, Quebec, Canada.* Vol. 2, pp. 475–488.

Brockett, B. and D.E. Lawson (1985) Prototype drill for core sampling fine-grained, perennially frozen sediment. USA Cold Regions Research and Engineering Laboratory, CRREL Report 85-1.

Burrows, R.L. and P.E. Harrold (1983) Sediment transport in the Tanana River near Fairbanks, Alaska, 1980–1981. U.S. Geolological Survey Water Resources Investigations Report 83-4064.

Calkins, D.J., D.S. Deck and C.R. Martinson (1982) Resistance coefficients from velocity profiles in ice-covered shallow streams. *Canadian Journal of Civil Engineering,* **9:** 236–247.

Carey, K.L. (1966) Observed configuration and computed roughness of the underside of river ice, St. Croix River, Wisconsin. U.S. Geolological Survey Professional Paper 550-B, pp. B192–B198.

Carey, K.L. (1967) The underside of river ice, St. Croix River, Wisconsin. U.S. Geological Survey Professional Paper 575-C, pp. C195–C199.

Chacho, E.F., Jr., T. Vincent, H. Elliot and S. Perkins (In press) Channel morphology of the Tanana River near Fairbanks, Alaska in 1984. USA Cold Regions Research and Engineering Laboratory, CRREL Report.

Emmett, W.W. (1980) A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler. U.S. Geological Survey Professional Paper 1139.
Harrold, P.E. and R.L. Burrows (1983) Sediment transport in the Tanana River near Fairbanks, Alaska, 1982. U.S. Geological Survey Water Resources Investigations Report 83-4213.
Kovacs, A. (1978) Remote detection of water under ice-covered lakes on the North Slope of Alaska. *Arctic,* **31**(4): 448–458.
Larsen, P.A. (1969) Head losses caused by an ice cover on open channels. *Journal of Hydraulics Division, American Society of Civil Engineers,* **96**(HY3): 703–724.
Larsen, P.A. (1973) Hydraulic roughness of ice covers. *Journal of Hydraulics Division, American Society of Civil Engineers,* **99**(HY1): 111–119.
Lau, Y.L. and B.G. Krishnappan (1981) Ice cover effects on stream flows and mixing. *Journal of Hydraulics Division, American Society of Civil Engineers,* **107**(HY10): 1225–1242.
Martin, S. (1981) Frazil ice in rivers and oceans. *Annual Review of Fluid Mechanics,* **13**: 379–397.
Michel, B. (1971). Winter regime of rivers and lakes. USA Cold Regions Research and Engineering Laboratory, CRREL Monograph III-B1a.
Morey, R.M. (1974) Continuous subsurface profiling by impulse radar. In *Proceedings, Engineering Foundation Conference on Subsurface Exploration for Underground Excavation and Heavy Construction.* New York: American Society of Civil Engineers, pp. 213–232.
Neill, C.R., J.S. Buska, E.F. Chacho, C.M. Collins and L.W. Gatto (1984) Overview of Tanana River monitoring and research studies near Fairbanks, Alaska. USA Cold Regions Research and Engineering Laboratory, CRREL Special Report 84-37.
Osterkamp, T.E. (1975) Observations on Tanana River ice. In *Proceedings, Third International Symposium on Ice Problems, August 18–21, Hanover, New Hampshire,* pp. 201–209.
Osterkamp, T.E. (1978) Frazil ice formation: A review. *Journal of Hydraulics Division, American Society of Civil Engineers,* **104**(HY9): 1239–1255.
Rand, J. (1982) The CRREL 2-in. frazil ice sampler. USA Cold Regions Research and Engineering Laboratory, CRREL Special Report 82-9.
Sayre, W.W. and G.B. Song (1979) Effects of ice covers on alluvial channel flow and sediment transport processes. Iowa Institute of Hydraulic Research, IIHR Report No. 218. Iowa City: University of Iowa.
Shen, H.T. and T.O. Harden (1978) The effect of ice cover on vertical transfer in stream channels. *Water Resources Bulletin,* **14**: 1429–1439.
Tywoniuk, N. and J.L. Fowler (1972) Winter measurements of suspended sediments. In *Proceedings, Banff Symposium, The Role of Snow and Ice in Hydrology.* Vol. 1 UNESCO–WMO–IAHS, pp. 814–827.
Ueda, H., P.V. Sellmann and G. Abele (1975) USA CRREL snow and ice testing equipment. USA Cold Regions Research and Engineering Laboratory, CRREL Special Report 146.
Uzuner, M.S. (1975) The composite roughness of ice-covered streams. *Journal of Hydraulic Research, International Association of Hydraulic Research,* **13**: 79–102.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Lawson, D.E.
Morphology, hydraulics and sediment transport of an ice-covered river: Field techniques and initial data / by D.E. Lawson, E.F. Chacho, Jr., B.E. Brockett, J.L. Wuebben, C.M. Collins, S.A. Arcone and A.J. Delaney. Hanover, N.H.: Cold Regions Research and Engineering Laboratory. Springfield, Va.: available from National Technical Information Service, 1986.
v, 49 p., illus.; 28 cm (CRREL Report 86-11.)
Prepared for Office of the Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory under Civil Works Projects 31722 and 31568.
Bibliography: p. 36.
1. Alaska. 2. Braided rivers. 3. Field tests. 4. Frazil ice. 5. Ice-covered rivers. 6. River currents. 7. Tanana River. I. Chacho, E.F., Jr II. Brockett, B.E. III. Wuebben, J.L. IV. Collins, C.M. V. Arcone, S.A. VI. Delaney, A.J. VII. United States. Army. Corps of Engineers. VIII. Cold Regions Research and Engineering Laboratory, Hanover, N.H. IX. Series: CRREL Report 86-11.