FINAL REPORT

SNOW DEPTH UNDER ELEVATED PIPELINES IN WESTERN NORTH SLOPE OILFIELDS

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EXECUTIVE SUMMARY

As oilfield infrastructure extended west and southwest from the Kuparuk Oilfield for the Alpine, Tarn, and Meltwater development projects in the late 1990s, snow accumulation under elevated pipelines and its potential impacts emerged as an issue of concern for the residents of Nuiqsut, the nearest village. Those concerns focused on the potential for snow to accumulate under and around elevated pipelines, possibly reducing ground clearance and interfering with the ability of wildlife (particularly caribou) and subsistence users on snowmachines to cross under pipelines. Observations made during spring wildlife surveys suggested that pipelines influence either snow deposition or ablation patterns, or both, but no quantitative data were available to evaluate the extent or dynamics of winter accumulation of snow under and adjacent to elevated pipelines.

To address these data gaps, snow depths under pipelines that were elevated to the stipulated minimum height of 5 feet (152 cm) above ground level were measured and compared with undisturbed tundra areas nearby in three study areas in the western North Slope oilfields in late winter 2001. Sections of the Tarn pipeline and Alpine pipeline were sampled during 26–30 March 2001 and repeat measurements were performed during 17–20 April 2001, in addition to sites on the Colville River Delta. For sampling, the Tarn area was subdivided into an east–west pipeline orientation (east of DS–2L) and a north–south pipeline orientation (between DS–2L and DS–2N).

The snow depth under pipelines at most sampling sites (59% in March and 55% in April) did not differ significantly from nearby background areas located upwind. Significant snow accumulation under pipelines occurred at 24% of the sites sampled in March and 27% of the sites sampled in April, with the difference in snow depth at those sites averaging ~37 cm in March and ~17 cm in April. In both March and April, snow depth under pipelines was significantly less than upwind background depths at the remaining 18% of sites sampled.

At least one sampling point with low pipe clearance (defined as <152 cm measured from the bottom of the pipeline to the snow surface, ignoring compression of the snow surface) was observed within 7 (70%) of the 10 segments sampled along the Tarn pipeline and 5 (83%) of the 6 segments sampled in the Alpine Corridor study area in April. Snow depth was variable, however, and sites with greater pipe clearance usually were located nearby; no areas of low pipe clearance were observed along the Alpine pipeline on the Colville River Delta. Local factors such as landform class (thaw basin or terrace terrain), pipeline orientation, and pipe clearance can be used to identify areas where significant accumulations of snow under the pipeline are most likely to occur. In general, the snow pack under pipelines was most likely to be significantly deeper than background levels under east–west pipelines traversing thaw basins. Snow depth tended to be higher at sites where the pipe clearance was reduced below 152 cm.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This study was funded by PHILLIPS Alaska, Inc.; we appreciate the support and assistance of Caryn Rea, Environmental Studies Coordinator. Additional logistic support was provided by the Spill Response Unit at the Alpine Project facility. We appreciate the field efforts of John Rose, Mike Knoche, Angela Palmer, and Pam Seiser. Allison Zusi-Cobb managed the GIS data and created the map figures. Caryn Rea, Torre Jorgenson, and Steve Murphy reviewed the document and provided many helpful comments.

INTRODUCTION

As oilfield infrastructure extended west and southwest from the Kuparuk Oilfield to the Alpine, Tarn, and Meltwater development projects in the late 1990s, snow accumulation under elevated pipelines and its potential impacts emerged as an issue of concern for the residents of Nuiqsut, the nearest village. The concerns expressed by Nuiqsut residents focused on the potential for snow to accumulate under and around elevated pipelines, possibly reducing the effective ground clearance and interfering with the ability of wildlife (particularly caribou) and humans on snowmobiles (hereafter, snowmachines) to cross under pipelines. This issue reached prominence in summer 2000 during the permitting process for several North Slope projects: the new Meltwater project (DS-2P) located south of the Tarn drill sites (DS-2L and DS-2N), the infield pipeline between the CD-1 and CD-2 pads of the Alpine Project, and the pipeline for BP's Schrader Bluff project.

Incidental observations and photographs by ABR biologists during spring surveys of caribou and waterfowl recorded remnant bands of snow running parallel to elevated pipelines in some parts of the Kuparuk Oilfield (Figure 1). These observations suggested that pipelines influence either snow deposition or ablation patterns, or both, but no quantitative data were available to evaluate the extent or dynamics of winter accumulation of snow under and adjacent to elevated pipelines.

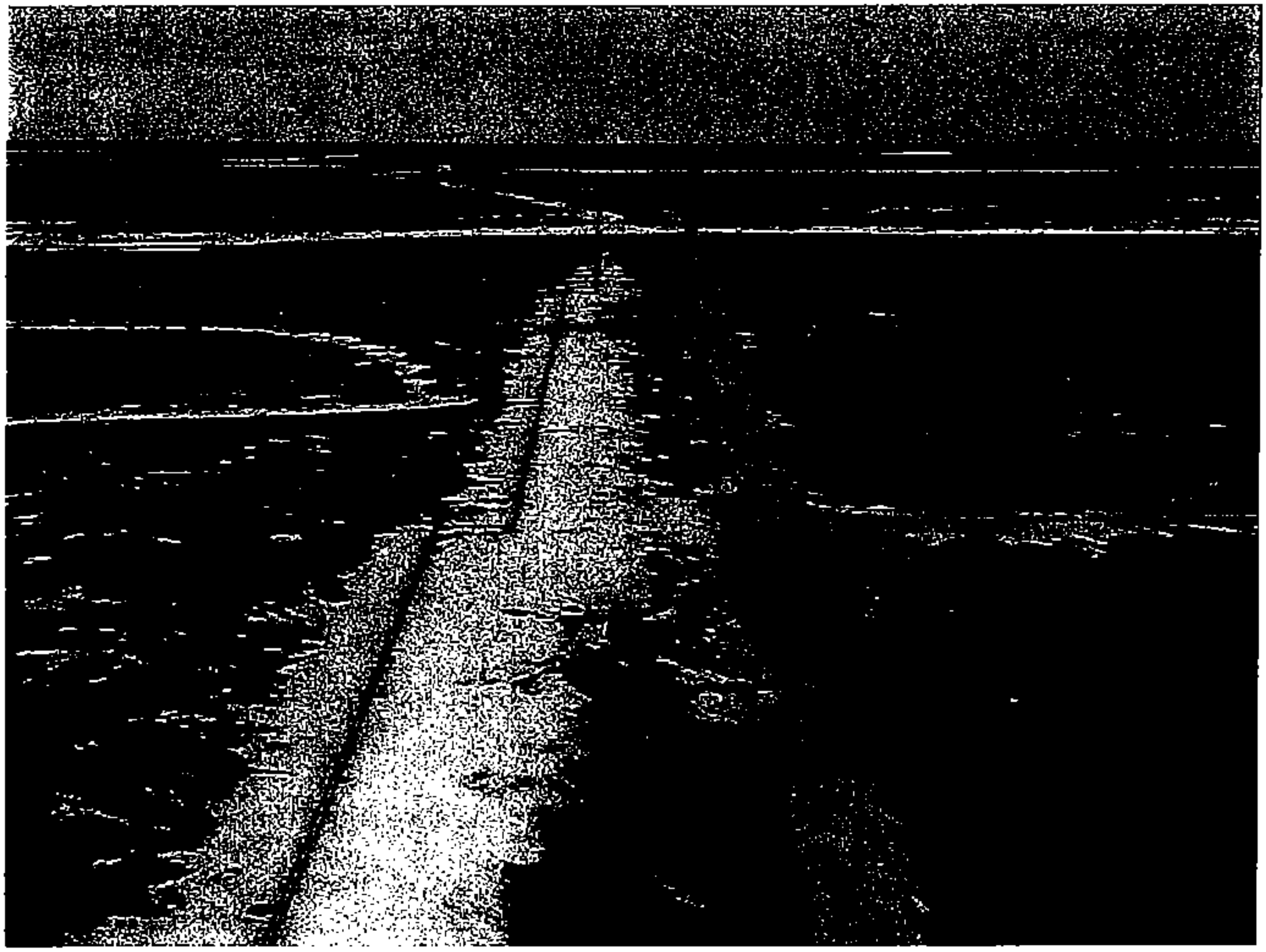

Figure 1. Remnant snow drifts (left) and ice road (right) along E-W-oriented portion of the Alpine pipeline in the Alpine Corridor study area (looking east), 10 June 2001.

The work reported herein was performed to address this issue by collecting and analyzing snow-depth measurements under and near elevated pipelines. This study was designed to evaluate the effect of elevated pipelines on snow accumulation beneath pipelines. The study had two principal objectives:

1. Measure the minimum clearance between elevated pipelines and the snow surface, and
2. Determine the influence of physical variables (terrain type and pipeline orientation with respect to prevailing winds) affecting snow depth under and adjacent to elevated pipelines.

Few data exist on snow cover on the North Slope, and weather service records are incomplete and typically under-report snow accumulation (Benson and Sturm 1993). Snow accumulation on the Arctic Coastal Plain of Alaska results from the net effect of vegetation snow-holding capacity (determined by height and density of vegetation), wind-dependent snow-transport processes, and the balance of sublimation and precipitation (Liston and Sturm 1998). Pipelines affect snow deposition mainly by modifying local wind fields near the ground surface, thereby altering local transport processes that can result in a net increase in snow accumulation (Figure 1). In practice, we expect accumulation of snow under pipelines to be affected principally by three configuration variables: (1) orientation of the pipeline with respect to the prevailing winter wind direction, (2) the number and diameter of pipes on the pipe rack, and (3) the distance from the bottom of the pipeline to the snow surface (pipe clearance). Landscape features and vegetation characteristics affect the latter variable because they determine the local snow-holding capacity (snow-pack depth). The diameter and spacing of vertical support members (VSMs) also may be important, but because they tend to be constant along the length of a pipeline, this variable was not included in this study. It is important to understand that the minimum height for the construction of elevated pipelines in the western North Slope fields has been stipulated to be at least 5 feet (152 cm) above the ground surface (during the snow-free season) under pipeline construction permits issued by state and federal agencies since the early 1980s. In addition, this study did not include the older design of elevated pipelines adjacent to gravel roads, because current designs call for larger separation distances between elevated pipelines and roads (usually by 120–300 m [400–1000 feet]) wherever practicable. In recent developments on the western North Slope such as Meltwater (DS-2P) and Palm (DS-3S), pipelines have been constructed to a minimum height of 7 feet (213 cm) above the snow-free surface of the ground to accommodate the concerns of local residents.

Pipeline orientation affects both the pattern and amount of snow deposition beneath the pipe racks. As wind direction and pipeline orientation converge, the windrows of snow that form on the lee side of VSMs become oriented closer to the direction of the pipeline. As the wind angle decreases from 90° (wind perpendicular to the pipeline), the effective cross-sectional area of the pipeline increases as a function of the incident angle, approaching a maximum as the angle decreases to 0° (wind exactly parallel to pipeline).

The number and diameter of the pipes supported on the pipe racks and their distance from the snow surface determines the absolute magnitude of the pipeline effect on ground-level winds. Casual observation of pipe racks in the older Prudhoe Bay Oilfield suggests that wide pipe racks situated close to the ground make excellent snow capture sites. As the pipe elevation above the ground surface increases, the width of the pipe rack probably becomes less important to snow accumulation under the pipeline.

Natural depressions in terrain and the presence of "tall" vegetation (shrub willows) should increase the snow-holding capacity (depth of snow) both in undisturbed areas and beneath pipelines. These natural variations in terrain and vegetation can be identified on existing habitat maps produced for environmental evaluation documents for the Tarn, Alpine, and Meltwater projects.

Data collected from the field sampling segments were used to evaluate the potential of pipelines to obstruct the movement of both caribou and people (on snowmachines) during winter based on the current and historic snow-pack depths. Field measurements were distributed in relation to pipeline orientation and landscape features in the

Colville River Delta, the Alpine Pipeline corridor between the delta and Kuparuk, and the Tarn area in the GKA (Greater Kuparuk Area). These three areas were chosen primarily due to the lack of gravel roads adjacent to the pipelines, the availability of suitable terrain mapping to allow stratification of field sampling, and reasonable winter access to the pipelines.

STUDY AREA

The study was conducted in three areas of the western North Slope oilfields: the Tarn area, the Alpine Pipeline corridor (Alpine Corridor) and the Colville River Delta (Figure 2). For sampling purposes, the Tarn sampling effort was subdivided into two categories of pipeline orientation: the east–west (E–W) section of pipeline east of DS-2L and the north–south (N–S) section between DS-2L and DS-2N. The Tarn pipeline consists of three adjacent pipelines mounted on a single pipe rack supported by VSMs spaced at intervals of ~17 m (55 feet). Terrain types in the Tarn area consist mostly of alluvial-marine terrace and ice-rich thaw basins.

In the Alpine Corridor, the Alpine pipeline consists of a 24-inch production line, an 18-inch seawater line, and a 2-inch fuel/multipurpose line mounted on single VSM supports, with a minimum design height of 152 cm (5 feet) above the tundra surface and VSM intervals of ~20 m (65 feet). The terrain types in the Alpine Corridor consist mainly of alluvial-marine terrace, alluvial terrace, and thaw basins. Sampling segments were located only along E–W orientations of the pipeline because that is the only directional orientation that occurs in the Alpine Corridor between the Tarn pipeline and the Colville River Delta.

Proceeding west from the Alpine Corridor, the Alpine pipeline continues onto the Colville River Delta, where it is supported by larger-diameter VSMs and elevated higher above the ground because of its location in a major river delta and floodplain. Sampling along the pipeline in the Colville River Delta was done along NW–SE and N–S sections of the pipeline.

METHODS

Snow-sampling locations (called segments) were initially selected to obtain roughly equal sample sizes from two predominant pipeline orientations (N–S and E–W). Terrain-unit maps produced for previous projects were used to locate sampling segments in a homogeneous landform class (terrain groups: terrace, thaw basin, riverine) and were distributed across the three study areas (Figure 2). The final number of sites sampled depended on weather and site access at the time of the field survey (see details below). Each sampling segment consisted of 10 stations spaced evenly across 5 VSM spans, with paired transects of equal length located 100 m distant from, and parallel to, each side of the pipeline (background transects). At each station, three snow depths and one pipe clearance measurement (from the bottom of the pipe to the snow surface) were taken. Segment locations were stratified by study area (Tarn, Alpine Corridor, and Colville River Delta), pipeline orientation (N–S or E–W), and landform (terrace or basin). Landform determinations were derived from previous mapping of integrated terrain units in the Colville River Delta and Alpine Transportation Corridor (Jorgenson et al. 1997) and the Tarn development area (Anderson et al. 1998). Terrace and basin classifications were created by grouping terrain types into local areas of higher or lower elevations; terrain-type groupings are summarized in Table 1.

FIELD MEASUREMENTS

Snow depth and pipe clearance were measured during two sampling visits in late winter 2001, on 26–30 March and 17–20 April. Initial measurements were performed during 26–30 March in the Tarn and Alpine Corridor study areas. Snow depth and pipe clearance were measured at 15 locations along the Tarn pipeline between DS-2N and DS-2M (Figure 3) and at 3 locations along the Alpine pipeline in the Alpine Corridor study area (Figure 4). Planned sampling in the remainder of the Alpine Corridor and the Colville River Delta areas could not be completed because of poor weather travel restrictions and extreme wind chills.

A second set of measurements was obtained during 17–20 April. On that visit, the complete set of sites was sampled, except for two segments along the Tarn pipeline where snow disturbance from with ice-road maintenance disrupted the snow

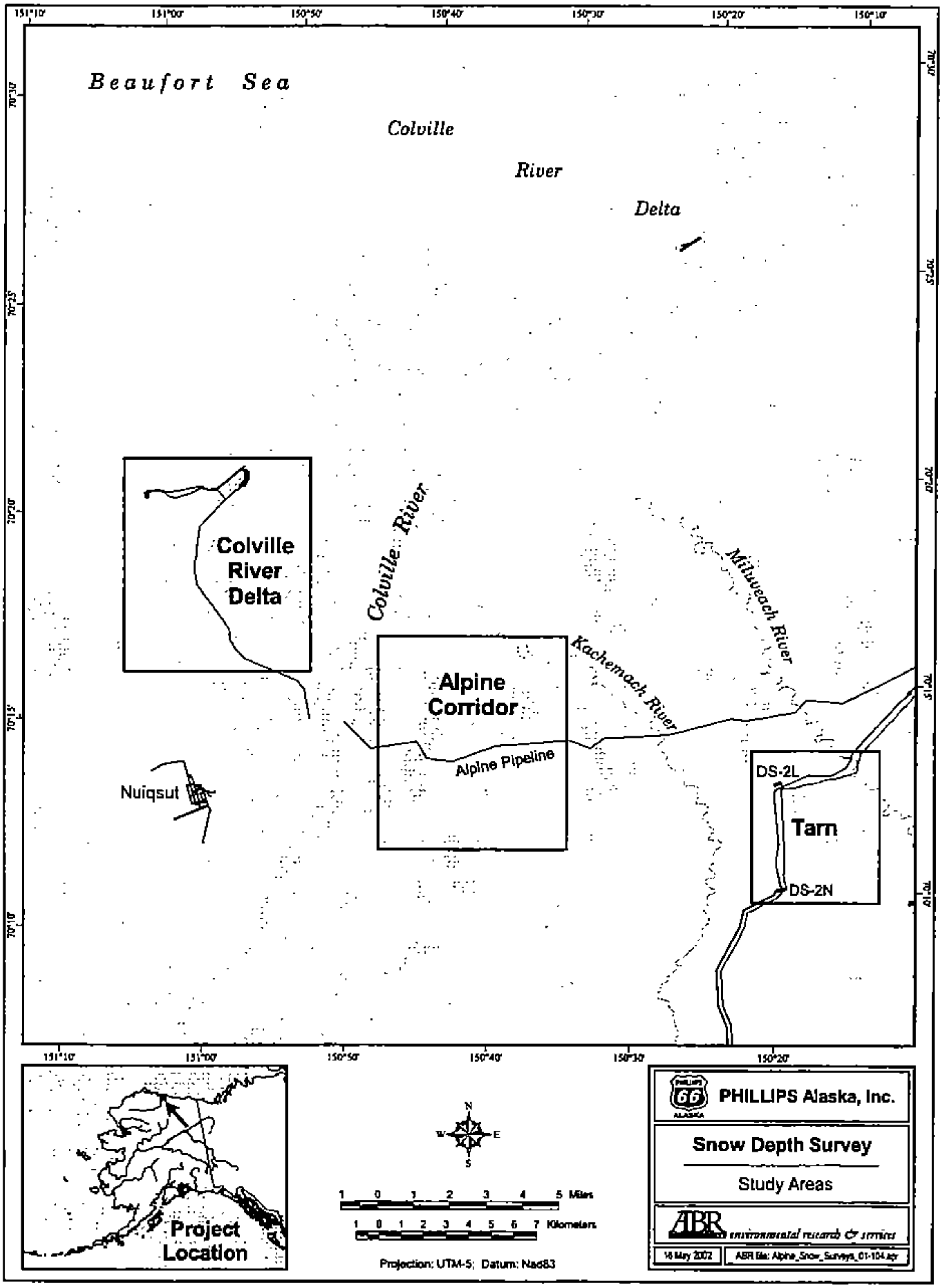

Figure 2. Study areas for snow-depth surveys in the western North Slope oilfields, March–April 2001.

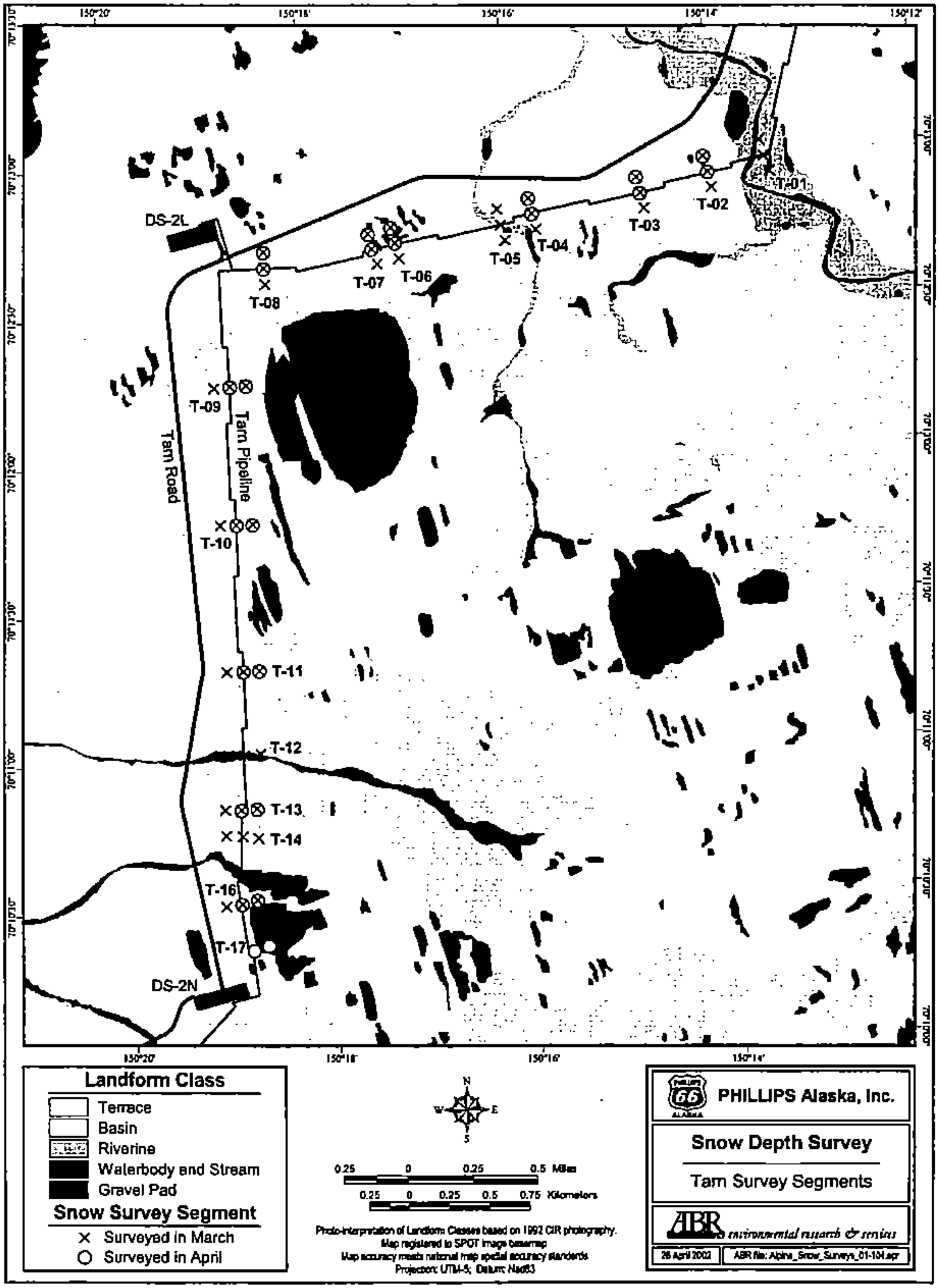

Figure 3. Location of survey segments for snow-depth surveys in relation to terrain in the Tam study area, March–April 2001.

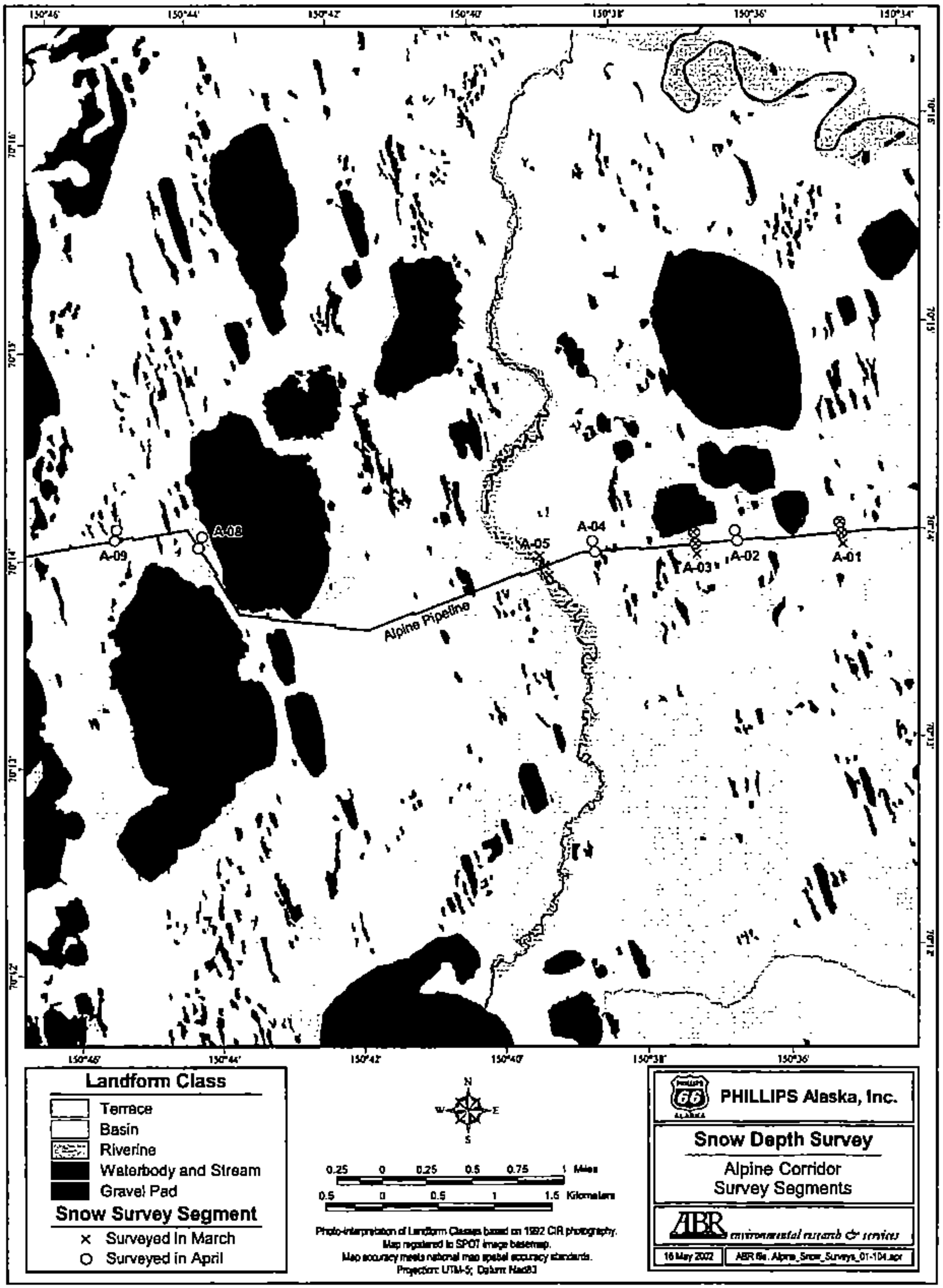

Figure 4. Location of survey segments for snow-depth surveys in relation to terrain in the Alpine Corridor study area, March–April 2001.

Table 1. Terrain-type groupings (landform classes) in study areas for snow-surveys in the western North Slope oilfields, March–April 2001.

Terrain Group	Tarn	Alpine Corridor	Colville River Delta
Terrace	Alluvial marine terrace	Alluvial terrace	Delta, abandoned floodplain
Basin	Thaw basin, ice-rich	Thaw basin, ice-rich	Delta thaw basin, non-ice-rich
Riverine	Floodplain, inactive cover deposit	Floodplain, inactive cover deposit	N/A

cover under the pipeline. The same measurements were taken in April as in March, except that the downwind background transects were eliminated. Sampling was accomplished in two days (17 and 20 April), with two days of inclement weather intervening between the sampling bouts. The weather days were characterized by ground-blizzard conditions—extremely limited visibility and high winds—although no new snowfall accompanied the blizzard. The storm was from the prevailing direction of winter winds (NE to ENE) with gusts reaching 40 knots.

At each sampling segment, a total 30 snow-depth measurements and 10 pipe clearance measurements were taken beneath the pipe across five consecutive VSM spans. To account for microscale topographical variation of the tundra surface, snow depth at each sampling point was determined by recording three measures of the snow-pack thickness (within a 1.5-m radius) using a meter stick. Snow depth was then presented as the mean of these three measurements. At each location, snow depths were also measured along two control transects oriented parallel to and 100 m distant from the pipe. Background transects were sampled both upwind and downwind of the pipeline during the 26–30 March sampling period. An ice road was constructed parallel to the Alpine pipeline east of the Colville River, ~70–100 m distant on the downwind (south) side of the pipeline. The downwind background transects were not sampled in April due to the proximity of this ice road in the Alpine Corridor and uncertainty as to whether these sites represented true "control" samples.

During both field sampling periods, surveys ongoing construction and operation of an ice road immediately adjacent to the pipe for access by workers and equipment. This ice road was maintained and repeatedly cleared of drifts; therefore, several segments could not be sampled due to the ongoing construction or extensive perturbation of the snow pack, resulting in spurious depth measurements. In a number of instances, the snow beneath the pipe had been disturbed and we had to search for undisturbed sites to measure depths (Figure 5).

Nearly all segments were sampled by parking on adjacent access roads and walking to and along the pipeline. Four of the six segments sampled in April along the Alpine pipeline on the Colville River Delta (Figure 6) were far enough from the ice road to make walking to the sampling points impractical, so we used a tracked vehicle (Tucker Snowcat) for access from the Alpine camp.

During the April sampling trip, perpendicular transects were sampled in eight pipeline segments (T-02, T-03, T-09, T-10, A-01, A-09, D-04, and D-06), extending from the pipeline to a distance of 100 m upwind. Snow depths were measured at 10-m intervals, averaging three measurements made within a 1.5-m radius.

PIPE CLEARANCE EVALUATION

Pipe clearances required for snowmachine passage typically range from 110–135 cm for large, late-model machines. Older models with smaller engines typically require less clearance (down to 105 cm). To encompass this variability, we considered a clearance of 140 cm or more to be adequate for a snowmachine to pass easily beneath a pipeline.

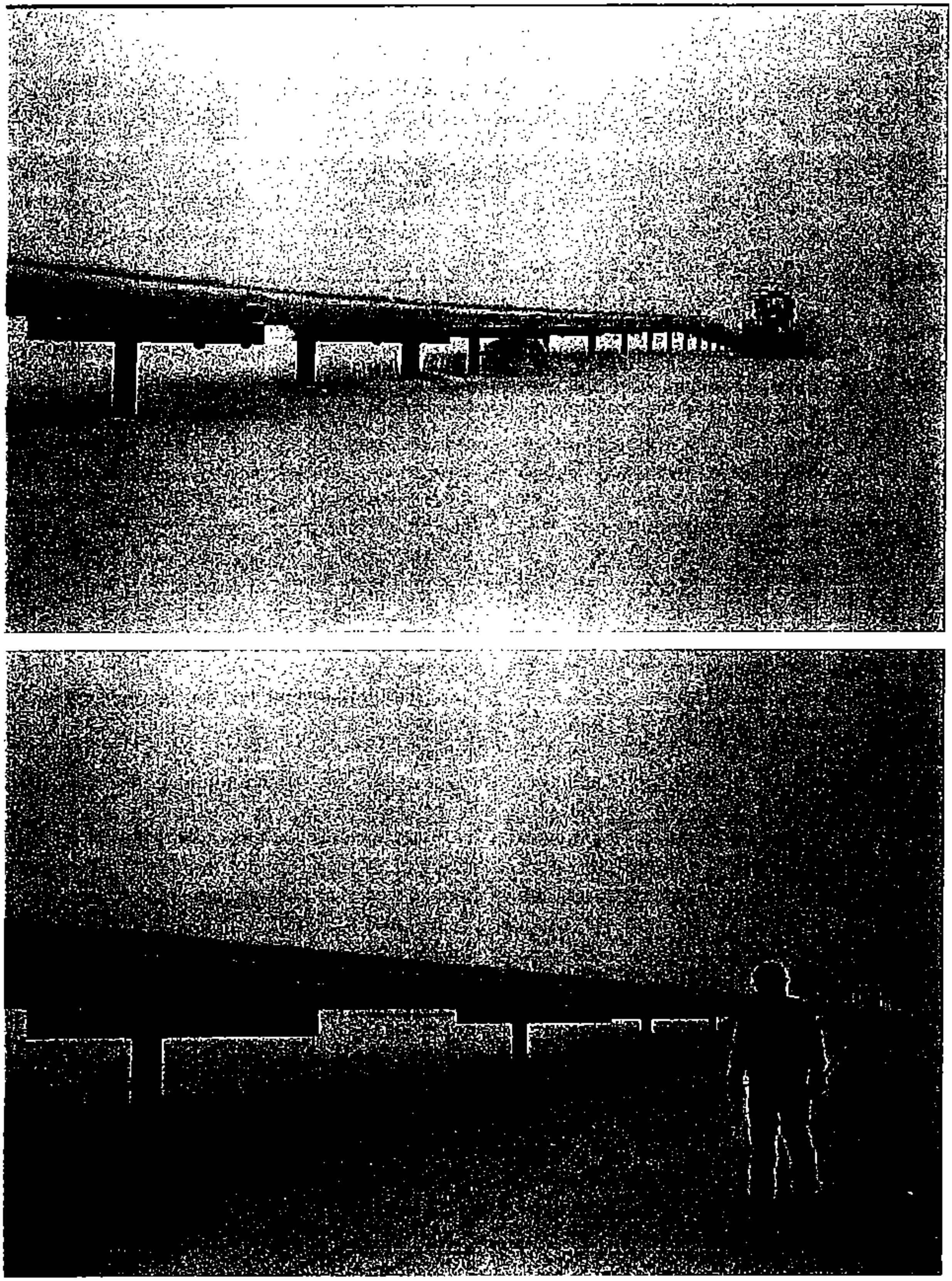

Figure 5. Disturbance of snow under the Tarn pipeline due to ice-road maintenance, March 2001.

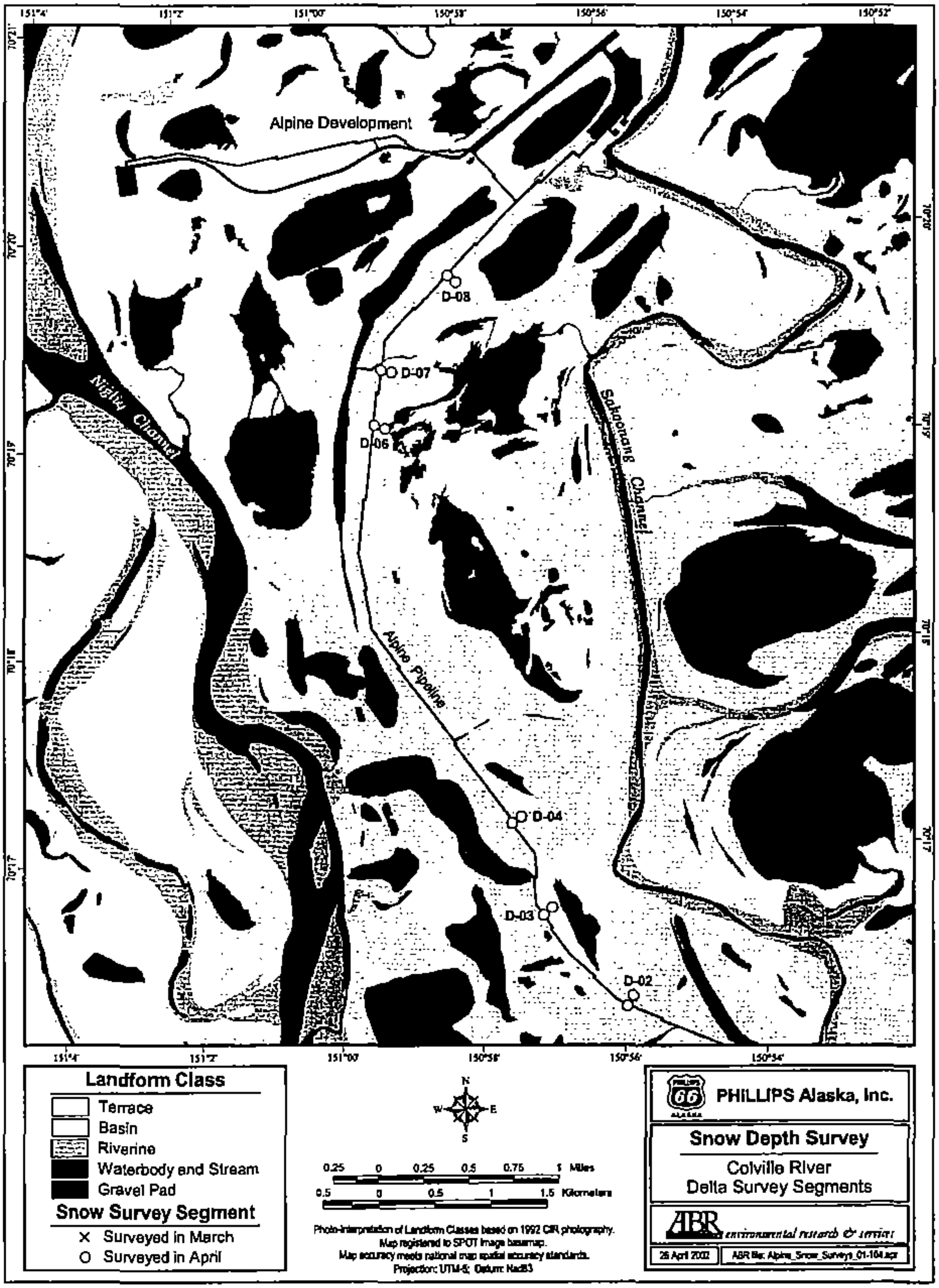

Figure 6. Location of survey segments for snow-depth surveys in relation to terrain in the Colville River Delta study area, March–April 2001.

The ability of caribou to cross unimpeded under elevated pipelines has been the subject of extensive discussion and study on the North Slope since the early 1980s. Mitigation research summarized by Cronin et al. (1994) demonstrated that pipeline elevated to the standard stipulated minimum height (ground clearance) of 5 feet (152 cm) was sufficient to allow free passage of caribou during the snow-free season. Winter crossing studies have not been conducted because most caribou winter far south of the oilfields, but it is assumed that the clearance requirement would be similar for caribou attempting to cross beneath elevated pipelines when snow covers the ground.

Thus, at 140–152 cm, the minimum ground clearance for crossings was similar for both snowmachines and caribou. Pipelines high enough to assure free passage of caribou would also permit unobstructed passage by humans on snowmachines. These heights are conservative values that do not consider compression of the snow cover by the snowmachines or the animals; that is, both machines and animals would sink into the snow to some extent while crossing beneath pipelines. We had no practical way to assess the extent of compression, however, so for the purposes of this study we used 152 cm as the threshold for defining low clearance, thereby including the values for both snowmachines and caribou.

DATA ANALYSIS

The field data were analyzed to evaluate patterns of snow accumulation under pipelines, pipe clearance, and the relationship of pipe clearance to snow accumulation in the three study areas. Snow accumulation was compared with background (upwind) samples within areas of like pipeline orientation in each study area. Differences in depth were considered significant at $P < 0.05$, as determined by univariate analysis of variance (using SPSS, Inc. analytical software). In a similar analysis, measurements for individual segments were compared with those from adjacent upwind (and downwind) background transects. Mean snow depths under pipelines and adjacent background depths for each study area (Tarn, Alpine Corridor, and Colville River Delta) were similarly compared. To examine the relationship between pipe clearance and snow depth under the pipeline, a linear regression was computed using all points measured in both March and April. Riverine sites were excluded due to the complicating effects of local topography (see above), and sites where pipe clearance exceeded 3 m (the limit of our measurement capability) also were excluded.

RESULTS

SNOW DEPTH

In March, inclement weather limited field measurements to the Tarn study area (Figure 3) and three segments in the Alpine Corridor (Figure 4). Along N–S portions of the Tarn pipeline, snow depth averaged 33 cm in basins, 37 cm on terraces, and 63 cm in riverine terrain (Table 2 values rounded to the nearest cm). Corresponding upwind background depths were 44 cm in basins, 38 cm on terraces, and 31 cm in riverine areas. Along E–W portions of the Tarn pipeline, snow depth under the pipeline averaged 35 cm in thaw basins, 32 cm on terraces, and 94 cm in riverine terrain. In comparison, upwind background depths were 21 cm in basins, 28 cm on terraces, and 35 cm in riverine areas. In the Alpine Corridor, mean snow depths under the pipeline were 37 cm on terraces and 47 cm in riverine areas, compared with upwind background depths of 38 cm on terraces and 49 cm in riverine areas (no basin terrain was sampled in this study area in March).

Background snow depths in March were significantly greater in downwind transects than under the pipeline along the N–S-oriented portion of the Tarn pipeline (Table 3). While this difference could have been due to the presence of an elevated pipeline running perpendicular to the prevailing winds, other local factors also may have contributed to this result. A number of the downwind transects were on or near the transition areas between basin and terrace landform types. Such areas often act as snow traps (Benson and Sturm 1993) and thus may have significantly deeper snow deposits than the surrounding terrain. The second confounding factor along the Tarn pipeline was the presence of the ice road immediately adjacent to the VSMs on the west side of the pipeline. Ice-road construction and snow clearing along the ice road disrupted natural snow

Table 2. Snow depth (mean ± S.D., in cm) for segments stratified by month, study area, pipeline orientation, and terrain group. Different letters indicate significant differences between means within a column.

	Basin			Terrace			Riverine		
Month / Location	Mean ± S.D.	*n*	Sig.[1]	Mean ± S.D.	*n*	Sig.[1]	Mean ± S.D.	*n*	Sig.[1]
MARCH									
Tarn N–S Orientation									
Pipeline	32.8 ± 10.3	20	a	36.8 ± 10.9	30	a	63.3 ± 57.7	10	a
Upwind	43.7 ± 14.3	20	a	37.8 ± 12.3	30	a	31.2 ± 8.6	10	a
Downwind	57.6 ± 30.8	20	b	56.7 ± 16.3	30	b	36.9 ± 15.2	10	a
Tarn E–W Orientation									
Pipeline	34.7 ± 15.7	20	a	31.9 ± 13.6	40	ab	94.2 ± 65.7	20	b
Upwind	21.1 ± 9.2	20	b	28.3 ± 8.8	40	a	34.8 ± 16.9	20	a
Downwind	26.5 ± 9.5	20	b	37.8 ± 16.4	40	b	64.9 ± 43.7	20	b
Alpine Corridor									
Pipeline				37.2 ± 12.8	20	a	47.1 ± 11.4	10	a
Upwind				38.0 ± 10.8	20	a	49.0 ± 10.4	10	a
Downwind				24.6 ± 6.5	20	b	79.1 ± 23.8	10	b
APRIL									
Tarn N–S Orientation									
Pipeline	29.8 ± 12.7	20	a	33.8 ± 11.3	20	a			
Upwind	39.0 ± 8.3	20	b	36.1 ± 6.1	20	a			
Tarn E–W Orientation									
Pipeline	36.0 ± 13.3	30	b	26.4 ± 9	30	a			
Upwind	26.9 ± 7.0	30	a	23.6 ± 8.5	30	a			
Alpine Corridor									
Pipeline	49.4 ± 13.4	30	b	30.5 ± 16.2	30	a			
Upwind	30.3 ± 9.8	30	a	40.7 ± 18.6	30	b			
Colville River Delta									
Pipeline	23.1 ± 10.1	30	a	19.1 ± 9.8	30	a			
Upwind	24.8 ± 10.5	30	a	23.5 ± 10	30	a			

[1] Significance of means test: different letters indicate significant differences among means. For example, the mean snow depth in March in basins along the Tarn E–W orientation differed significantly between the pipeline and the mean background depths: the snow depth under the pipeline (a) was greater than either the upwind or downwind means (b), which did not differ.

Table 3. Summary of statistical differences of snow depth under pipelines compared to background measures in three study areas of the western North Slope, 2001. (NS = not significant, dash = not sampled).

Sample Area/Terrain	26–30 March	17–20 April
Tarn E–W		
Terrace	Pipeline > Background	NS
Basin	Pipeline > Background	Pipeline > Background
Riverine	Pipeline > Background	–
Tarn N–S		
Terrace	NS	NS
Basin	Pipeline < Background	Pipeline < Background
Riverine	NS	–
Alpine Corridor		
Terrace	NS[1]	Pipeline < Background
Basin	–	Pipeline > Background
Riverine	NS[1]	–
Colville River Delta		
Terrace	–	NS
Basin	–	NS

[1] Sampling was incomplete at these sites.

accumulation patterns along the pipeline (Figure 5) and likely resulted in aberrant patterns of snow transport near the pipeline. Because of these problems, downwind background transects were not repeated during the April field survey.

Measurements in April were obtained at all planned sampling locations except for two sites along the Tarn pipeline that were relocated due to their proximity to ice pads and roads. In addition, the riverine terrain group was eliminated from the sampling design due to the large variance in snow depth associated with uneven terrain and drifting in that terrain group. Overall, April snow depths were only slightly less than those measured in March.

April snow depths under N–S portions of the Tarn pipeline averaged 30 cm in thaw basins and 34 cm on terraces (Table 2 values rounded to the nearest cm), compared with average background depths upwind of 39 cm and 36 cm, respectively. Along E–W portions of the Tarn pipeline in April, average snow depths under the pipeline were 36 cm in basins and 26 cm on terraces, compared with upwind background depths averaging 27 cm in basins and 24 cm on terraces. In the Alpine Corridor, April snow depths under the pipeline averaged 49 cm in basins and 31 cm on terraces, whereas upwind background snow depths averaged 30 cm in basins and 41 cm on terraces. In the Colville River Delta study area, snow depths under the pipe averaged 23 cm in basins and 19 cm on terraces. Upwind background snow depth means were 25 cm in basins and 24 cm on terraces (Table 2).

In both March and April, snow depths under pipelines were significantly higher ($P < 0.05$) than background (upwind) measures in some segments and lower in others (Table 3). In March, snow depths under pipelines were significantly higher in all terrain groups along the E–W areas of the Tarn pipeline. On the N–S sections of the Tarn pipeline, snow depths under the pipeline were less than background levels in basin areas and were not significantly different in the other terrain groups.

A similar pattern was observed in April. Snow depths under pipelines were significantly higher than upwind background measures on terraces and in basins along the E–W sections of the Tarn pipeline and in basins in the Alpine Corridor (Table 3). Snow depths under the N–S sections of the Tarn pipeline on terraces and under the Alpine Corridor pipeline in thaw basins were less than background levels. Snow depths under the Alpine pipeline in the Colville River Delta study area did not differ significantly from background levels.

Snow depths under pipelines along individual sampling segments were compared with the adjacent background samples to present a more detailed view of the patterns of snow accumulation. Segments with a significant difference in snow depths under the pipeline compared with local background levels only occurred along E–W sections of pipeline in the Tarn and Alpine Corridor study areas (Table 4).

Across the three study areas, the depth of snow under pipelines and on background transects varied significantly in April (Table 5). Snow depths in April under pipelines were greatest in the Alpine Corridor (39.9 ± 17.6 cm), intermediate in the Tarn area (31.4 ± 12.1 cm) and least in the Colville River Delta area (21.1 ± 10.1 cm). Background snow depths did not differ significantly between the Tarn area and the Alpine Corridor (30.2 ± 9.8 cm vs. 35.5 ± 15.6 cm), but were significantly greater than background depths on the Colville River Delta (24.2 ± 10.1 cm).

A record of snow depths extending back to 1983 was obtained for the Kuparuk Field. Over the 19 years of the record, Kuparuk snow depths in early April ranged from 5.1 cm to 35.6 cm, with a mean of 19.5 cm. Snow depths in 2001 slightly exceeded the average, ranging from 22.8 cm to 25.4 cm, with a mean of 24.6 cm.

Transects measured perpendicular to pipelines illustrate the pattern of snow deposition along the two principal pipeline orientations (E–W and N–S). Elevated pipelines running nearly parallel to the prevailing wind direction (NE) tended to have a plume of deeper snow within 20 m of the pipeline (segments T-02 and T-03 [Figure 7], segments A-01 and A-09 [Figure 8]). This pattern was obscured somewhat by the presence of the ice road in the Tarn area. Transects extending out from N–S-oriented pipelines (segments T-10 and T-09 [Figure 7] and segments D-06 and D-04 [Figure 9] did not show any pattern of accumulation near the pipeline.

PIPE CLEARANCE

In March, clearance under the E–W portions of the Tarn pipeline ranged from 81 to 286 cm among sampling locations (Table 4), with a grand mean of 158.4 cm for seven segments. Along the N–S portions of the Tarn pipeline, clearance ranged from 119 to 193 cm, with a grand mean of 160.7 cm for seven segments. Clearance was greater in the stations measured along the Alpine Corridor, ranging from 148 to 218 cm, with a grand mean of 169.4 cm for three segments.

In April, clearance under the E–W portions of the Tarn pipeline ranged from 94 to 179 cm among sampling locations (Table 4), with a grand mean of 145.7 cm for five segments. Along the N–S portions of the Tarn pipeline, clearance ranged from 81 to 286 cm, with a grand mean of 173.8 cm for five segments. Clearance again was greater along the Alpine Corridor, ranging from 118 to 289 cm, with a grand mean of 173.8 cm for six segments. Pipe clearance in the Colville River Delta was high, often exceeding our ability to measure it (>3 m). The minimum clearance encountered on the delta was 190 cm. Overall, snow depth under pipelines in April was negatively correlated with pipe clearance measurements (r = 0.254, P <0.001; all individual measures combined).

In the Tarn study area, 7 of 10 segments sampled in April (70% of total segments, both E–W and N–S orientations) had at least one occurrence of a clearance less than 152 cm within the 100-m transect surveyed beneath the pipeline, and the mean clearance height was <152 cm in 4 (40%) of those segments (Table 4). However, in all but one segment (i.e., 90% of total segments), clearances greater than 152 cm occurred within the same 100-m length of pipeline sampled. In the Alpine Corridor (E–W orientation), 5 of 6 sampling segments (83%) had at least one occurrence of pipe clearance less than 152 cm, and the mean clearance for 3 of 6 segments (50%) was less than 152 cm (Table 4). No areas of low clearance below 152 cm were observed in the Colville River Delta. Continuous stretches of lowered clearance were observed only along the Tarn pipeline, where 2 of 10 100-m segments (20%) sampled in April had pipe clearances entirely below 152 cm (Table 4). Pipe clearance on the Colville River Delta was rarely below 200 cm and often exceeded 300 cm.

Table 4. Pipeline clearance heights (mean and range in cm), and snow depths (mean ± S.D., in cm) under elevated pipelines and in background transects in three study areas, March–April 2001.

			March			April		
Segment	Landform	Type	Pipe Clearance Mean (Range)	Snow Depth Mean ± S.D.	Sig.[1]	Pipe Clearance Mean (Range)	Snow Depth Mean ± S.D.	Sig.[1]
Tarn E–W Orientation								
T-01	Riverine	Pipeline	112.0 (81–159)	147.0 ± 44.3	c			
		Upwind		42.3 ± 20.3	a			
		Downwind		104.8 ± 21.0	b			
T-05	Riverine	Pipeline	247.7 (223–286)	41.3 ± 30.7	a			
		Upwind		27.4 ± 8.2	a			
		Downwind		24.9 ± 6.8	a			
T-03	Terrace	Pipeline	162.2 (156–168)	25.6 ± 4.4	a	157.4 (147–166)	26.5 ± 7.7	a
		Upwind		21.3 ± 9.9	a		24.3 ± 10.8	a
		Downwind		23.5 ± 8.3	a			
T-04	Terrace	Pipeline	141.7 (130–150)	25.7 ± 10.3	a	143.4 (134–153)	32.4 ± 8.3	b
		Upwind		23.6 ± 4.5	a		19.1 ± 6.7	a
		Downwind		57.8 ± 16.3	b			
T-08	Terrace	Pipeline	127.7 (116–137)	52.9 ± 2.9	c			
		Upwind		37.5 ± 4.4	b			
		Downwind		30.3 ± 7.9	a			
T-02	Basin	Pipeline	170.6 (158–177)	21.4 ± 4.4	a	168.6 (159–179)	22.2 ± 4.7	a
		Upwind		15.4 ± 7.3	a		24.3 ± 6	a
		Downwind		19.2 ± 5.3	a			
T-06	Basin	Pipeline	132.0 (121–144)	48.0 ± 10.4	b	129.4 (121–145)	43.6 ± 8.8	b
		Upwind		26.8 ± 7.3	a		25.7 ± 8.3	a
		Downwind		33.7 ± 6.8	a			
T-07	Basin	Pipeline				112.7 (94–130)	42.2 ± 12.2	b
		Upwind					30.6 ± 5.4	a
Tarn N–S Orientation								
T-12	Riverine	Pipeline	159.5 (124–181)	63.3 ± 57.7	a			
		Upwind		31.2 ± 8.6	a			
		Downwind		36.9 ± 15.2	a			
T-09	Terrace	Pipeline	173.0 (161–179)	23.5 ± 3.7	a	162.6 (150–169)	20.3 ± 7.2	a
		Upwind		30.9 ± 4.4	b		27.3 ± 5.5	b
		Downwind		39.5 ± 5.7	c			
T-11	Terrace	Pipeline	171.1 (162–176)	35.0 ± 5.2	a	165.5 (159–172)	33.4 ± 9.8	a
		Upwind		29.8 ± 8.0	a		33.2 ± 5.4	a
		Downwind		56.9 ± 11.7	b			
T-13	Terrace	Pipeline	153.3 (124–181)	39.3 ± 12.5	a	151.9 (135–162)	34.1 ± 13.1	a
		Upwind		43.1 ± 9.4	a		39.0 ± 5.6	a
		Downwind		62.7 ± 21.0	b			
T-14	Terrace	Pipeline	146.3 (131–155)	36.2 ± 13.7	a			
		Upwind		40.5 ± 15	a			
		Downwind		50.4 ± 13.8	a			

Table 4. (Continued).

			March			April		
Segment	Landform	Type	Pipe Clearance Mean (Range)	Snow Depth Mean ± S.D.	Sig.[1]	Pipe Clearance Mean (Range)	Snow Depth Mean ± S.D.	Sig.[1]
T-10	Basin	Pipeline	169.6 (162–178)	25.0 ± 3.8	a	165.7 (160–176)	22.5 ± 9.7	a
		Upwind		37.5 ± 12.3	b		39.7 ± 11	b
		Downwind		30.2 ± 2.5	a			
T-16	Basin	Pipeline	164.4 (119–193)	40.5 ± 8.8	a	152.5 (119–184)	37.0 ± 11.4	a
		Upwind		50.0 ± 14	a		38.4 ± 4.8	a
		Downwind		85.0 ± 18.1	b			
Alpine Corridor								
A-01	Terrace	Pipeline	154.7 (148–161)	35.9 ± 16.9	ab	154.0 (137–167)	30.6 ± 10.2	a
		Upwind		44.7 ± 11.2	b		34.9 ± 13.5	a
		Downwind		28.5 ± 6.9	a			
A-03	Terrace	Pipeline	169.1 (160–180)	38.5 ± 7.4	b	145.3 (124–156)	46.9 ± 9.2	a
		Upwind		31.3 ± 4.6	a		37.4 ± 24.4	a
		Downwind		20.8 ± 2.8	a			
A-08	Terrace	Pipeline				282.6 (276–289)	14.0 ± 7.7	a
		Upwind					49.8 ± 14.1	b
A-02	Basin	Pipeline				145.4 (132–156)	48.1 ± 8.6	b
		Upwind					34.2 ± 8.2	a
A-04	Basin	Pipeline				146.0 (118–166)	52.4 ± 12.2	b
		Upwind					28.0 ± 4.6	a
A-09	Basin	Pipeline				169.4 (150–183)	47.8 ± 18.4	b
		Upwind					28.6 ± 14.1	a
A-05	Riverine	Pipeline	184.5 (160–218)	47.1 ± 11.4	a			
		Upwind		49.0 ± 10.4	a			
		Downwind		79.1 ± 23.8	b			
Colville River Delta								
D-02	Terrace	Pipeline				232.6 (198–249)	22.1 ± 11.3	a
		Upwind					18.5 ± 9.3	a
D-03	Basin	Pipeline				>300 (>300)	13.1 ± 3.7	a
		Upwind					14.6 ± 5.4	a
D-04	Terrace	Pipeline				320.7 (310–325)	11.5 ± 4.2	a
		Upwind					26.2 ± 8.7	b
D-06	Basin	Pipeline				>300 (>300)	32.6 ± 7.7	a
		Upwind					29.7 ± 7.9	a
D-07	Basin	Pipeline				>300 (>300)	23.5 ± 6.6	a
		Upwind					30.1 ± 9.4	a
D-08	Terrace	Pipeline				202.2 (190–213)	23.8 ± 8.5	a
		Upwind					25.8 ± 10.6	a

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[1] Significance of means test: different letters indicate significant differences among means. For example, for the Tarn E–W Orientation at segment T-01 in March, the mean snow depth differed significantly among all 3 types: the upwind snow depth was lowest (a) and it differed from the intermediate measurement of downwind snow depth (b), which also differed from the highest snow depth measured at the pipeline (c).

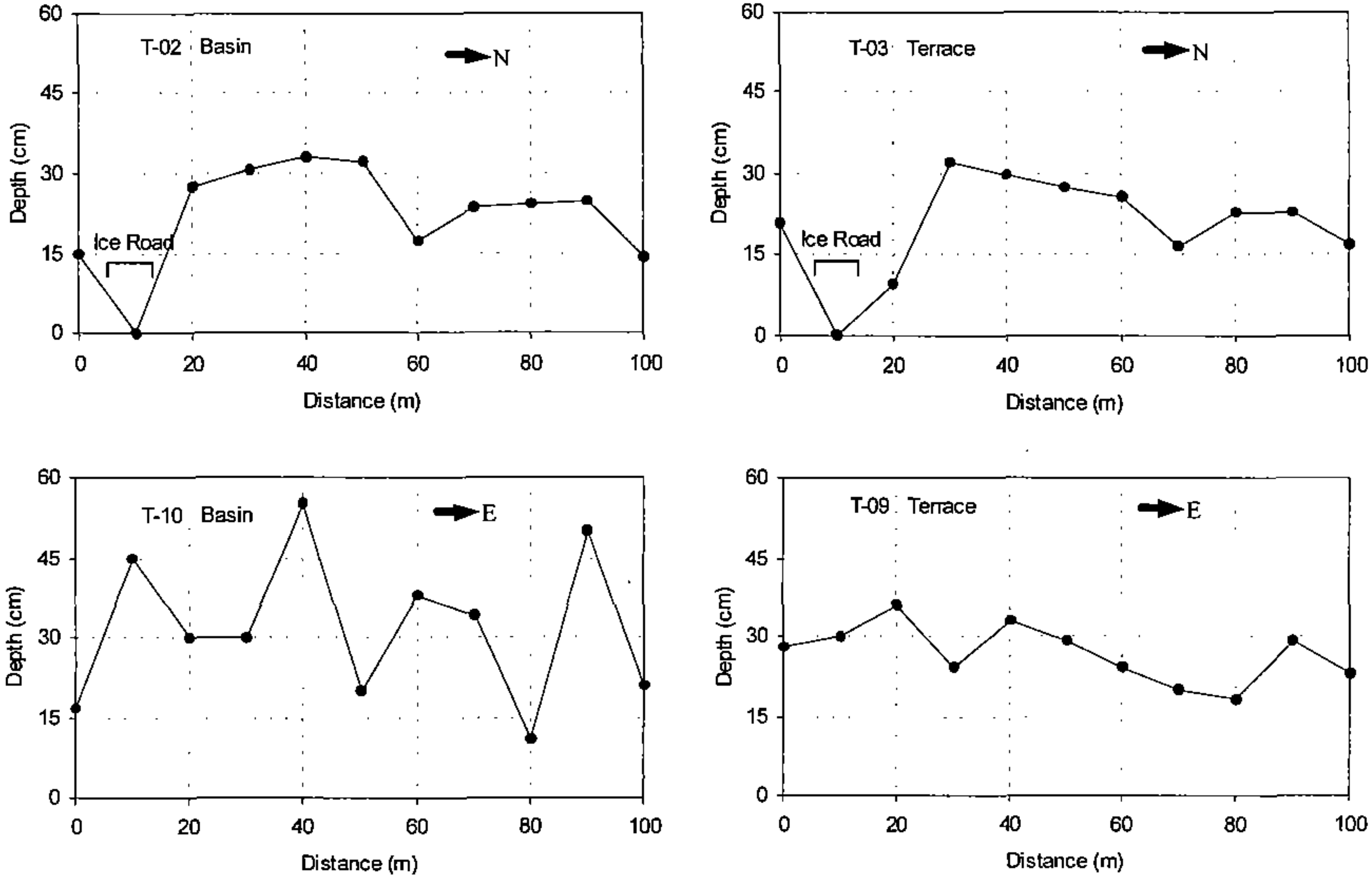

Figure 7. Snow depth measured on upwind transects perpendicular to pipeline orientation in the Tarn study area, April 2001. Transects extended north from E-W-oriented pipeline (top) and east from N-S-oriented pipeline (bottom).

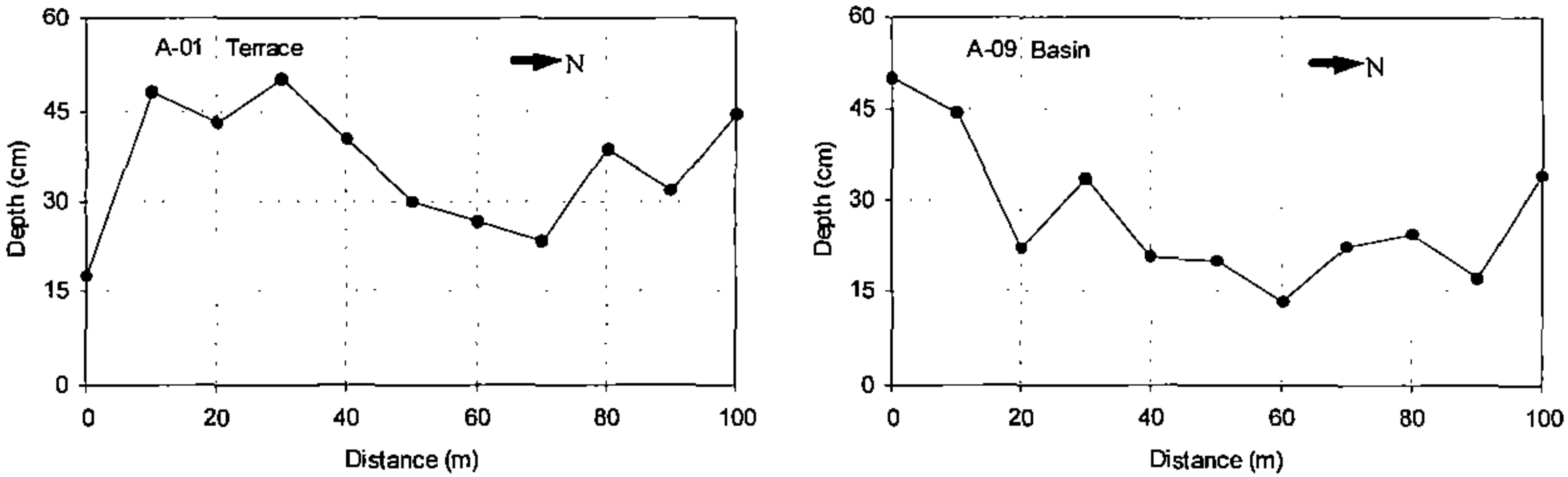

Figure 8. Snow depth measured on upwind transects perpendicular to pipeline orientation in the Alpine Corridor study area, April 2001.

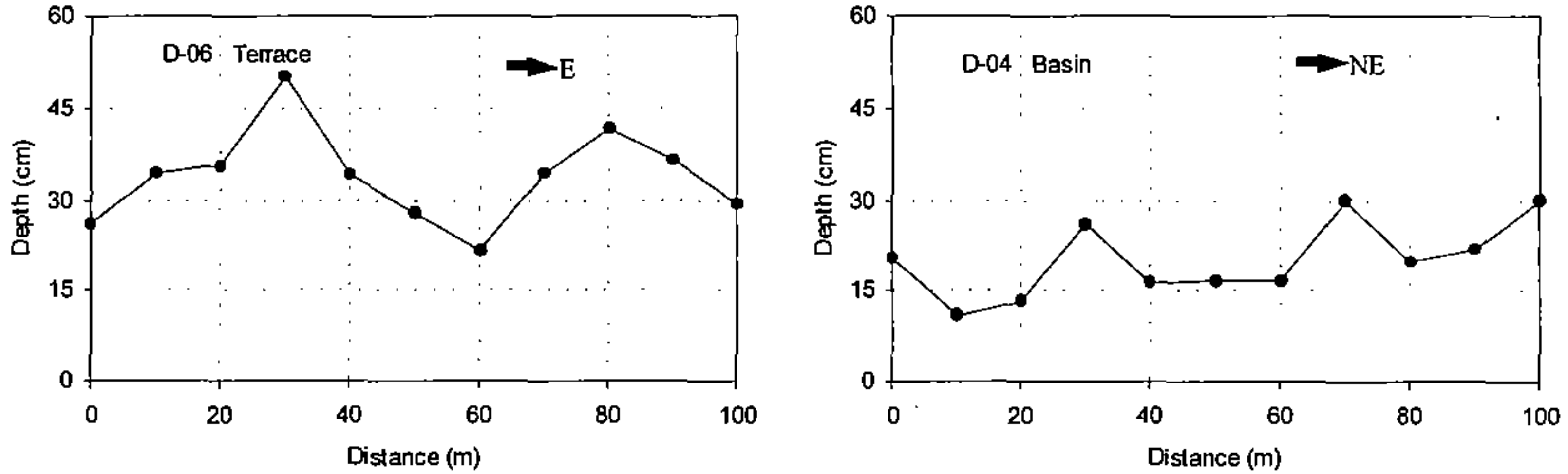

Figure 9. Snow depth measured on upwind transects perpendicular to pipeline orientation in the Colville River Delta study area, April 2001.

Table 5. Snow depth (in cm) under pipelines and in adjacent background locations in three study areas surveyed in April 2001. Different letters indicate significant differences between means within a column.

	Snow Depth under Pipelines		Background Snow Depth	
Study Area	Mean ± S.D.	Sig.[1]	Mean ± S.D.	Sig.[1]
Tarn	31.4 ± 12.1	b	30.2 ± 9.8	b
Alpine Corridor	39.9 ± 17.6	c	35.5 ± 15.6	b
Colville River Delta	21.1 ± 10.1	a	24.2 ± 10.1	a

[1] Significance of means test: different letters indicate significant differences among means.

DISCUSSION

Snow depths at most sampling segments (59% of March segments and 55% of April segments) did not differ significantly between the pipelines and background levels upwind. Significant accumulation of snow under pipelines compared with background levels upwind occurred at about one quarter of the sites sampled in both periods — 4 (24%) of the 17 segments surveyed in the three study areas in March and 6 (27%) of the 22 segments surveyed in April 2001 (Table 4). The average difference in March was 37.1 cm, or 14.6 inches more, under the pipelines (range 7.2–104.7 cm, or 2.8–41.2 inches) at the 4 sites) than in background areas; the March results were heavily influenced by one segment of unusually deep snow in riverine terrain, however. In April, the average difference was 16.7 cm, or 6.6 inches, more under pipelines (range 11.6–24.4 cm, or 4.6–9.6 inches) at the 6 sites than in background areas. In both March and April, snow depth under pipelines was significantly less than upwind background depths at 18% of the segments sampled.

Local factors such as landform (thaw basin or terrace terrain), pipeline orientation, and pipe clearance can be used to identify areas where significant accumulations of snow under pipelines can be expected. Snow cover was most likely to be significantly deeper than background levels under E–W pipelines traversing thaw basins. Snow-depth measurements in Kuparuk taken as part of a long-term (19-year) monitoring project suggest that snow depths in 2001 were slightly above average.

For snow to accumulate, elevated pipelines need to present enough of an obstruction to reduce wind velocities below a threshold value. This obstruction effect may explain why most of the observations of increased snow depths under pipelines occur along stretches of E–W-oriented pipelines. Pipelines oriented at oblique angles or parallel to prevailing winter winds present the largest cross-sectional area (and hence the largest wind obstruction). Significant accumulation of snow under pipelines was more frequent in basin areas than on terraces. Thaw basins are known to be natural traps for blowing snow (Benson and Sturm 1993). This trap effect is most noticeable on the lee side of basin rims.

Decreased clearance between an elevated pipeline and the ground enhances the windbreak effect of the pipeline. Observations in both March and April 2001 showed that snow was more likely to be deeper under pipelines than background levels in areas where the mean pipe clearance above the snow surface was less than 152 cm. In April, 5 of the 6 sites with significant snow accumulation under the pipeline compared with local background levels had mean pipe clearances of less than 152 cm. Ice-road construction and maintenance immediately adjacent to the pipeline in the Tarn study area may have caused artificially low measures of snow depths under the pipeline. During the March survey in the Tarn area, it appeared that snow was cleared under the pipe rack. In both March and April, we were careful to sample only areas that appeared undisturbed, but high winds probably erased signs of prior snow-pack disturbance. Based on the results from the Alpine Corridor study area, we expected to see a greater accumulation of snow under the pipeline in the Tarn study area due to the somewhat lower pipeline elevations present there.

In addition to information gained on the dynamics of snow accumulation around pipelines, these observations show how the distribution of snow varies over relatively small distances on the North Slope. Few data are available on snow-pack depths in this area of Alaska, and little is known about the distribution of snow across the North Slope (Benson and Sturm 1993). Based on our background measurements, snow depths in the Colville River Delta study area were significantly lower than in the Tarn and Alpine Corridor study areas.

We conclude from this study that E–W-oriented elevated pipelines with a clearance height above the snow surface of 152 cm (5 feet) or less are most likely to accumulate snow at depths greater than surrounding background levels. Furthermore, the greatest snow depth likely will occur where pipelines pass through low-lying terrain such as thaw basins and riverine areas. On the Colville River Delta, where pipe clearances typically exceeded 250 cm (8.2 feet), no evidence of significant snow accumulation under pipelines was observed. The results of this study indicate that the effective clearance for the passage both of caribou and humans on snowmachines beneath elevated pipelines may be reduced below the 152-cm threshold value in certain types of terrain (thaw basins and riverine habitats) and along stretches of 5-foot-minimum height, E–W-oriented pipelines (such as portions of the Tarn pipeline). Throughout most of the three study areas, these stretches of reduced pipe clearance rarely were continuous and sufficient clearance above the threshold clearance value usually occurred nearby.

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