Design Options for Offshore Pipelines in the US Beaufort and Chukchi Seas

APPENDIX A

Report R-07-078-519
MMS Contract M-07-PC-13015

Prepared for:
US Department of the Interior
Minerals Management Service

March 2008

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Prepared for:
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Prepared by:
C-CORE

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United States Department of the Interior
Minerals Management Service

Review of Existing Ice Gouge Data from the Beaufort Sea, Alaska

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EXECUTIVE SUMMARY

This report presents the results of a study to research, review and analyze existing ice gouge data pertinent to the Alaskan Beaufort Sea in the 0m – 60m water depth range. Review and analysis has been conducted of multiple years of ice gouge data obtained from existing surveys conducted in the US Beaufort Sea and assessed on the basis of data quality, data accuracy, and applicability to the area. Summary plots of the compiled data are provided in the report Appendices.

Factors which influence ice gouge depths include the size and shape of the gouging ice keel, seabed geotechnical conditions, environmental driving forces, and gouge orientation, among others. Ice gouge incisions may exhibit narrow, single keeled incision patterns or wide, multi-keeled patterns with multiple gouge incisions in a raking pattern.

Design ice gouge depths are imperative to comprehensive pipeline design within areas prone to ice-gouging events in order to ensure the integrity of a trenched and buried pipeline during its designed operational lifetime. Key ice gouge factors obtained from the existing data set assessments include location, water depth, gouge depth, gouge width, dominant orientation, obliteration rates, and recurrence and / or crossing rate, among other pertinent parameters for pipeline design.

Data sets analyzed included those of known age (termed "new") and those of unknown age. Maximum ice gouge data has been observed and recorded, which includes a maximum observed ice gouge depth of 5.5m and an unrelated maximum ice gouge width of 265m. The depth measurement corresponded to an ice gouge event of unknown age, whereas the width measurement was from a new gouge. The maximum width resulted from a multiplet gouge event which contained multiple individual ice gouges, although the number of individual gouges within the multiplet was not recorded. Multiplet ice gouges occur when wide ice keels with multiple keel projections rake the seabed to produce a wide multi-gouge feature.

The maximum observed new ice gouge depth was 3.0m and corresponded to gouges located in 12.1m and 15m water depths. The maximum new ice gouge

width was 265m, which corresponded to a multiplet gouge located in 16.5m water depth. Ice gouge depths were generally observed to increase with increasing water depth, with the deeper ice gouges occurring beyond the 20m isobar. Ice gouge width data exhibited significant scatter among the analyzed data sets, with the wider gouges occurring in the 10m – 60m water depth range. Limited new gouge data was available beyond 20m water depths. The deepest and widest new gouges occurred in the 10m – 20m water depth range. Analysis of ice gouge width/depth relationships and distributions has indicated a general data trend of decreasing gouge width with increasing gouge depth.

Little information regarding the most probable ice gouge shape and ice keel attack angle was determined from the current study. The effect of ice keel attack angle/shape requires further investigation, as this preliminary work has not produced any conclusions regarding the most probable ice gouge shape or ice keel attack angle that may be expected and utilized in pipeline design. Similarly, insufficient data was available for substantial analysis of short-term ice gouge infilling processes. Long-term ice gouge infilling and obliteration were investigated, with the effects of these processes predominantly observed in sandy seabed sediments. Stiff silt seabed sediments have commonly displayed significantly lower infilling rates. These results are based on limited available data sets and associated investigations.

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1. INTRODUCTION

A number of years of ice gouge statistical data are required for pipeline design. Ice gouge statistics are normally reported as having a maximum depth and an overall or maximum width. This could lead to the interpretation that there could be a deep gouge over a significant width, when, in fact, the maximum gouge depth may have been the result of the deepest part of the keel (or a single keel in a multi-keeled event) acting over a significantly smaller width (on the order of meters). Not only is the maximum gouge depth important, but also the localized width over which this maximum depth occurs. The current method of analyzing subgouge soil deformation interaction with a trenched pipeline uses the design ice gouge depth in conjunction with a design ice gouge width. Alternatively, a parametric study is conducted to determine the “worst case” ice gouge width. Both approaches can potentially lead to over-conservative designs.

Investigation and further analysis of existing seabed gouge data is required to determine the appropriate data to be used in design and how widths should be related to design depths (either in a deterministic or a probabilistic design methodology). If data analysis indicates that ice gouge widths can then be described as a function of the individual gouge depths, the potential relationship can be used to evaluate pipeline response to specific design ice gouge events. This ice gouge data would then be updated as more area-specific data becomes available.

The effects of infill rate on ice gouge statistics is a potential design issue that needs to be addressed. Gouges of different depths infill at different rates, which is dependent upon the sediment type and sediment transport characteristics of the area. The effect on ice gouge statistics in relatively benign environments such as the Beaufort Sea should be small but should be addressed.

The ice keel shape in contact with the seafloor during a gouging event is uncertain. This shape and the attack angle have significant effects on the forces required to create a gouge feature and on the associated subgouge soil deformations (for given seabed conditions).

1.1 Scope of Work

The project work scope for the current study is defined by the following four tasks:

(1) Conduct a comprehensive review and analysis of existing, publicly available ice gouge data from the Beaufort Sea and compile relevant design data. Assess the quality and accuracy of the data based on the age of the data, the technology used to collect the data, and other relevant factors. Key information pertaining to ice gouges required from the assessment includes:

- Location
- Water Depth
- Seabed Geotechnical Conditions and Soil Properties
- Age of Gouge (if possible)
- Maximum Gouge Depth
- Overall Gouge Width
- Multi-Incision or Single Incision Gouge
- Side Berm Height
- Observed Length
- Orientation
- Immediate and Long-term Gouge Infill and Weathering
- Gouge Cross Section
- Gouge Crossing Rate

(2) Investigate and develop width/depth relationships/distributions for ice gouges, if such relationships/distributions exist.

(3) Determine the most probable ice keel geometry associated with extreme ice gouge events in the Beaufort Sea, based upon the technical data and reports reviewed as part of the current study.

(4) Generate a comprehensive final report (current report), which integrates the above tasks and results.

1.2 Study Deliverables

The main study deliverable for the current project is this report, which presents the results of comprehensive research and review of existing ice gouge data from a variety of regions of the Alaskan Beaufort Sea. Data is presented for the ice gouge data sets used in analysis, complete with relevant discussions and analyses of ice gouge parameters and extreme events. The quality and accuracy of the compiled data was assessed in its application to pipeline design and burial depths.

Ice gouge width and depth distribution relationships are provided for the analyzed data as well as implications of immediate and long-term gouge infilling.

2. INVESTIGATED REPORT SUMMARIES

Numerous technical reports and studies of ice gouging on the inner shelf of the Alaskan Beaufort Sea have been researched and reviewed as part of the current project desktop study.

Reports have been obtained from the United States Geological Survey (USGS), the U.S. National Geophysical Data Center (NGDC) and the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL).

Table 1, below, presents a summary of the Alaskan Beaufort Sea inner shelf ice gouge data which has been reviewed as part of the current study. Some data sets are the subject of more than one report or study and, therefore, the most applicable report / study has been identified in the table.

Table 1: Summary of Reviewed Ice Gouge Reports and Presented Data

Report / Data Reviewed	Summary of Report / Data Contents	Most Comprehensive Analysis Presented In:
USGS Open-File Report 81-950	Ice gouge data collected West of Canning River, Alaskan Beaufort Sea	USGS Open-File Report 83-706
USGS Open-File Report 82-974	Ice gouge data collected East of Canning River, Alaskan Beaufort Sea	USGS Open-File Report 83-706
USGS Open-File Report 83-706	Collective presentation of USGS Open-File Report 81-950 & 82-974	USGS Open-File Report 83-706
USGS Open-File Report 85-463	Ice gouge data collected in Camden Bay region and Westward	USGS Open-File Report 89-151
USGS Open-File Report 89-151	Updated data previously presented in USGS Open-File Report 85-463	USGS Open-File Report 85-463
CRREL Report 83-21	Independent analysis of USGS Open-File Report 81-950 & 78-730 data. 78-730 analysis of recurrence rates only.	USGS Open-File Report 81-950 & 78-730 (Recurrence Rates Only)
USGS Open-File Report 78-730	Ice gouge data collected in Harrison Bay, Alaskan Beaufort Sea	USGS Open-File Report 78-730

2.1 USGS Open-File Report 85-463

***Rates of Sediment Disruption by Sea Ice as Determined From Characteristics of Dated Ice Gouges Created Since 1975 on the Inner Shelf of the Beaufort Sea, Alaska* (Barnes & Rearic, 1985).**

Geophysical surveys have been conducted and ice gouge data compiled within the above noted United States Geological Survey report for the Thetis Island, Spy Island, Cross Island, Cape Hackett, Flaxman Island, Karluk Island, Cooper Island and Camden Bay areas of the Alaskan Beaufort Sea inner shelf, along nine established survey tracklines. Refer to Figure 1 for an approximate location map of the ice gouge survey tracklines.

Geophysical ice gouge features have been observed along established tracklines oriented perpendicular to the shoreline, which were navigated by a research vessel that performed repetitive side-scan sonar and precision bathymetric surveys. Surveys were conducted in these areas from 1975 – 1982. Range-range electronic navigation provided survey location accuracies of approximately 10 meters. Surveys were conducted in water depths ranging from shore to the 25-meter isobath.

Recorded gouge measurements include gouge depth, width, berm height, dominant gouge trend / orientation, overall length, and the total disruption width for multiple ice gouge swaths (termed ‘multiplet’ gouge events), with measurements referenced from the ‘average’ sea floor position. The majority of recorded gouge depths and associated berm heights were below the lower limit of the fathometer resolution (0.2m), and are thus reported as <0.2m. See Section 4.3, below, for further discussion of the survey sonogram and fathogram resolution. Relative gouge age and morphology of dated gouges is established on the basis of repetitive trackline surveys. More detailed analysis of this data is presented within *Data on the Characteristics of Dated Gouges on the Inner Shelf of the Beaufort Sea, Alaska; 1977-1985,* USGS Open-File Report 89-151 (Section 2.6).

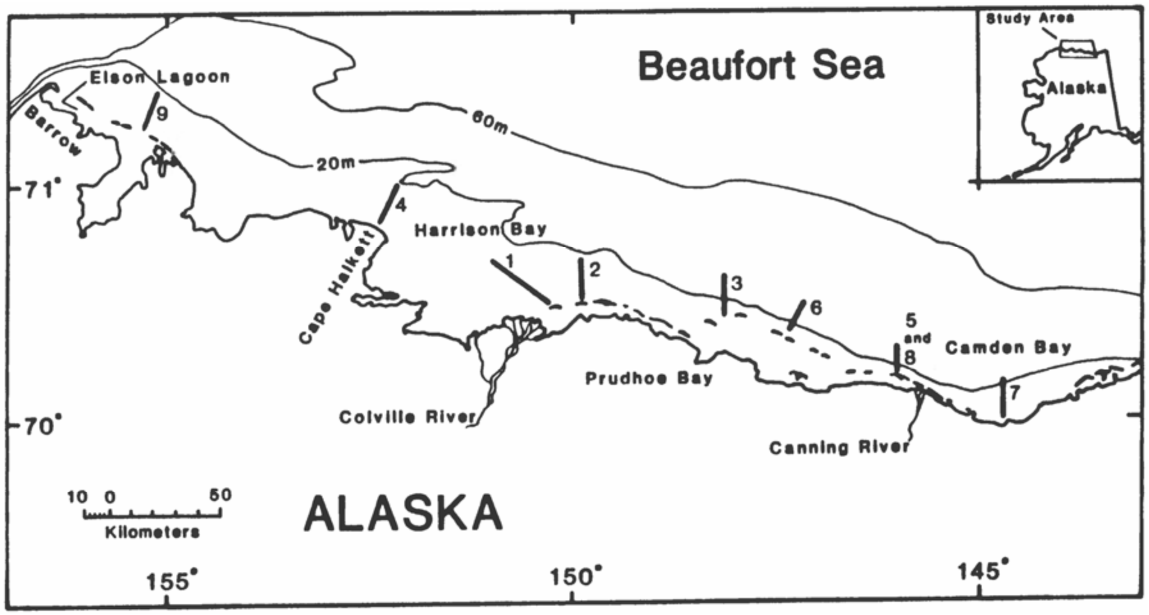

Figure 1: Location Map For Ice Gouge Data Presented Within USGS Open-File Report 85-463 (Barnes & Rearic, 1985).

2.2 USGS Open-File Report 81-950

Ice-Gouge Data, Beaufort Sea, Alaska, 1972-1980 **(Rearic et al., 1981).**

This United States Geological Survey report contains ice gouge data from 2071 records and observations of ice gouges obtained along 2000 km of survey trackline on the inner shelf of the Alaskan Beaufort Sea, west of the Canning River. Ice gouge survey and data collection coverage extends from Smith Bay to Camden Bay. Refer to Figure 2 for an approximate location map of the survey and associated navigation plates. A detailed *Base Map of Correlated Tracklines and Updated Bathymetry* is included within the report figures, and is presented below in Figure 3. Electronic text files of the recorded data have been obtained from the United States National Geophysical Data Center (NGDC).

Ice gouge surveys were conducted from 1972 – 1973 using sonographs and fathograms, with precision bathymetry and increased navigational accuracy used in surveys from 1975 – 1980. Navigational accuracy of the geophysical surveys is broad, ranging from on the order of a few meters in near shore locations, to reported worst-case errors on the order of 1 kilometer. Ice gouge measurements from 1972 – 1973 were measured using 0.3m – 0.4m resolution, whereas observations obtained from 1975 – 1980 were obtained with gouge feature resolution as small as 0.15m gouge depth, which is attributed to the use of different bathymetric equipment and technologies.

Collected data was divided into 1 kilometer trackline segments in order to facilitate detailed analysis of ice gouging in specific sub-environments, as well as general characterization of the inner shelf gouging (Barnes et al., 1981). Recorded gouge data includes water depth, gouge depth, berm (or ridge) height, gouge width, length, density, dominant gouge orientation and multiplet gouge data, among other parameters. Note that observed gouges displaying depths of less than 0.2m, as well as gouges observed on sonar records but not distinguishable on fathograms, were categorized as gouges displaying 'No Measurement Possible'. Ice gouge measurements are referenced from the surrounding undisturbed or average sea floor datum. Refer to Figure 4 for a diagram of the typical ice gouge measurements obtained during the USGS 81-950 ice gouge survey.

The data obtained from this report is also utilized, referenced and included within USGS Open-File Report 83-706, *'Ice Gouge Data Sets From the Alaskan Beaufort Sea; Magnetic Tape and Documentation for Computer Assisted Analyses and Correlation'* by D. M. Rearic and A. G. McHendrie (Section 2.4).

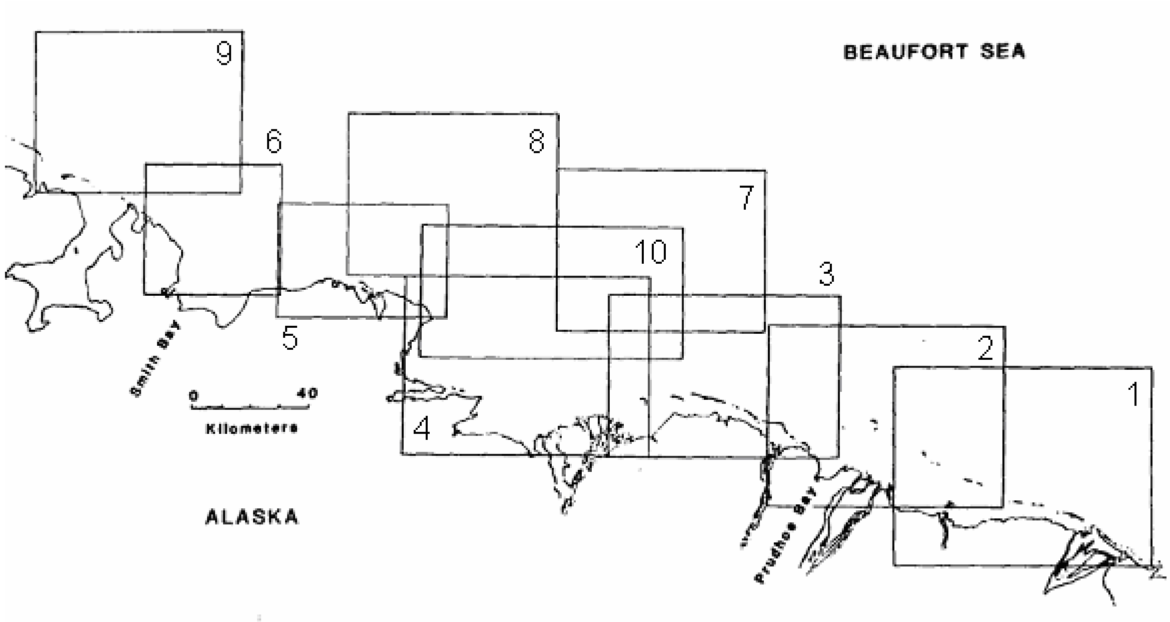

Figure 2: Location Map of Navigation Plates For Ice Gouge Data Presented Within USGS Open-File Report 81-950 (Rearic et al., 1981).

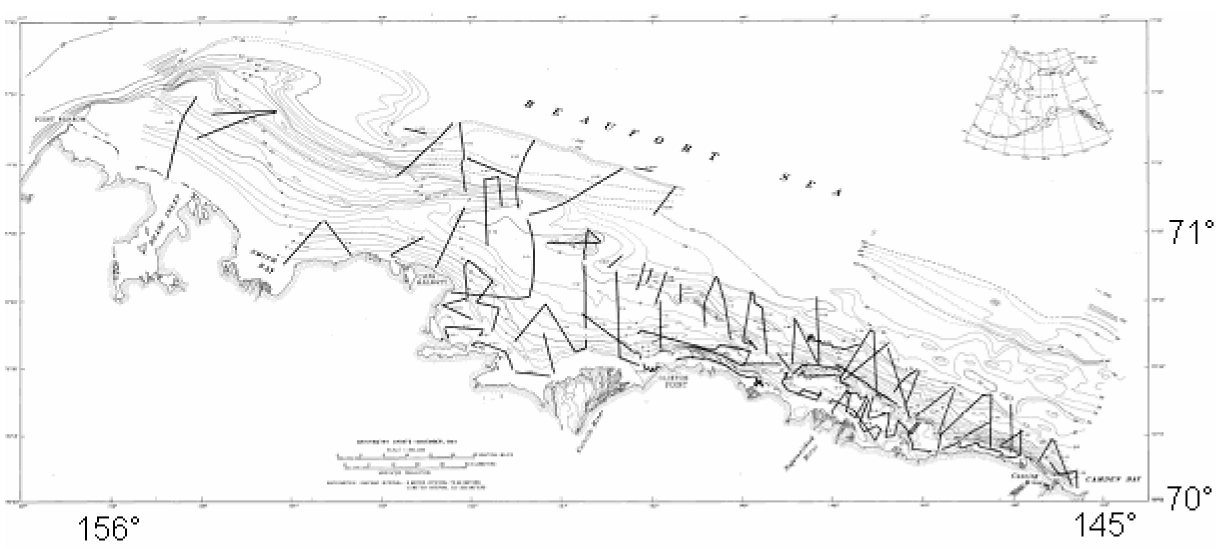

Figure 3: *Base Map of Correlated Tracklines and Updated Bathymetry* Presented Within USGS Open-File Report 81-950 (Rearic et al., 1981).

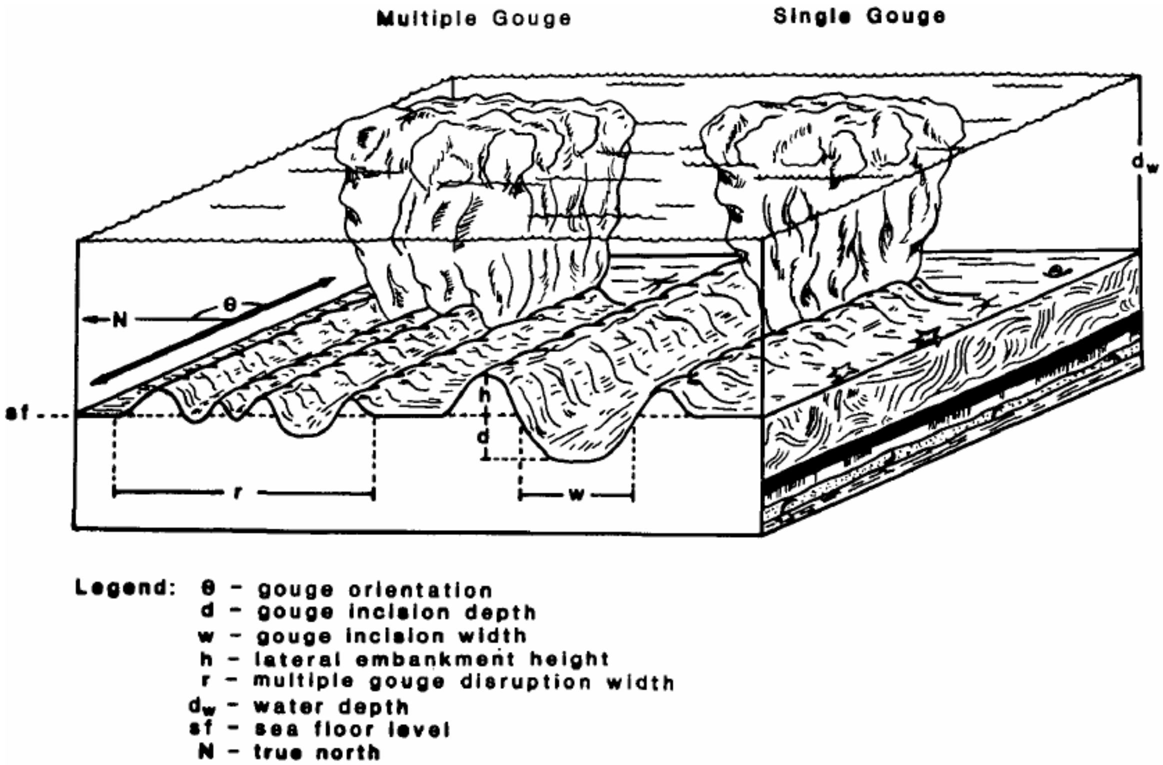

Figure 4: Diagram of Typical Ice Gouge Measurements Presented Within USGS Open-File Report 81-950 (Rearic et al., 1981).

2.3 USGS Open-File Report 82-974

***Marine Geological Investigations in the Beaufort Sea in 1981 and Preliminary Interpretations for Regions from the Canning River to the Canadian Border* (Reimnitz et al., 1982).**

Ice gouge data has been collected and compiled within this United States Geological Survey report through reconnaissance seismic surveys conducted on the inner shelf of the Alaskan Beaufort Sea, eastward from the Canning River to the Canadian border. Refer to Figure 5 and Figure 6 for approximate location maps of the ice gouge survey tracklines.

The surveys were conducted during the summer of 1981 along established survey tracklines and within site-specific areas. The surveyed tracklines were subdivided into 1 km sections for the purposes of statistical analyses (Reimnitz et al., 1982). Subsea sediment sampling was also conducted for the ice gouge survey trackline areas, thus allowing soil and sediment properties to be analyzed. Navigational accuracy of the surveys is reported to be in the range of 100 meters – 200 meters, with an extreme worst-case error of 3 km while surveying without the use of electronic navigational aids.

Collected geophysical ice gouge data is presented within the report Appendix, although ice gouge measurement criteria (i.e. datum and reference points) are not defined. It is assumed that gouge measurements are referenced from the 'average' sea floor position, as presented above in Figure 4 (pertaining to USGS 81-950 data). Recorded data includes water depth, gouge depth, berm height, gouge width, gouge density, dominant gouge orientation and sediment cohesion, among other parameters.

Limited statistical analysis of ice gouge observations are included within the report, as well as preliminary analysis of recorded geotechnical conditions. A total of 372 recorded ice gouge data points are provided within the survey report.

The data obtained from this report is also utilized, referenced and included within USGS Open-File Report 83-706, *'Ice Gouge Data Sets From the Alaskan Beaufort Sea; Magnetic Tape and Documentation for Computer Assisted Analyses and Correlation'* by D. M. Rearic and A. G. McHendrie (Section 2.4).

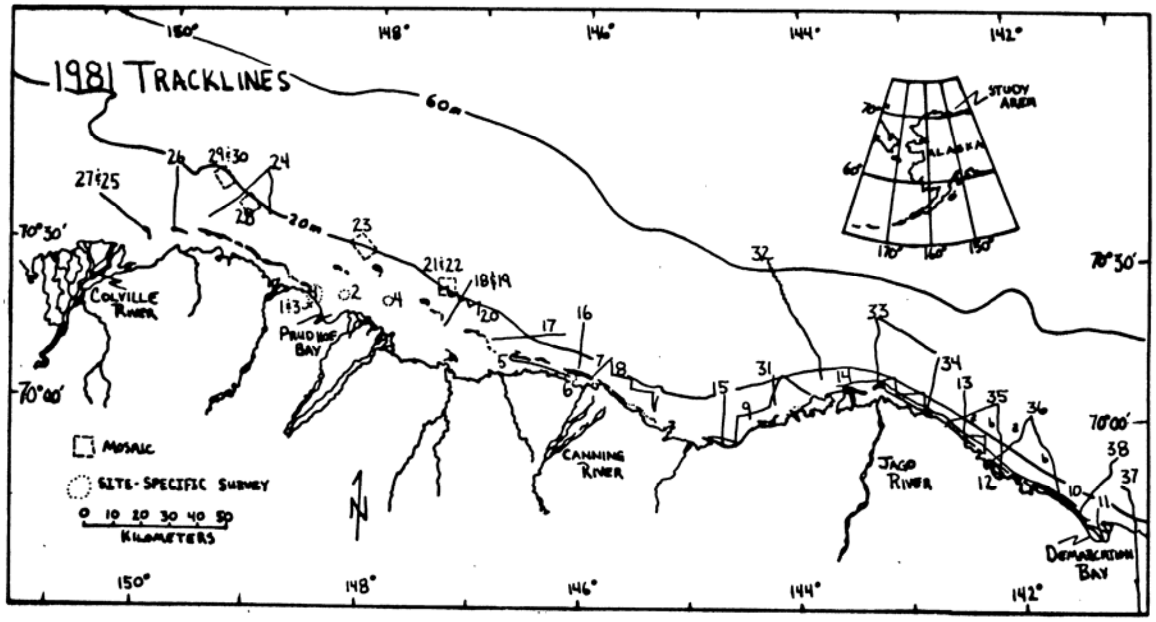

Figure 5: Location Map For Geophysical Survey Tracklines Presented Within USGS Open-File Report 82-974 (Reimnitz et al., 1982).

Note: See Table 1: Geophysical Data, of USGS Report 82-974, for listings of geophysical data coverage for each of the numbered tracklines.

2.4 USGS Open-File Report 83-706

***Ice Gouge Data Sets From the Alaskan Beaufort Sea; Magnetic Tape and Documentation for Computer Assisted Analyses and Correlation* (Rearic et al., 1983).**

This report presents combined United States Geological Survey ice gouge data referenced from two separate Alaskan Beaufort Sea surveys; USGS Open-File Report 81-950 (Data File 1, see Section 2.2) and USGS Open-File Report 82-974 (Data File 2, see Section 2.3). Refer to Figure 6 for the general survey area of each report.

Ice gouge data referenced within this report is presented in two accompanying electronic text files. The report contains a data dictionary that indicates the data format and key for the electronic text files. Recorded ice gouge data includes gouge location, water depth, maximum gouge depth, incision width, berm height, dominant orientation and gouge length for single and multiplet gouge events, among other pertinent gouge parameters. Ice gouge locations are recorded in NAD27 datum geodetic format coordinates. Ice gouge observation statistics / frequencies are recorded within specified ice gouge depth classes for gouge depth ranges from less than 0.4m (0.2m – 0.4m) to less than 4.0m (3.8m – 4.0m). Examination of the data files indicates a maximum single ice gouge incision depth of 5.5m, which is significantly greater than the upper limit of the reported specified ice gouge depth classes. No discussion of this deviation is provided within the report text. Note that no ice gouge class limit frequencies are recorded for Data File 2, corresponding to USGS Open-File Report 82-974, although maximum gouge depths are presented. This inconsistency with Data File 1 is not addressed within the report.

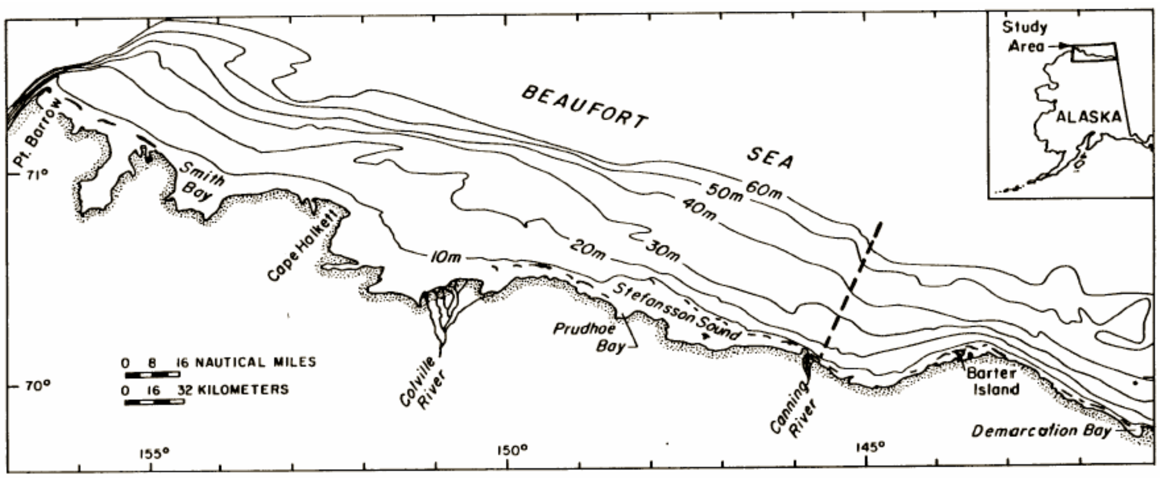

Figure 6: Location Map For Ice Gouge Data Presented Within USGS Open-File Reports 81-950 & 82-974 (Rearic & McHendrie, 1983).

Note: Dashed line represents approximate division between two separate reports; the scope of 81-950 (Data File 1) is west of the line, whereas the scope of 82-974 (Data File 2) is east of the line.

2.5 CRREL Report 83-21

***Statistical Aspects of Ice Gouging on the Alaskan Shelf of the Beaufort Sea* (Weeks et al., 1983).**

This report presents independent data analysis of Beaufort Sea ice gouge data collected as part of USGS Open-File Report 81-950 (see Section 2.2) between Smith Bay and Camden Bay on the Inner Alaskan Shelf. Refer to Figure 7 for the general locations of survey lines referred to within the report. Ice gouge data was collected using side-scan sonar and precision bathymetric survey equipment between 1972 – 1979, along approximately 2000 km of trackline.

The data obtained and used in analysis is presented in Table 1 of the report for varying water depths and trackline observation areas. Ice gouge measurements are referenced from the surrounding ‘undisturbed’ sea floor. Table 2 of the report provides the mean ice gouge orientation observed in each trackline. Note that the ice gouge data presented within this report is limited to recorded gouge depth measurements, which are reported as the frequency of occurrence (number of observed gouges) as a function of the midpoint of the gouge depth class interval. Table 5 of the report presents ice gouge temporal frequency of recurrence data that has been duplicated from USGS Open-File Report 78-730.

Statistical ice gouge data analysis was conducted through the application of an exponential distribution that has been deemed to be a convenient and reasonable initial approximation by the report authors (Weeks et al., 1983). Statistical analysis is also presented regarding observed ice gouge frequencies and exceedence probability based on negative exponential, Poisson and gamma distribution analysis of gouge event recurrence rates, among other relevant topics. The report clearly presents the theory and methodologies used in analysis of the ice gouge data.

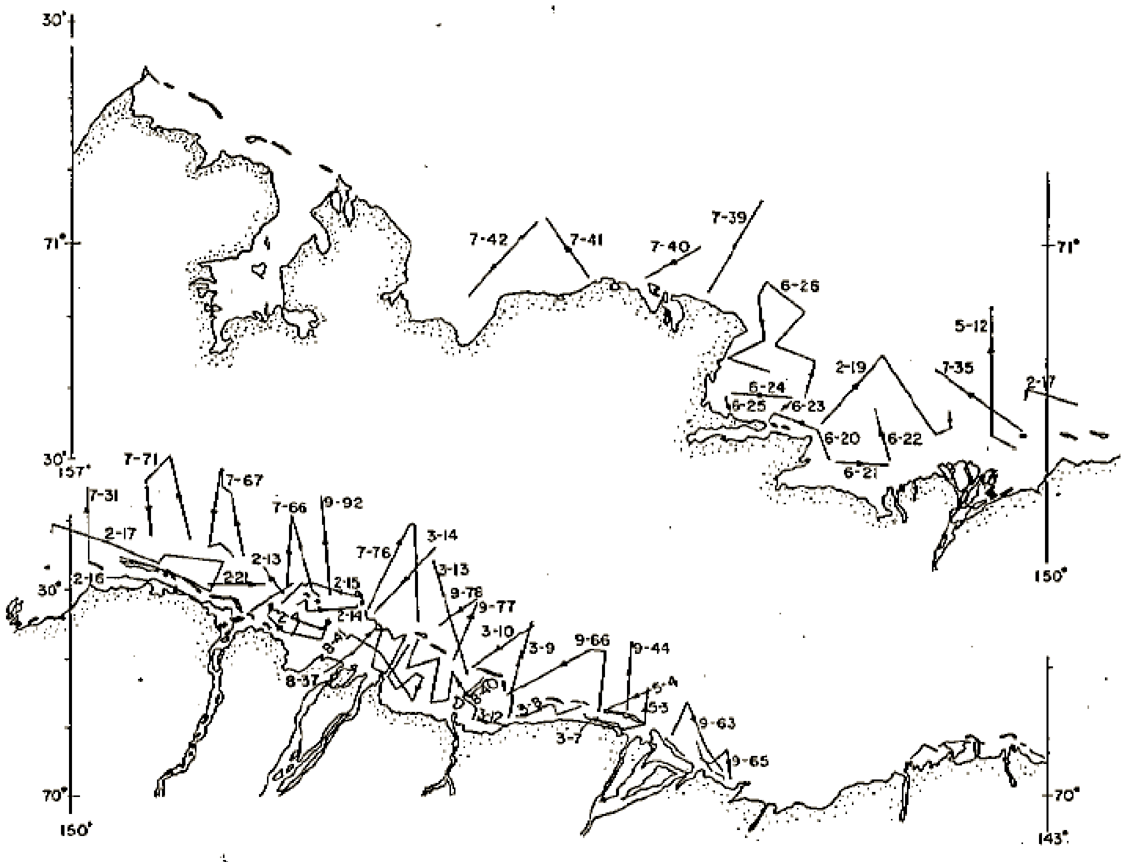

Figure 7: Map Indicating Approximate Sampling Line Locations of Ice Gouge Data Presented Within CRREL Report 83-21 (Weeks et al., 1983).

2.6 USGS Open-File Report 89-151

Data on the Characteristics of Dated Gouges on the Inner Shelf of the Beaufort Sea, Alaska; 1977-1985 **(Weber et al., 1989).**

This United States Geological Survey report presents ice gouge data and characteristics that have been collected along nine established tracklines / corridors on the Inner Shelf of the Alaskan Beaufort Sea during 1977 – 1985. Refer to Figure 8 for approximate survey corridor locations.

Data presented within this report provides an update to the data presented in USGS Open-File Report 85-463 (Section 2.1).

The data presented within this report is more detailed than that previously presented by USGS report 85-463, with new data from two 1985 ice gouge surveys added. The tabulated data presented within the previous USGS report (85-463) records all observed gouge depths of less than 0.2m as '<0.2m', whereas this report presents gouge depth data points to an accuracy of 0.1m. The method of obtaining greater gouge depth accuracy within this report is not addressed.

As presented in Figure 8, survey corridors 5 and 8 are located in approximately the same area; this is due to the loss of the navigation stations used for the corridor 5 survey procedures conducted in 1979 and 1980. Survey corridor 8 was subsequently established nearby using more permanent navigation stations. Ice gouges of known age have been observed and reported through repetitive surveying techniques carried out using side-scan sonar and precision bathymetry. Ice gouge data is contained within Appendix I of the report; no details regarding the background, methods, conclusions or recommendations regarding ice gouge processes are discussed within the report. Recorded gouge measurements include gouge depth, orientation, width, overall length, and the total disruption width for multiple ice gouge swaths which occur when wide ice keels rake the seabed (termed 'multiplet' gouge events (Weber et al., 1989; Barnes & Rearic, 1985)).

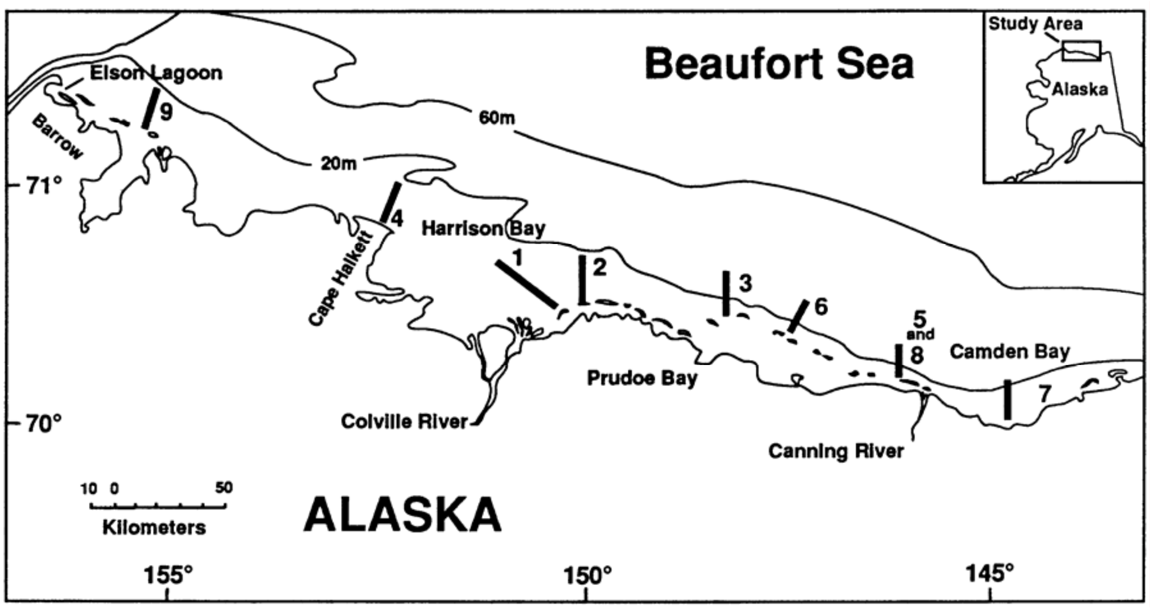

Figure 8: Map Indicating Survey Corridor / Trackline Locations and Generalized Bathymetry, as Referenced Within USGS Open-File Report 89-151 (Weber et al., 1989).

2.7 USGS Open-File Report 78-730

Ice-Gouging Characteristics: Their Changing Patterns from 1975-1977, Beaufort Sea, Alaska. USGS Open-File Report 78-730 (Barnes et al., 1978).

Repetitive ice gouge surveys of two established tracklines located within Harrison Bay in the Alaskan Beaufort Sea, northeast of the Colville River Delta, have been conducted during 1973 and 1975 – 1977 and are presented within this United States Geological Survey report. Refer to Figure 9: Location Map for Ice Gouge Data Presented within USGS Open-File Report 78-730, below, for the general survey area of each trackline.

Ice gouge surveys have been conducted using side-scan sonar and precision fathometers, which provided accuracy within 10 cm for the detection of subsea features and bottom relief. Vessel navigation was provided by ranging onshore landmarks and range-range electronic navigation systems that provided an accuracy of +/- 3 metres. The multi-year aspect of the surveys allowed the identification of new ice gouges occurring each season. Dominant ice gouge trend / orientation, density, maximum incision depth and maximum disruption widths, among other ice gouge characteristics, have been recorded and analyzed within the report for 500m test line segments. Discussions of gouge reoccurrence rate, the fraction of sea bottom impacted with time and gouge re-plow / superimposition is included. Ice gouge measurements are referenced from the surrounding sea floor, exclusive of ridges.

Observed ice gouge data is graphically provided within report figures, in addition to Tables I & II – ICE GOUGE DATA – New Gouges. A similar ice gouge study conducted within Harrison Bay is also available (see below); *Temporal and Spatial Character of Newly Formed Ice Gouges in Eastern Harrison Bay, Alaska, 1977-1982*, USGS Open-File Report 86-391, by D.M. Rearic. Additionally, a subset of the data presented within this report is provided in Part E of USGS Open-File Report 77-477, *Miscellaneous Hydrologic and Geologic Observations on the Inner Beaufort Sea Shelf, Alaska* (Part E entitled *Rates of Ice Gouging, 1975-1976, Beaufort Sea, Alaska* by Barnes et al).

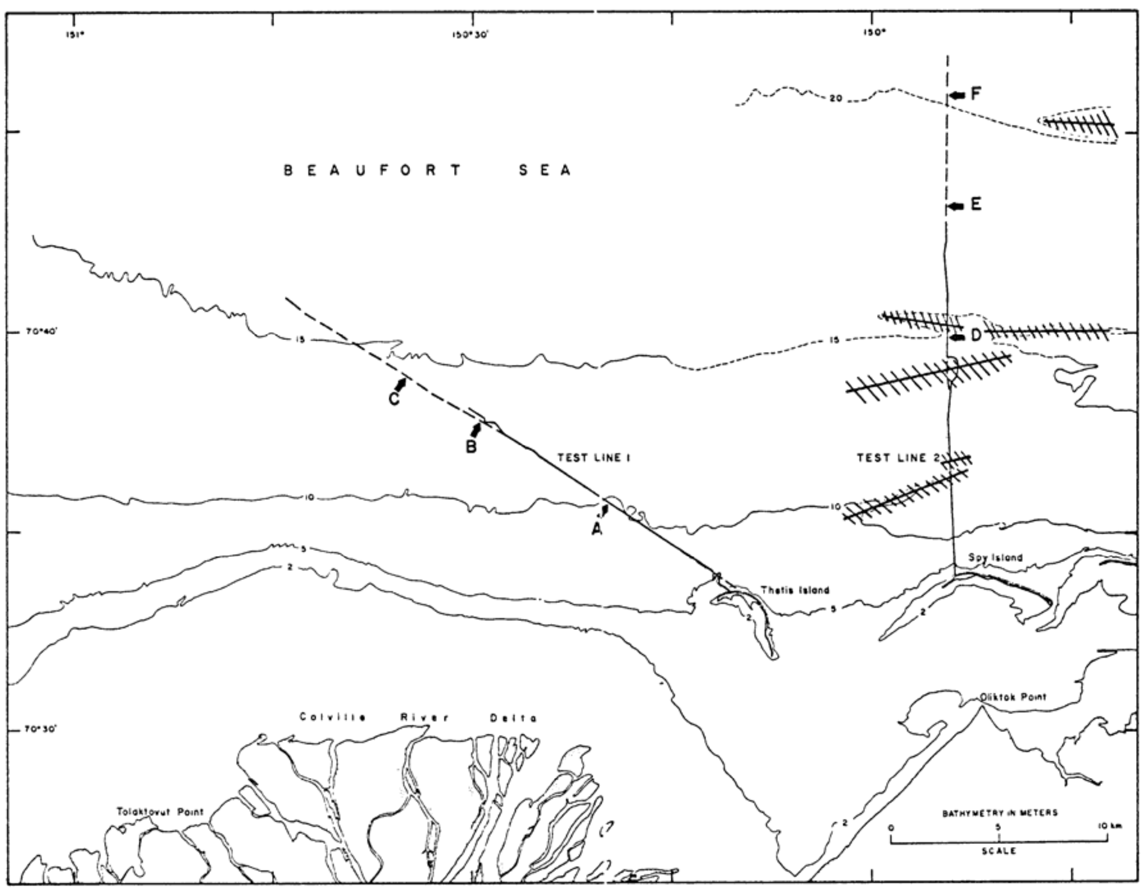

Figure 9: Location Map for Ice Gouge Data Presented within USGS Open-File Report 78-730 (Barnes et al., 1978).

Note: Letters 'A' through 'F' designate the location of sonographs and fathograms, as discussed within the report.

2.8 USGS 86-391

Temporal and Spatial Character of Newly Formed Ice Gouges in Eastern Harrison Bay, Alaska, 1977 – 1982. USGS Open-File Report 86-391 (Rearic, 1986)

This report presents the ice gouge survey results and analysis of two tracklines located in Eastern Harrison Bay which were resurveyed with precise navigation techniques, side-scan sonar and precision fathometers between 1977 – 1982. Ice gouge recurrence data was thus obtained from the surveys. Refer to Figure 10, below, for a location map of the report study area.

In total, 1292 individual ice gouges formed from 1977 – 1982 were analyzed as part of this study. Ice gouge data for 1 km segments of each trackline are provided within report tables with some accompanying analyses. Recorded ice gouge parameters include water depth, maximum gouge depth, total gouge disruption width, and the number of observed ice gouges resulting from single and multiplet ice gouge events. Ice gouge recurrence and seabed morphology, among other pertinent topics, are discussed within the report.

It should be noted that the data used in analyses is duplicated within USGS Open-File Report 85-463 (and subsequently USGS 89-151), *Rates of Sediment Disruption as Determined from Characteristics of Dated Ice Gouges Created Since 1975 on the Inner Shelf of the Beaufort Sea, Alaska* (Barnes & Rearic, 1985). Refer to Section 2.1 for discussion of the original data set and report.

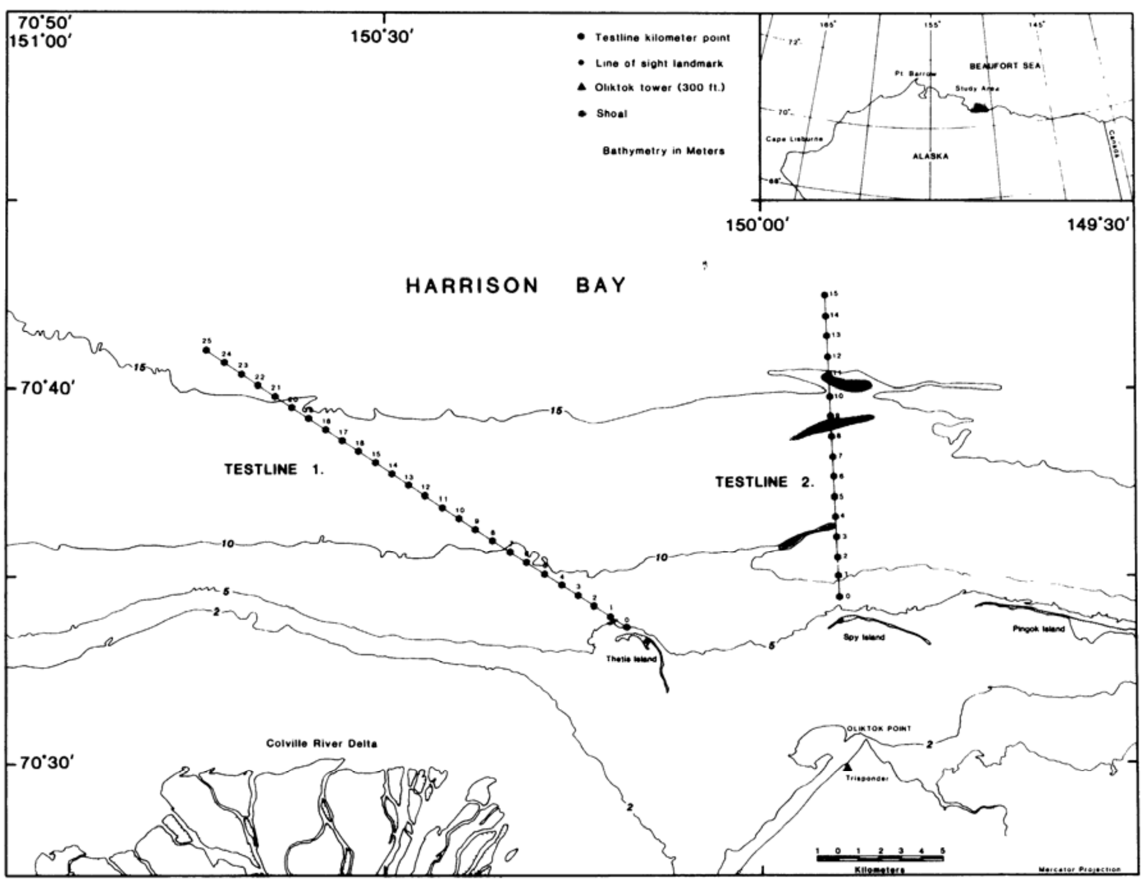

Figure 10: Location Map of the Study Area Presented in USGS Open-File Report 86-391 (Rearic, 1986).

2.9 NRC 1982

***Ice Gouge Characteristics Related to Sea-ice Zonation, Beaufort Sea, Alaska.* USGS, Pacific-Arctic Branch of Marine Geology, Menlo Park, CA. Prepared for Presentation at NRC Canada Ice Scour Workshop, Montebello, QC, April 1985 (Barnes, Reimnitz & Rearic, 1982).**

This report presents comprehensive data and analysis of Beaufort Sea inner shelf ice gouge data, ice regime characteristics, and summary statistics of observed ice gouges and discussions of results. The data used in analysis is duplicated from USGS Open-File Report 81-950 (Rearic et al., 1981). Graphical plots and figures are provided for analysis, complete with detailed descriptions of observed ice gouge characteristics, measurements, relationships, etc. The survey areas covered in this report range from Camden Bay to Smith Bay (including Harrison Bay, Prudhoe Bay, Oliktok Point, Cape Halkett, etc). Refer to Section 2.2 for discussion of the original data set and report.

2.10 ESRF 049

***Ice-Gouge Studies, Alaskan Beaufort Sea*. USGS, Menlo Park, CA. Proceedings of Ice Scour and Seabed Engineering (1986), Environmental Studies Revolving Funds Report 049 (Barnes & Reimnitz, nd.)**

This report presents a summary of USGS ice gouge surveys in the Alaskan Beaufort Sea with associated discussions of observed ice gouge population distribution, gouge dating, seabed morphology and deep-water gouges. Results of surveys are graphically presented and analyzed for specific survey areas, with no tabulated data provided. Data extraction from report figures was not completed due to poor scaling and incrementation of figure data. The morphology of the Beaufort Sea inner shelf is also addressed.

3. ICE GOUGE DATA

3.1 Gouge Parameters and Characteristics

The dynamic process of an ice keel impacting and scraping along the seabed often produces many characteristic seabed deformations that may be observed and measured for further analysis through marine surveying techniques. The impact and grounding of an ice keel upon the seabed typically produces 'pock mark' indentations upon the seafloor, which become noticeable once the ice has sufficiently melted to allow the indenting ice keel to dislodge and move off of the grounding site.

If the grounded ice possesses enough momentum or driving force to facilitate further movement, the impacting ice keel may scrape along the seabed and thus create a noticeable ice gouge (or ice scour) on the seafloor. Single-keeled ice features have a single keel projection contacting the seafloor, which generally creates gouge deformations that produce a localized ridge berm and furrowed seabed micro-topography with associated vertical and horizontal sediment displacement and redistribution (Rearic & Ticken, 1988). 'Multiplet' ice gouges are created by multi-keeled ice features, which possess multiple keel projections contacting and gouging the seafloor. These gouge deformations typically exhibit a characteristic multiplet gouge deformation which simulates rake marks upon the seabed surface (Rearic & Ticken, 1988).

Common ice gouge deformation parameters and associated characteristics are presented below. Figure 11 presents single keeled ice gouge characteristics. Figure 4, above, provides a diagram of a multiplet gouge event. The geotechnical conditions, morphology and localized bathymetry of the seabed areas subject to ice gouging events influences gouge attributes, thus producing gouge characteristics that may fluctuate along the length of the gouge with changing seabed conditions. Annual variations in ice concentrations also strongly affect the distribution of seabed gouges.

The scraping of an ice keel along the seabed poses a significant threat to subsea pipelines, among other facilities, which may be damaged by the gouging ice keel. Subsea pipelines are generally trenched and buried beneath the seabed in areas prone to ice gouging and sediment reworking events caused by grounding ice keels. The required burial depth for the protection of pipelines from interactions with ice keels and the associated pressure ridges formed during gouging is a function of the maximum gouge depth that may be expected to occur in a specific area, during the installation's designed lifetime. Figure 12 presents a schematic of a trenched and buried pipeline located below an ice gouge deformation.

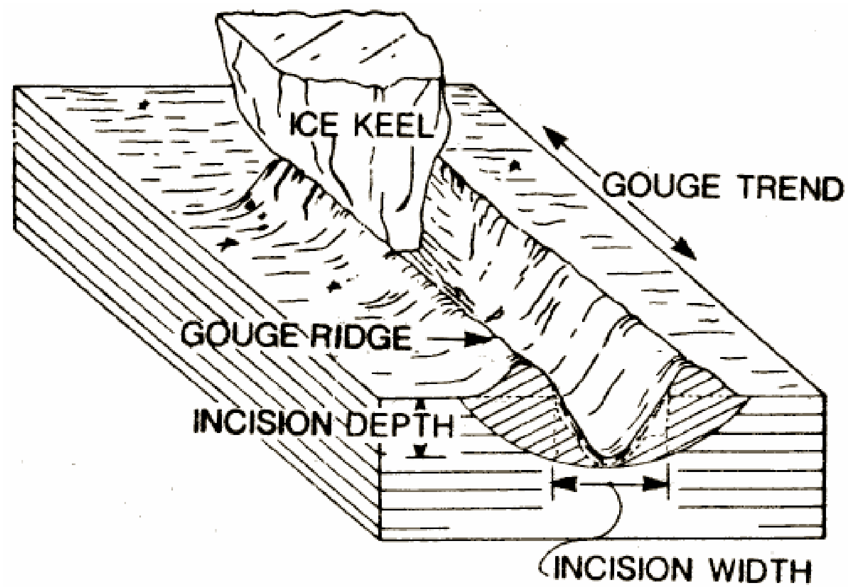

Figure 11: Illustrated Single Keeled Ice Gouge Characteristics (Ticken & Toimil, 1992).

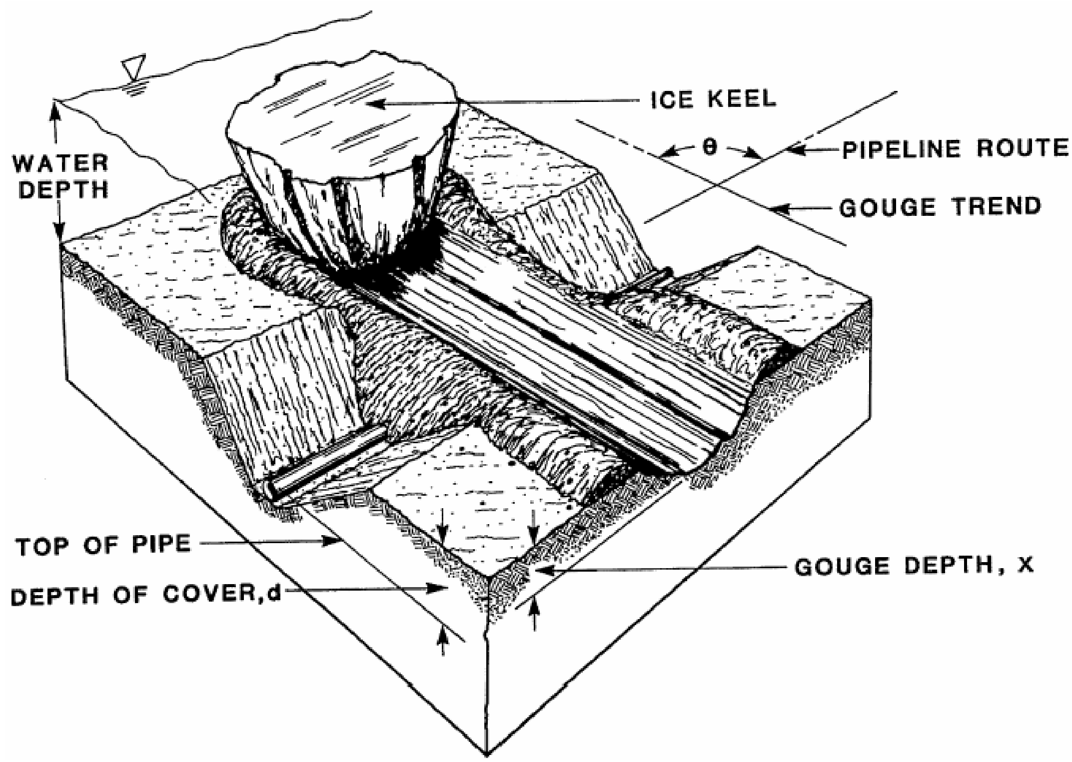

Figure 12: Illustrated Trenched and Buried Pipeline Below an Ice Gouge Deformation (Lanan et al., 1986).

3.2 Gouge Depth

The measured ice gouge incision depth is the vertical distance between the average gouge trough (or floor) and the undisturbed seabed. This measurement practice allows the minimum penetration of the impacting ice keel into the seabed to be accurately measured and recorded. The total gouge relief height, as measured from the gouge trough to the maximum berm height is a misleading ice gouge characteristic as it may lead to over-estimation of the size of the gouging ice keel.

3.3 Gouge Width

Traditionally, the maximum gouge width has been taken as the horizontal distance across the ice gouge, measured at the undisturbed seabed level. The gouge width thus excludes the width of the gouge berm, or ridge, and is a characteristic of the impacting ice keel. Commonly, ice gouges occur in the form of a ‘V’ or ‘U’ shape gouged into the seabed and thus possess varying widths with vertical position through the gouge depth.

3.4 Berm Height

The gouge berm height is the vertical height of the ridge embankment (or berm) of sidecast seabed soil on either side of the gouge trough(s) created by the gouging of an ice keel along the seabed. Similar to the gouge depth and width measurements, the berm height is referenced from the level of the surrounding undisturbed seabed.

3.5 Ice Gouge Crossing / Recurrence Rate

Ice gouge recurrence (g), or crossing rate, is reported as the total number of gouges observed per linear kilometer of survey trackline in a given year (number of gouges / km / year), determined by dividing the total number of observed ice gouges during a specific survey by the overall trackline length.

The United States Geological Survey counts every gouge feature present within a multiplet deformation swath as a single ice gouge. The USGS then normalizes the total gouge count to correct for the angle formed between the dominant gouge trend and the survey vessel’s course using a calculation procedure presented within USGS Open-File Reports 78-730 and 81-950.

3.6 Ice Gouge Density

Ice gouge density is commonly presented for base year or single-year surveys, which fundamentally do not present dated new gouge occurrence data. In such cases, the ice gouge density is often reported as the number of gouges observed per linear kilometer of surveyed trackline or the number of gouges observed per survey area (km^2). The survey area is dependent upon the visible width of the seabed reconnaissance equipment used.

3.7 Dominant Gouge Trend / Orientation

An ice gouge generally reflects a predominant direction of ice keel movement. The dominant gouge trend is the angular orientation of the gouge deformation and is often measured with respect to true north

3.8 Gouge Infilling / Weathering

The weathering, infilling and obliteration of ice gouges is a dynamic and time dependent process, which is highly contingent upon the soil and sediment properties of the seabed and sediment reworking processes which are present. Sediment reworking displaces material from high vertical relief, such as ice gouge berms, and deposits this material into the gouge trough (Barnes & Reimnitz, 1979; Palmer & Niedoroda, 2005). Sediment transport from wave and current action can be a significant, although intermittent, factor affecting ice gouge characteristics (Barnes & Reimnitz, 1979). Gouge infilling and obliteration rates may be observed and analyzed through repetitive surveying of dated gouges.

4. ASSESSMENT OF AVAILABLE DATA

Electronic data files of available ice gouge data have been compiled from existing technical reports and studies applicable to the Alaskan Beaufort Sea. Individual data sets are discussed below, with particular detail to the data extracted from each report and the method of data assessment. The availability and quality of data presented in the sections, sub-sections, appendices and illustrations of each individual report have also been assessed as part of this current review. Data sets for the current report have been assessed on the basis of the relevant ice gouge parameters, including ice gouge depths, widths and crossing rates, among other pertinent characteristics discussed below. Appendix A1 of this report presents summary plots of the various ice gouge parameters extracted from each data set and are discussed within the following subsections of this report.

4.1 Data Set #1 – USGS Open-File Report 83-706

Ice Gouge Data Sets From the Alaskan Beaufort Sea; Magnetic Tape and Documentation for Computer Assisted Analyses and Correlation (Rearic et al., 1983).

This data set is a combination of two ice gouge data files obtained from two separate USGS Open-File Reports; 81-950 and 82-974 (data files 1 and 2, respectively). No discussion of the ice gouge data is provided in the report with the exception of limited descriptions of the ice gouge parameters recorded in the accompanying data files.

Analysis of the data set indicates a maximum recorded single ice gouge depth of 5.5m and an unrelated maximum single ice gouge width of 67m. The maximum observed ice gouge length within this data subset was 1150m, which did not correspond to either of the maximum gouge depth or width events. A maximum gouge density of 4903 gouges / km^2 has been observed. Analysis of the data set indicated that the dominant ice gouge orientation frequency of occurrence occurred in the 70° – 80° range, which was corrected for the survey vessel route and measured relative to true north. The limits of gouge orientation measurements are 0° and 90°. Ice gouge recurrence rate, infilling rate or obliteration data cannot be obtained from this data set as it does not represent a repetitive ice gouge survey and no such survey was conducted. Seabed sediment cohesion properties have been recorded as ‘SN’, ‘RC’ or ‘T’, although no discussion of the meaning or definition of these letters and/or acronyms is provided within the report text or data legend. The number of observed ice gouges within defined gouge depth class interval ranges is provided, which range from a minimum depth class of 0.2m – 0.4m to a maximum depth class of 3.8m – 4.0m. It is noted that the depth class intervals do not cover all observed ice gouge depths when the full data set is examined. Additional pertinent ice gouge parameters such as the maximum number of single and multi-incision gouges observed, the maximum disturbance width, and ice gouge ridge (or berm) height are also presented within the data set / subset, among others.

Data extraction for these data files was limited to the export of the original data plain text files to Microsoft Excel worksheets; the original data text files are arranged by column, with the data format provided within the accompanying report text and tables.

Appendix A1 of this report contains summary plots of the data set that have been used in analysis. The summary plots include scatter plots of the Maximum Single Ice Gouge Depth vs. Water Depth, the Maximum Single Ice Gouge Width vs. Water Depth, and Maximum Single Ice Gouge Width vs. Gouge Depth. A dominant ice gouge orientation rosette (or ‘radar’ plot) has been created for 10° increment ranges of observed dominant gouge orientations used in analysis and is provided within Appendix A1 of this report.

Surficial sediment properties are discussed in USGS Open-File Report 82-974 for surface sediment samples obtained in 1981, which subsequently contributed to report 83-706. Seabed surface sediments have been qualitatively classified as ‘muddy, cohesive’ or ‘coarse, granular, non-cohesive’ sediment types but are recorded within the report Appendix, *Ice Gouge Data Sheets*, as ‘SN’, ‘RC’ or ‘T’, similar to report 83-706. No insight as to the explicit definition of these acronyms is provided. Seabed relief forms have been classified as ‘rough’ or ‘subdued’. Report figures are provided which plot surface sediment textures (cohesive or non-cohesive) for specified tracklines within the survey area. Generally, coarse, granular sediment has been observed on the seabed to a water depth of 15m, with a seaward zone of fine, cohesive surface sediment which again grades seaward into coarse, granular material.

4.2 Data Set #2 – USGS Open-File Report 89-151

Data on the Characteristics of Dated Gouges on the Inner Shelf of the Beaufort Sea, Alaska; 1977-1985 (Weber et al., 1989).

The ice gouge data presented within this report augments the repetitive ice gouge survey data of Barnes and Rearic (1985) presented within United States Geological Survey Open-File Report 85-463 (Section 4.3). New ice gouge data from two 1985 surveys is provided in addition to updated interpretations of the original data set (85-463). Gouge data is presented with respect to new ice gouge events observed since the base year survey(s). The original data set did not provide any ice gouge parameter measurements from the baseline surveys and, therefore, no ice gouge measurement parameters were provided in the original data set for observed gouges of indeterminate age.

Little discussion is presented within this report with regards to ice gouge parameters or qualitative and quantitative gouge properties. Alternately, references are provided for further details on ice gouge background, methods, observations and conclusions, in addition to gouge processes, variability, sedimentary structure influences, morphology and sediment transport, among other pertinent topics. Refer to Section 4.3 below for further detail pertaining to the data presented within the original report.

Both USGS Open-File Reports (85-463 and 89-151) employ gouge counting methods which count each individual incision within a multiplet gouge as a single ice gouge event and only record the deepest gouge depth exhibited by the multiplet. The majority of recorded gouge depths were below the lower limit of the fathogram resolution (0.2m), but above the threshold sonograph resolution of 0.1m. Such gouges were recorded as <0.2m in USGS 85-463 and later presented as 0.1m in USGS 89-151. The method of obtaining greater gouge depth accuracy in the USGS 89-151 report is not addressed.

For the purposes of this report, reported multiplet ice gouges have been counted as a single ice gouge event, regardless of the number of individual incisions within the multiplet gouge. In this manner, a multiplet ice gouge event reported within USGS 85-463 / 89-151 to possess two or more gouge incisions has been recorded as a single gouge event within the development of the current report. This methodology will give a lower bound on ice gouge recurrence rates from

USGS ice gouge surveys. As presented above, the USGS counts each individual ice gouge feature present within a multiplet deformation swath as a single ice gouge, thus producing an upper bound of recurrence rates. The USGS's rationale behind counting each multiplet gouge feature as a single ice gouge is unknown.

Ice gouge data relevant to the current study has been extracted from tabulated data presented within the report.

The maximum recorded single ice gouge depth observed was 3m and was found along survey corridor number 1. An unrelated maximum recorded single ice gouge width was observed in both survey corridors 4 and 9 and measured 25m. An unrelated maximum single gouge length of 200m was also observed in survey corridor 9 for an ice gouge of known age. The maximum dominant ice gouge orientation frequency of occurrence was observed in the 60° – 70° range, which was corrected for the survey vessel route and measured relative to true North. The original limits of gouge orientation measurements were 0° and 180° as defined within the report abbreviations and also by USGS Open-File Report 85-463.

Appendix A1 of this report provides plotted data used in analysis, which includes Ice Gouge Depth vs. Water Depth – New Gouges, Ice Gouge Width vs. Water Depth – New Gouges, and Ice Gouge Width vs. Gouge Depth – New Gouges. Additionally, a dominant ice gouge orientation rosette (or 'radar' plot) has been created for 10° increment ranges of observed dominant gouge orientations used in analysis and is provided within Appendix A1 of this report.

4.3 Data Set #7 – USGS Open-File Report 85-463

Rates of Sediment Disruption by Sea Ice as Determined From Characteristics of Dated Ice Gouges Created Since 1975 on the Inner Shelf of the Beaufort Sea, Alaska (Barnes & Rearic, 1985).

Ice gouge data is presented in this USGS report for repetitive mapping surveys conducted along 9 established survey corridors in the Alaskan Beaufort Sea. Multiple tracklines have been surveyed within each corridor. Although repetitive ice gouge surveys were conducted from 1975 – 1982, limited records are available for some corridors. For instance, the initial survey for corridor 3 was conducted in 1975, although insufficient data was obtained. Another survey was thus completed in 1979 (the base year survey), with a single repetitive survey conducted in 1982. The yearly surveys for each of the 9 survey corridors, baseline survey length, and surveyed trackline numbers are provided in Table 1 of the USGS 85-463 report.

Qualitative seabed sediment properties have been reported for the survey corridors. Table 2 presents the total number of new gouges, deepest new gouge observed and predominant seabed sediment type presented in the USGS 85-463 report. No quantitative discussion of sediment cohesion or further definition of the qualitative terminology used is provided within the report.

Table 2: USGS 85-463 Survey Corridor Properties

Corridor	Total Number of New Gouges	Deepest New Gouge (m)	Predominant Seabed Sediment Type
1	845	1.0	Sands / muddy sand
2	447	1.4	Sandy muds
3	217	0.8	Sandy muds / muds
4	562	1.2	Muddy sands / sandy muds
5	25	0.1	Sand & gravel inshore with sandy mud / pebbly sandy mud seaward
6	88	0.7	Pebbly clays / stiff sandy muds
7	151	0.7	Sands / muddy sand / clay
8	39	0.8	Sand & gravel inshore with sandy mud / pebbly sandy mud seaward
9	158	1.1	Muds / muddy sands

New ice gouge data is tabulated within the report Appendix entitled *Ice Gouge Data Sheets* and presented graphically within the report figures. Graphical gouge data includes seabed depth profile, maximum gouge depth, gouge disruption width, and gouge density (number of gouges per survey kilometer), presented as a function of surveyed corridor trackline length. The gouge data presented within the report has been updated and presented by Weber et al. (1989) in USGS

Open-File Report 89-151, as discussed above in Section 4.2. The updated data of 89-151 presents ice gouge depth measurements of greater accuracy and has thus been used in the development of the current report. USGS Open-File Report 85-463 is discussed here as it is the basis for the subsequent USGS Open-File Report 89-151 data set.

Many observed gouge features that could be resolved on the survey sonographs were gouged into the seabed to a depth less than the lower limit of the fathometer resolution (0.2m). The minimum gouge depth sonograph resolution was 0.1m. More than 60% of the total new gouges observed among all survey corridors fell into this category, and a gouge depth of 0.1m was assumed for the purposes of statistical analyses (Barnes & Rearic, 1985). Tabulated report data presents these gouge depths as <0.2m. Based upon known fathometer and sonograph resolutions, it was decided that the gouge depths of gouges resolvable on the sonographs and not resolvable on the fathograms should fall between 0.1m – 0.2m (Barnes & Rearic, 1985). Gouge depths below the 0.1m – 0.2m range of resolution were not considered.

4.4 Data Set #8 – USGS Open File Report 78-730

Ice-Gouging Characteristics: Their Changing Patterns from 1975-1977, Beaufort Sea, Alaska. USGS Open-File Report 78-730 (Barnes et al., 1978).

Ice gouge data is presented in this USGS report for repetitive mapping surveys conducted along 2 established survey tracklines located in Harrison Bay, on the Alaskan Beaufort Sea. Repetitive ice gouge surveys were conducted for Test Line 1 in 1973, 1975, 1976, and twice during the summer of 1977. Test Line 2 was surveyed in 1975, 1976 and 1977.

No qualitative or quantitative seabed sediment properties have been reported for the two test line survey areas, with the exception of an estimated sedimentation rate of 10 cm per 100 years.

New and unknown age ice gouge data is graphically provided within report figures, with new ice gouge data also tabulated within report tables. Recorded gouge data includes test line survey segment location, observed water depth, number of gouges observed, maximum and average gouge depth, maximum and average gouge width, as well as the amount of trackline gouged (meters gouged per survey kilometer of trackline per year).

The ice gouge data obtained during the repetitive survey procedures indicated a maximum new gouge depth of 1.2m on Test Line 1 at a water depth of 13.5m with a corresponding maximum gouge width of 34m (for Test Line 1). A maximum new ice gouge depth of 0.8m on Test Line 2 was observed at a water depth of 13.5m, with a corresponding width of 12m. The maximum depth of an ice gouge of unknown age on either test line was observed along Test Line 2 and exhibited a depth of 1.8m at a water depth of 19m, with a corresponding width measurement of 25m. The maximum new gouge width observed was 48m and occurred on Test Line 2 at a water depth of 18m and with an associated gouge depth of 0.3m. The maximum observed gouge width of unknown age was 65m and occurred on Test Line 2 at a water depth of 14m and with an associated gouge depth of 0.1m. Maximum ice gouge widths were observed to increase with distance offshore. Width measurements were also corrected for associated gouge trend angles.

The dominant ice gouge orientations are graphically presented within the report figures for each surveyed test line, but poorly scaled and thus provide little useful information.

Summary plots of Ice Gouge Depth vs. Water Depth, Ice Gouge Width vs. Water Depth, and Ice Gouge Width vs. Gouge Depth are provided within Appendix A1 of this report for new gouge data, unknown age gouge data, and new and unknown age gouge data combined.

5. ANALYSIS OF DATA FOR PIPELINE DESIGN

5.1 Maximum Observed Parameters

Analysis of the ice gouge data sets considered applicable to the Alaskan Beaufort Sea has indicated the following maximum observed ice gouge parameters:

- A maximum depth of 5.5m was observed for an ice gouge event, which occurred at a water depth of 39.1m. A corresponding gouge width was not reported. This depth was observed during the single-year USGS 83-706 study and is thus of unknown age.

- The maximum exhibited ice gouge width was 265m, and was observed at a water depth of 16.5m with a corresponding gouge depth of 0.6m (Weber et al., 1989). This gouge width was observed for a mulitplet ice gouge event, although the USGS 89-151 report does not provide the number of individual gouge incisions in the multi-keeled gouge. This width was observed in 1985 along Corridor 4 of the multi-year USGS 89-151 ice gouge survey and is thus of known age, although the previous survey of Corridor 4 occurred in 1982, not 1984.

- The maximum ice gouge length observed among the data sets was 1150m, which corresponded to a gouge depth and width of 1.5m and 5m, respectively (Rearic & McHendrie, 1983). This gouge is presented within the USGS Open-File Report 83-706 data set and is of unknown age.

- The maximum observed ice gouge density is difficult to determine due to the difference in reporting method (units) from survey to survey. A maximum spatial gouge density of 4903 gouges / km^2 has been presented within USGS Open-File Report 83-706 (Rearic & McHendrie, 1983). A maximum linear gouge crossing rate was not available amongst the analyzed data sets. Variations in ice gouge measurement accuracy may potentially bias datasets containing combined data from multiple sources and / or survey locations, thus leading to potential biases within ice gouge density profiles. Refer to Section 3.5 for further discussion of ice gouge counting methods.

5.2 Data Set Combinations

Data from the ice gouge data sets analyzed as part of the current study have been combined for analysis in the following classifications:

- *New Gouge Data* (individual analysis of each applicable data set);
- *Unknown Age Gouge Data* (individual analysis of each applicable data set);
- *Combined New Gouge Data*, which corresponds to the combination of USGS Open-File Report 78-730 and USGS Open-File Report 89-151 data sets;
- *Combined Unknown Age Gouge Data*, which corresponds to the combination of USGS Open-File Report 78-730 and USGS Open-File Report 83-706 data sets; and
- *Combined New and Unknown Age Gouge Data*, which corresponds to the combination of all ice gouge data sets.

Summary plots are provided for each data set combination in Appendix A1 of this report, including ice gouge depth vs. water depth and ice gouge width vs. water depth. As example, summary plots created for the Combined New and Unknown Age Gouge Data are provided below in the following Figure 13 and Figure 14. Histograms of ice gouge depth and width frequency of occurrence (logarithmic scale) are provided in Figure 15 and Figure 16, respectively, for Combined New and Unknown Age Gouge Data in binned ice gouge depth and width class ranges. Binned ice gouge depth limits are incremented in class ranges of 0m – 0.25m, 0.25m – 0.5m, and so on. Binned ice gouge width limits are incremented in class ranges of 0m – 20m, 20m – 40m, and so on.

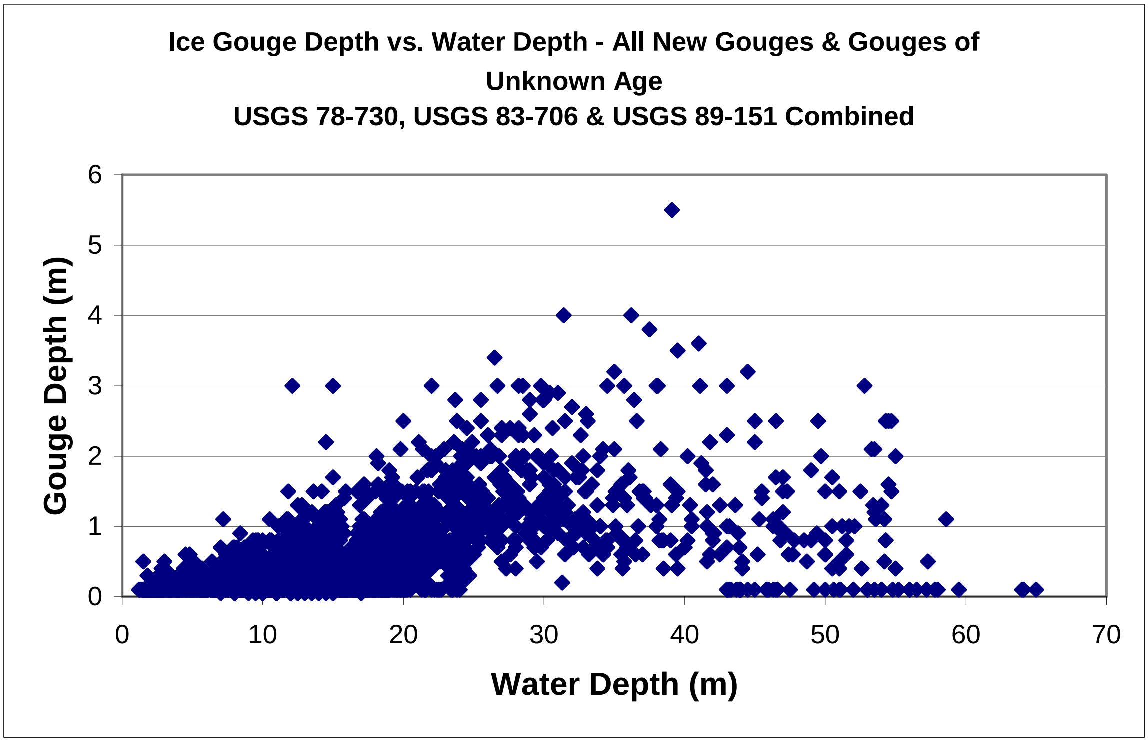

Figure 13: Summary Plot of Ice Gouge Depth vs. Water Depth, All New Gouges & Gouges of Unknown Age Combined

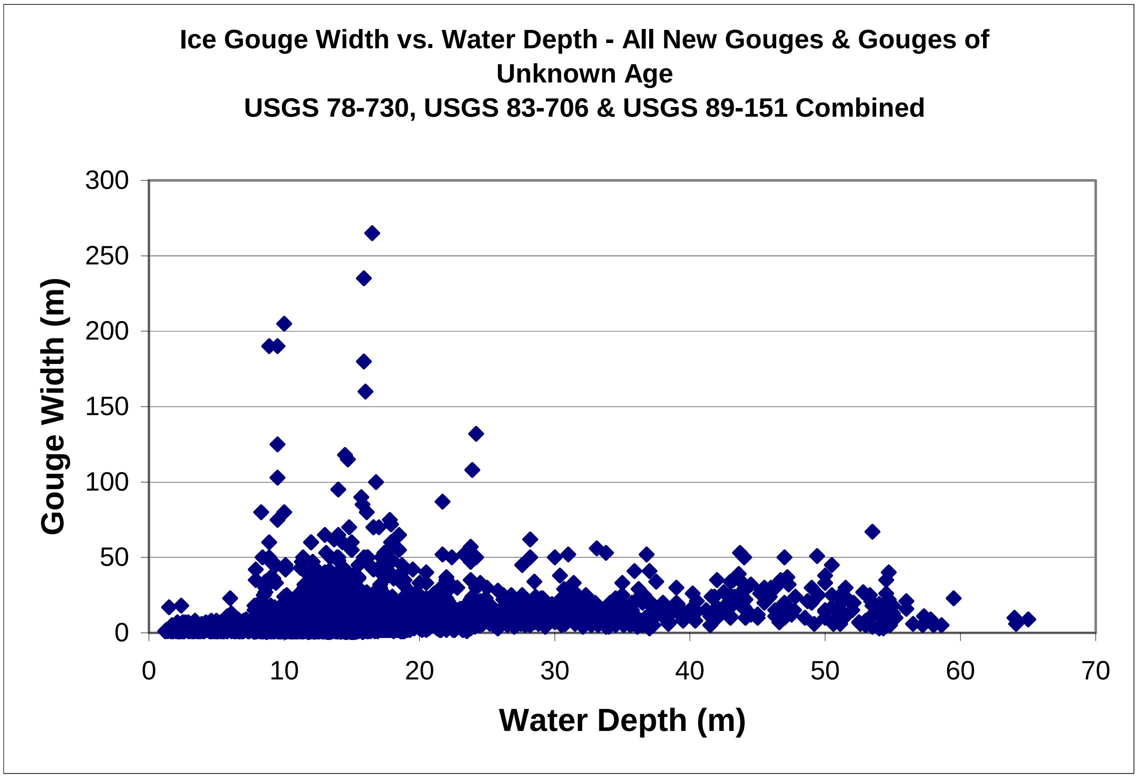

Figure 14: Summary Plot of Ice Gouge Width vs. Water Depth, All New Gouges & Gouges of Unknown Age Combined

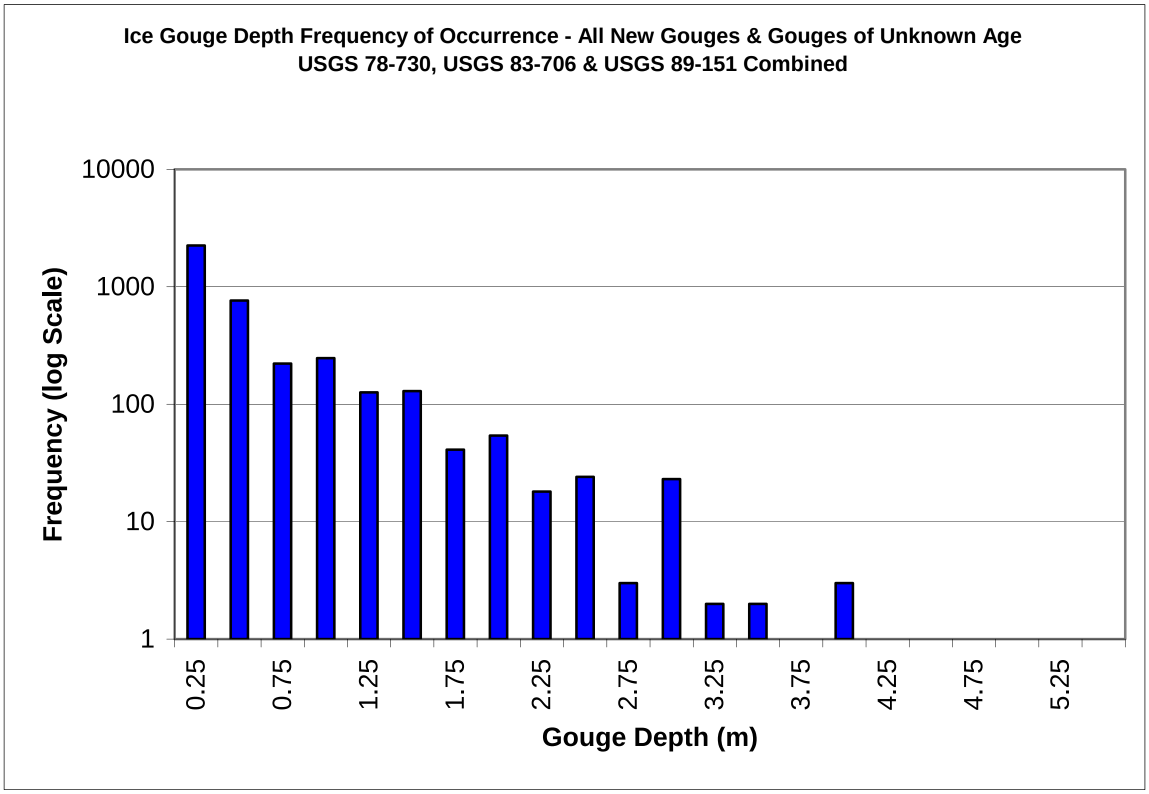

Figure 15: Ice Gouge Depth Frequency of Occurrence Histogram, All New Gouges & Gouges of Unknown Age

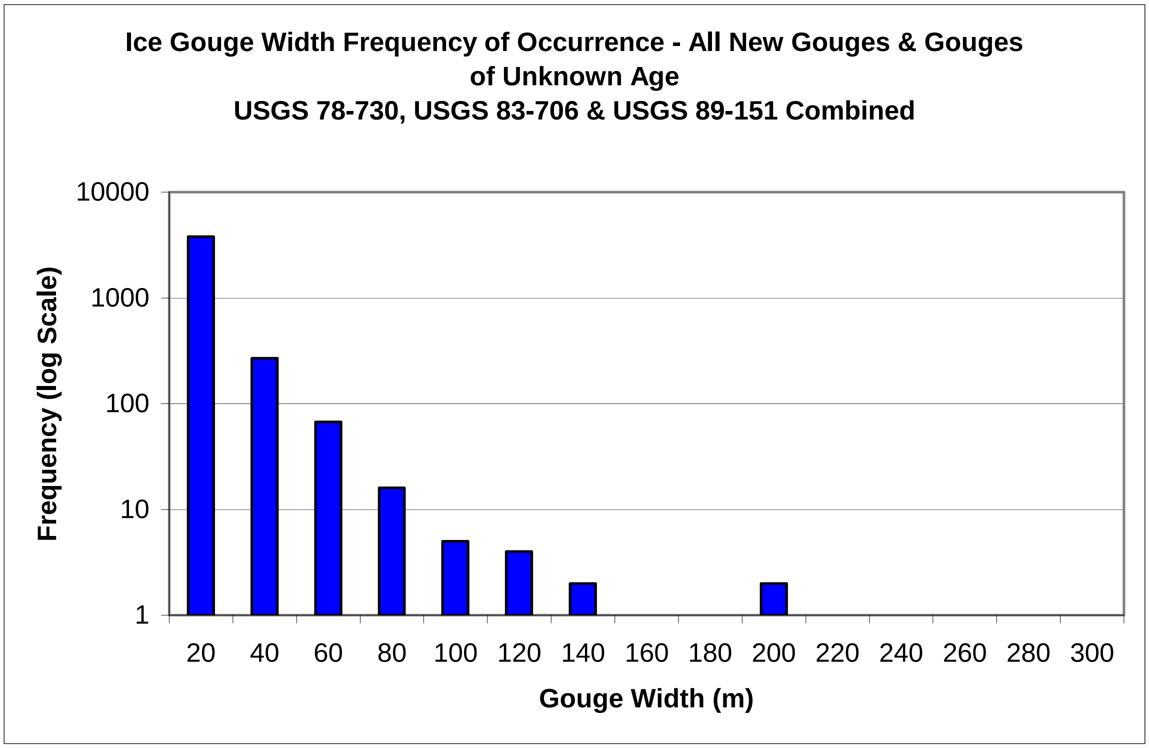

Figure 16: Ice Gouge Width Frequency of Occurrence Histogram, All New Gouges & Gouges of Unknown Age

5.3 Width / Depth Relationships

Summary plots of new ice gouge width vs. gouge depth are presented within Appendix A2 of this report. Plots are available for data sets presented in USGS Open-File Reports 89-151 and 78-730. Appendix A2 also contains summary plots of ice gouge width vs. gouge depth for undated gouge data provided in the USGS Open-File Reports 78-730 and 83-706 ice gouge data sets, as well as all data sets combined. Summary plots of ice gouge width vs. gouge depth for all available new and unknown age ice gouge data is presented in the following Figure 17 and Figure 18, respectively. A summary plot of ice gouge width vs. gouge depth for all available new and unknown age ice gouge data combined is presented in the following Figure 19. The resulting ice gouge width vs. gouge depth summary plots are also provided in Appendix A2 of this report. Refer to the applicable subsections of Section 4, above, for further discussion of the source of these summary plots.

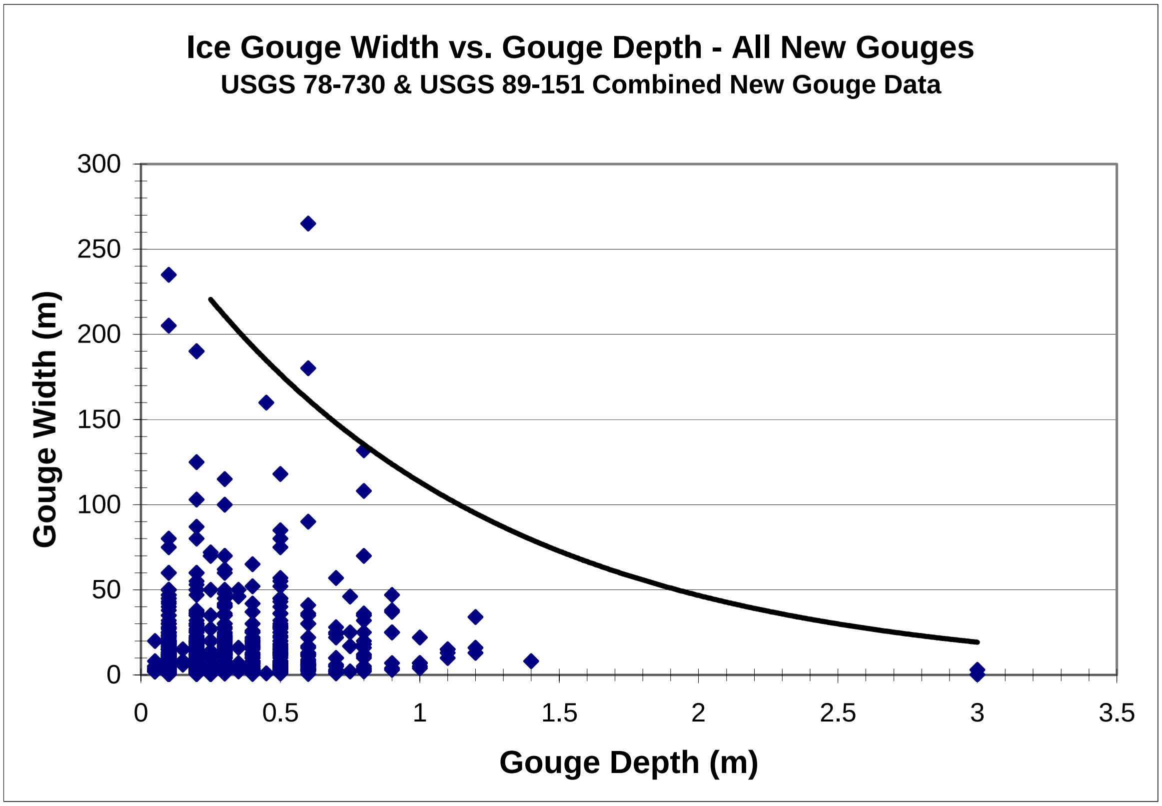

Figure 17: Summary Plot of Ice Gouge Width vs. Gouge Depth, All New Gouges

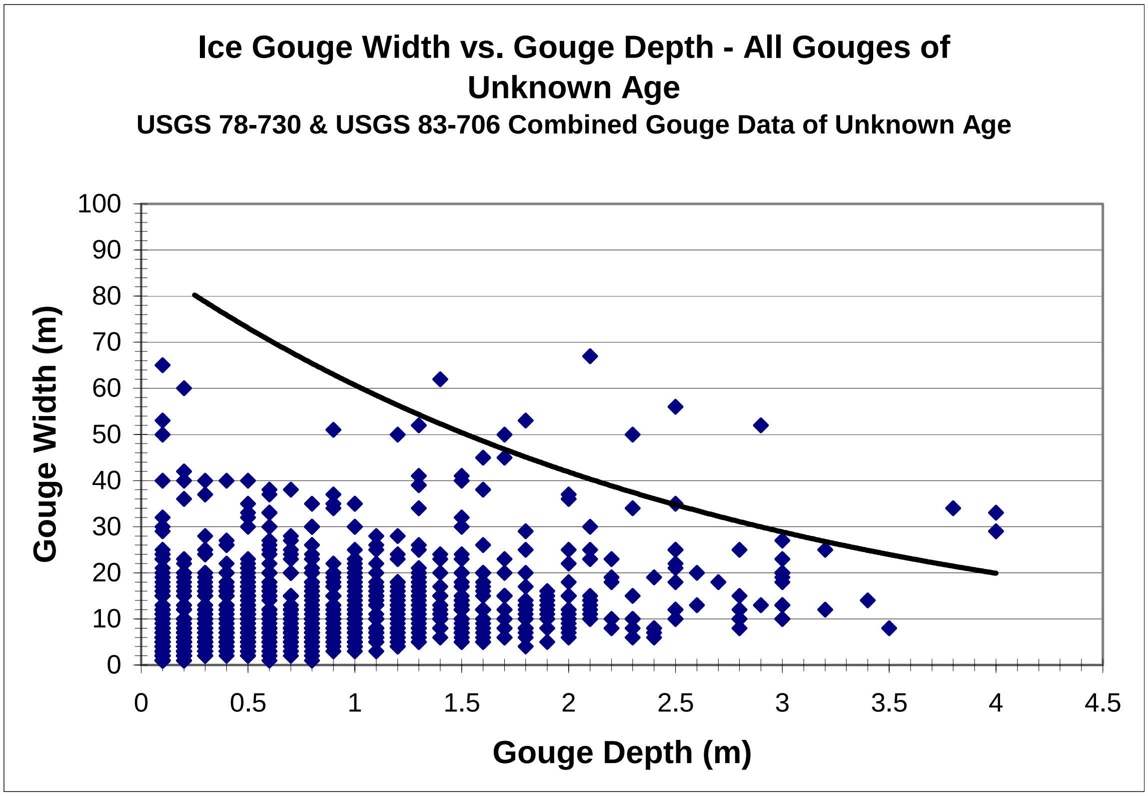

Figure 18: Summary Plot of Ice Gouge Width vs. Gouge Depth, All Gouges of Unknown Age

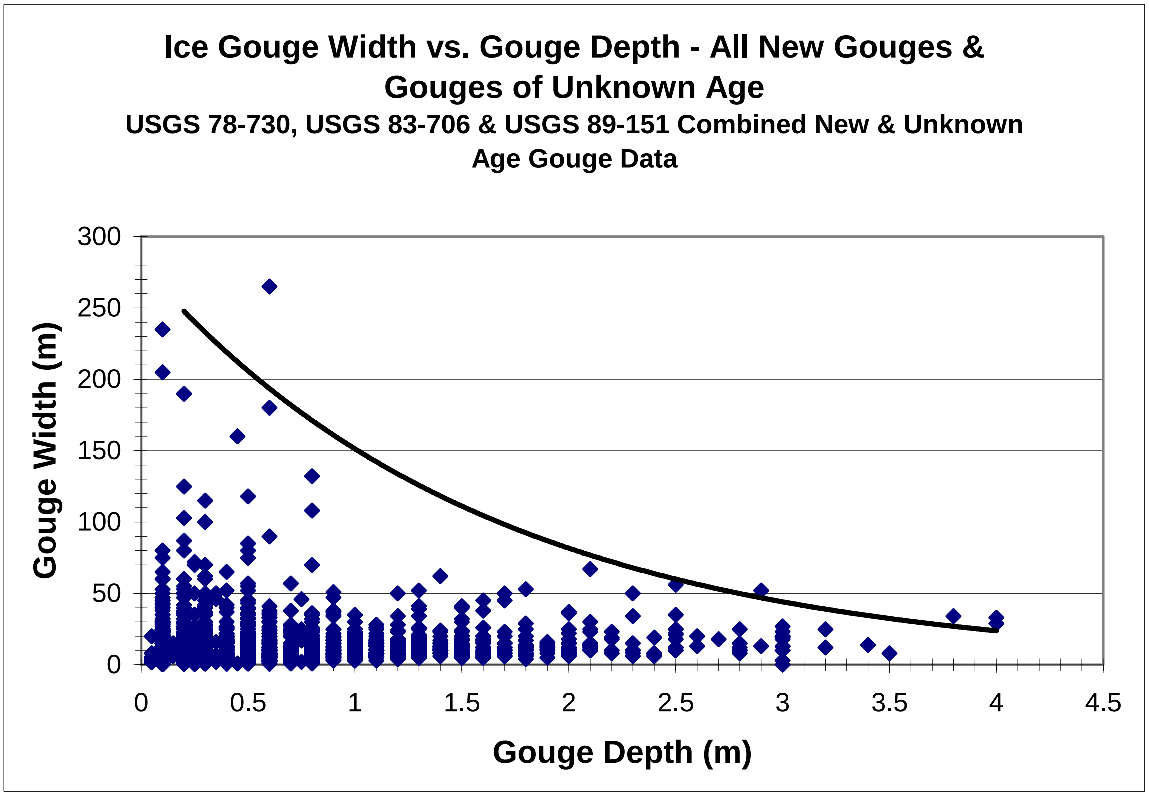

Figure 19: Summary Plot of Ice Gouge Width vs. Gouge Depth, All New Gouges & Gouges of Unknown Age Combined

Exponentially decaying data trends have been superimposed by hand on the abovementioned data summary plots in order to present a bound on ice gouge width vs. gouge depth relationships.

Ice gouge width and depth data from all new and unknown age data sources was combined and analyzed for data binned within the 0m – 20m, 20m – 40m, and 40m – 65m water depth class intervals. The resulting ice gouge width vs. gouge depth summary plots are provided in Appendix A2 of this report.

5.4 Ice Gouge Orientation

Little data has been found for dominant ice gouge orientation measurements within the Beaufort Sea Region, and is limited to new gouge data presented within USGS Open-File Report 89-151 (duplicate of USGS 85-463 data) data set. Gouge orientation data for Beaufort Sea region ice gouges of unknown age is presented within USGS Open-File Report 83-706. USGS Open-File Report 78-730 provides graphical, qualitative ice gouge orientations for new and unknown age gouge observations.

Preliminary analysis has been conducted for gouge orientation data presented within USGS Open-File Reports 83-706 and 89-151, and summary rosette plots (or ‘radar’ plots) created for observed ice gouge orientation frequencies within specified 10° gouge orientation range classes. USGS Open-File Report 83-706 corresponds to ice gouge data of unknown age, whereas report 89-151 presents new gouge data. The summary plots are provided within Appendix A1 of this report.

Analysis of the summary rosette plots indicates that the maximum new gouge orientation frequency of occurrence occurs within the 50° – 60° gouge orientation class for new gouge data presented in the USGS Open-File Report 89-151 data set. The USGS Open-File Report 83-706 indicates that the maximum gouge orientation frequency of occurrence occurs within the 70° – 80° gouge orientation class for ice gouges of unknown age. Both data sets present ice gouge orientation data which has been corrected to account for the survey vessel’s course, and is measured relative to true north. It must be noted that the range of gouges of unknown age orientation measurements reported within the 83-706 data set is 0° – 90°, whereas the range presented within the USGS 89-151 new gouge data set is predominantly 0° – 180° with few data points located in the 180° – 360° range. No discussions of these differences of measurements are available, as the purposes or causes for each range of data reporting is not provided within either report.

The new and unknown age ice gouge orientation data presented within USGS Open-File Reports 89-151 and 83-706 was combined for analysis of dominant ice gouge orientation. The resulting summary rosette plot is presented in Appendix A1 of this report and provided below in Figure 20. Analysis of the summary plot indicates that the dominant ice gouge orientation frequency of occurrence falls within the 70° – 80° gouge orientation class (approximately east – west orientation).

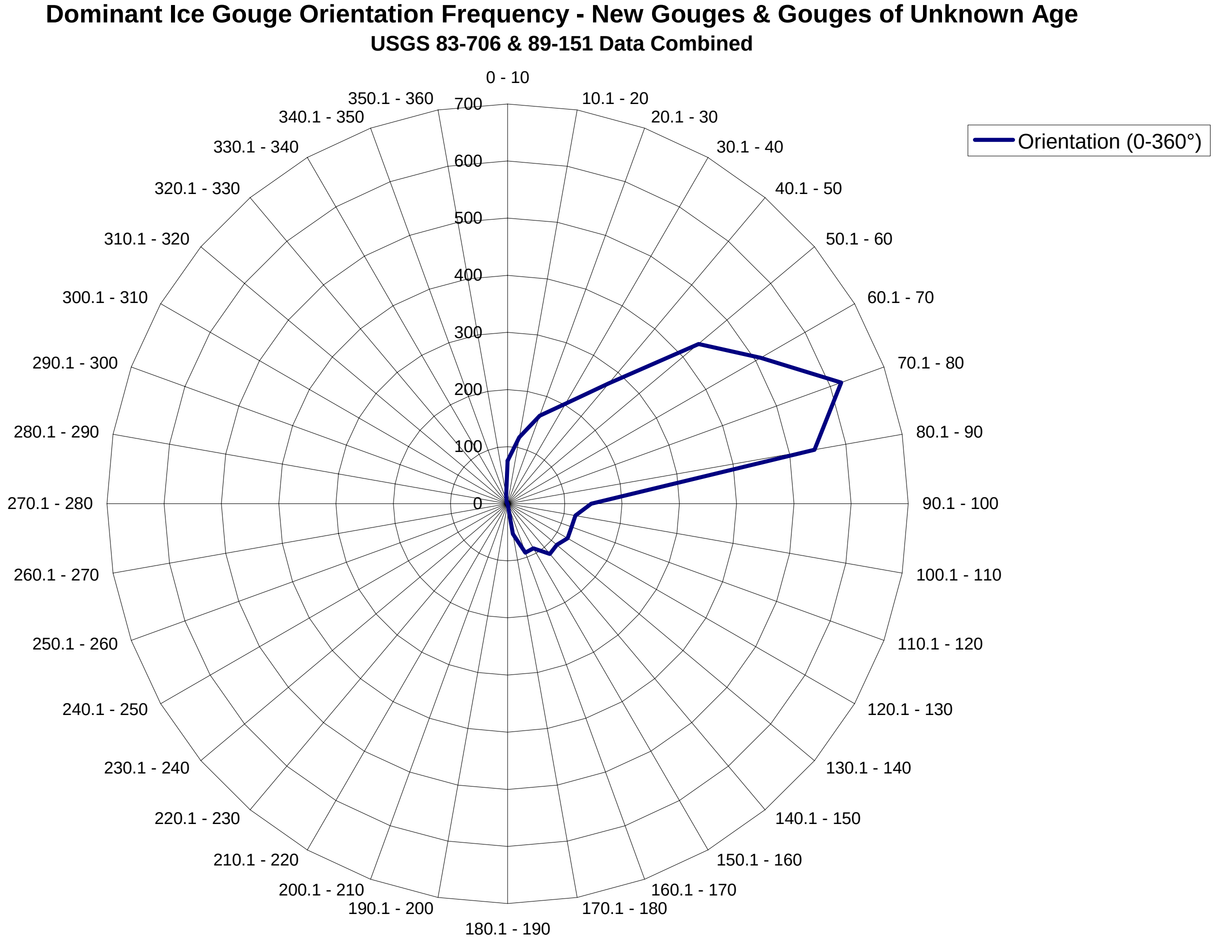

Figure 20: Dominant Ice Gouge Orientation Frequency

5.5 Infill Effects on Ice Gouge Statistics for the Beaufort Sea Area

5.5.1 Immediate Ice Gouge Infilling

Immediate ice gouge infilling rates have been analyzed by Barnes and Reimnitz (1979) within USGS Open-File Report 79-848: *Ice Gouge Obliteration and Redistribution Event; 1977 – 1978, Beaufort Sea, Alaska.* The data of Barnes and Reimnitz (1979) demonstrates the episodic influence of waves and currents upon seabed sediment reworking processes and ice gouge characteristics on the inner shelf of the Alaskan Beaufort Sea. The data analyzed by Barnes and Reimnitz (1979) was previously presented by Barnes et al. (1978) for ice gouge surveys conducted in Eastern Harrison Bay, and obtained from USGS Open-File Report 78-730.

Wave and current-driven reworking events redistribute seabed sediment material from high relief areas such as ice gouge berms (or ridges) and deposit sediment into areas of low relief, such as ice gouge troughs. The infilling of gouge depressions may thus occur promptly following gouge formation, depending upon the relative recency of a sediment redistribution event following gouge formation. It was subsequently postulated by Barnes and Reimnitz (1979) that measured depths of undated ice gouges may potentially underestimate the actual ice keel incision depth, due to rapid sediment infilling that may occur following gouge formation (Barnes & Reimnitz, 1979). This hypothesis is highly dependent upon the frequency of occurrence of wave and current-driven sediment reworking events following gouge formation, in addition to the age of the gouge at the time of survey.

No assessment of immediate ice gouge infilling for the current data sets has been attempted.

5.5.2 Long-Term Ice Gouge Infilling

Long-term ice gouge infilling may be attributed to global sedimentation and sediment redistribution upon the Alaskan Beaufort Sea inner shelf and is defined as the difference between the rates at which sediment is transported into and away from a particular ice gouge (Palmer & Niedoroda, 2005). Ice gouge infill rates thereby decrease as gouges fill in and become shallower and smoother (due to the gouge geometry). Long-term gouge infilling has been addressed within the USGS Open-File Report 78-730 ice gouge survey report. Various terminologies are synonymous to ‘ice gouge infilling’, including ‘ice gouge weathering’ and ‘ice gouge obliteration.’ Each of these terms have been encountered during the research and review associated with the current study, and are used interchangeably within this report.

Ice gouge in-fill rates are influenced by seabed hydrodynamic forces, sediment properties (cohesion, particle size, etc), in-situ water depth, and the specific geometry of the gouge (Palmer & Niedoroda, 2005). Model analysis of ice gouge in-fill rates by Palmer and Niedoroda (2005) has shown in-fill rates to be a function of water depth (among other factors) with increasing in-fill rates occurring with decreasing water depth.

Barnes et al. (1978) have analyzed seabed sedimentation rates, ice gouge re-plow and associated sedimentary structures within USGS Open-File Report 78-730, entitled *Ice Gouging Characteristics: their changing patterns from 1975 – 1977, Beaufort Sea, Alaska*. An estimated sedimentation rate of 10 cm per 100 years has been presented for the inner shelf of the Alaskan Beaufort Sea. This sedimentation rate has been estimated by Reimnitz and Barnes (1974), and subsequently quoted by Barnes et al. (1978).

Sediment reworking rates were estimated and proportional seabed ice gouge re-plow curve generated which suggests 20% undisturbed seabed per 100 year ice gouge period (Barnes et al., 1978). On this basis, any gouges present in the 20% undisturbed seabed area that are less than 10 cm deep will be filled-in during the long term (within 100 years). The seabed of the Beaufort Sea is generally clay or silt with small under-ice currents, on the order of less than 0.1 m/s, with no major sediment transport mechanisms (Palmer & Niedoroda, 2005). Beaufort Sea ice gouges thus typically remain until they are overprinted (or re-gouged) (Palmer & Niedoroda, 2005). Based on gouge model analysis, Palmer & Niedoroda (2005) postulate that the preponderance of shallow ice gouge survey observances may potentially be attributed to the severe effects which a modest Beaufort Sea storm may have upon measured ice gouge depth statistics. The generalized survey observation of most ice gouges being shallow (as may be observed in report datasets) is therefore unjustified as many gouges may fill in quickly to some degree. In this manner, typical dataset observations of numerous shallow gouges with few deep gouges intermixed may in reality be observations of many deep gouges, with most of the shallow gouge observations being remnants of deeper gouges already filled in to some extent (Palmer & Niedoroda, 2005).

6. ASSESSMENT OF ICE GOUGE EFFECTS ON A PIPELINE

6.1 Most Probable Ice Gouge Shape

Review of technical literature relevant to ice gouge shapes has been conducted as part of the current project in an effort to determine the most probable shape of ice gouge deformations. Qualitative ice gouge shape characteristics were obtained from reports of known ice gouge observations, and are presented below for use in determining the most probable ice gouge shape that may potentially be encountered by a trenched and buried offshore pipeline.

An idealized single-keeled ice gouge cross-section is presented in Figure 21 although observed ice gouge depressions are potentially narrower and shallower than the initial ice keel incision due to seabed reworking and sediment redistribution processes (Toimil, 1978). Figure 22 presents an additional idealized ice gouge formation, which depicts both the gouging ice keel (Figure 22A) and the resulting formation after slumping of the flanks and immediate gouge infill has occurred (Figure 22B). Ice gouge shapes may be influenced by the (underwater) ice keel profile, the nature and characteristics of the exposed seabed materials, the ice keel driving force, and the relative age of the ice gouge formation (Toimil, 1978; Reimnitz & Barnes, 1974). Wide, shallow ice gouges are often attributed to gouging by ice island fragments.

Fresh ice gouges observed in muddy sand seabed sediments have exhibited sharply defined features with steep side slopes of 30° to 40° angles of repose, an absence of soft sediment on the gouge floor, and highly unstable gouge ridge material, in comparison to the adjacent sediment (Reimnitz & Barnes, 1974). Ice gouging through stiff, silty clay commonly dislodges slabs of the consolidated material and scatters them about into bands of rubble, as opposed to forming well defined ice gouge features (Reimnitz & Barnes, 1974). In conflict with the idealized ice gouge deformations depicted within Figure 21 and Figure 22, Rearic (1986) calculates the volume of seabed sediment disrupted by ice gouging as the product of the gouge depth, width and length (Rearic, 1986). This calculation method thus ascribes the sediment material volume displaced by a gouging ice keel to a generalized block shape, as opposed to the actual keel deformation.

After thorough review of the existing ice gouge data and information used within the current project, no basis for recommendation of the most probable ice gouge shape has been determined. Thus, no conclusion regarding the most probable ice gouge shape resulting from an ice gouge event can be formed as part of the current study. Further technical research and review is required on this topic to determine gouging ice keel shapes.

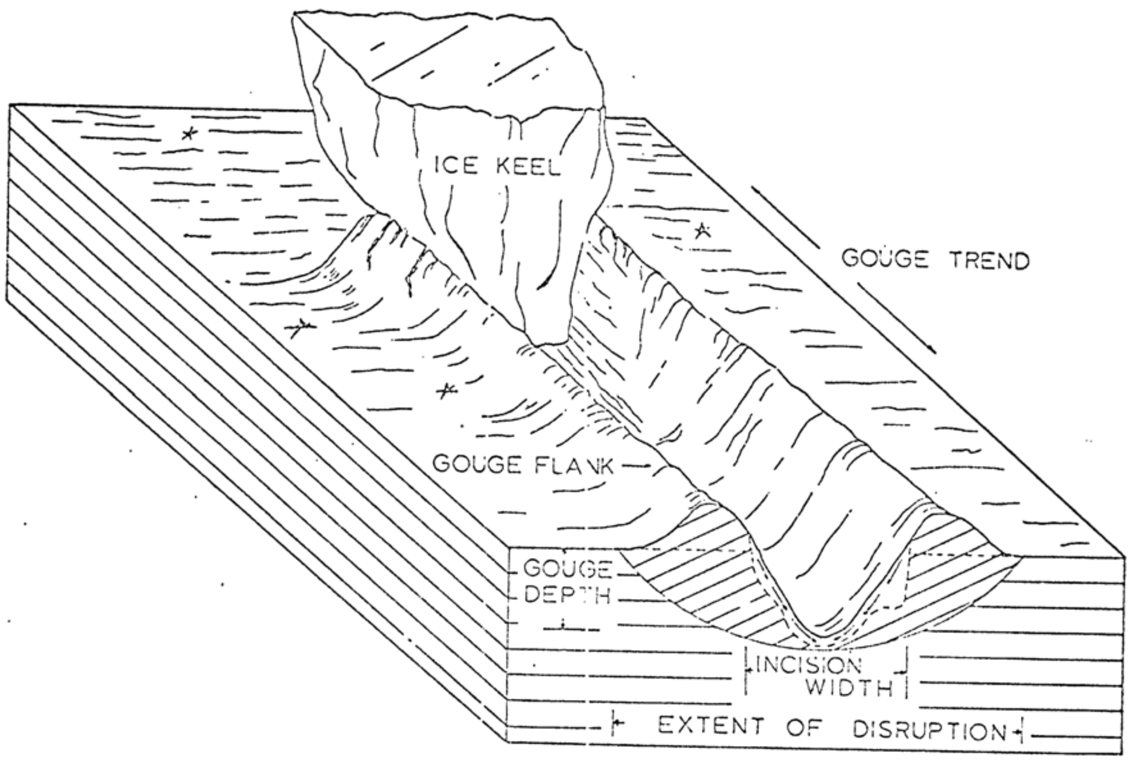

Figure 21: Idealized Single-Keeled Ice Gouge (Toimil, 1978).

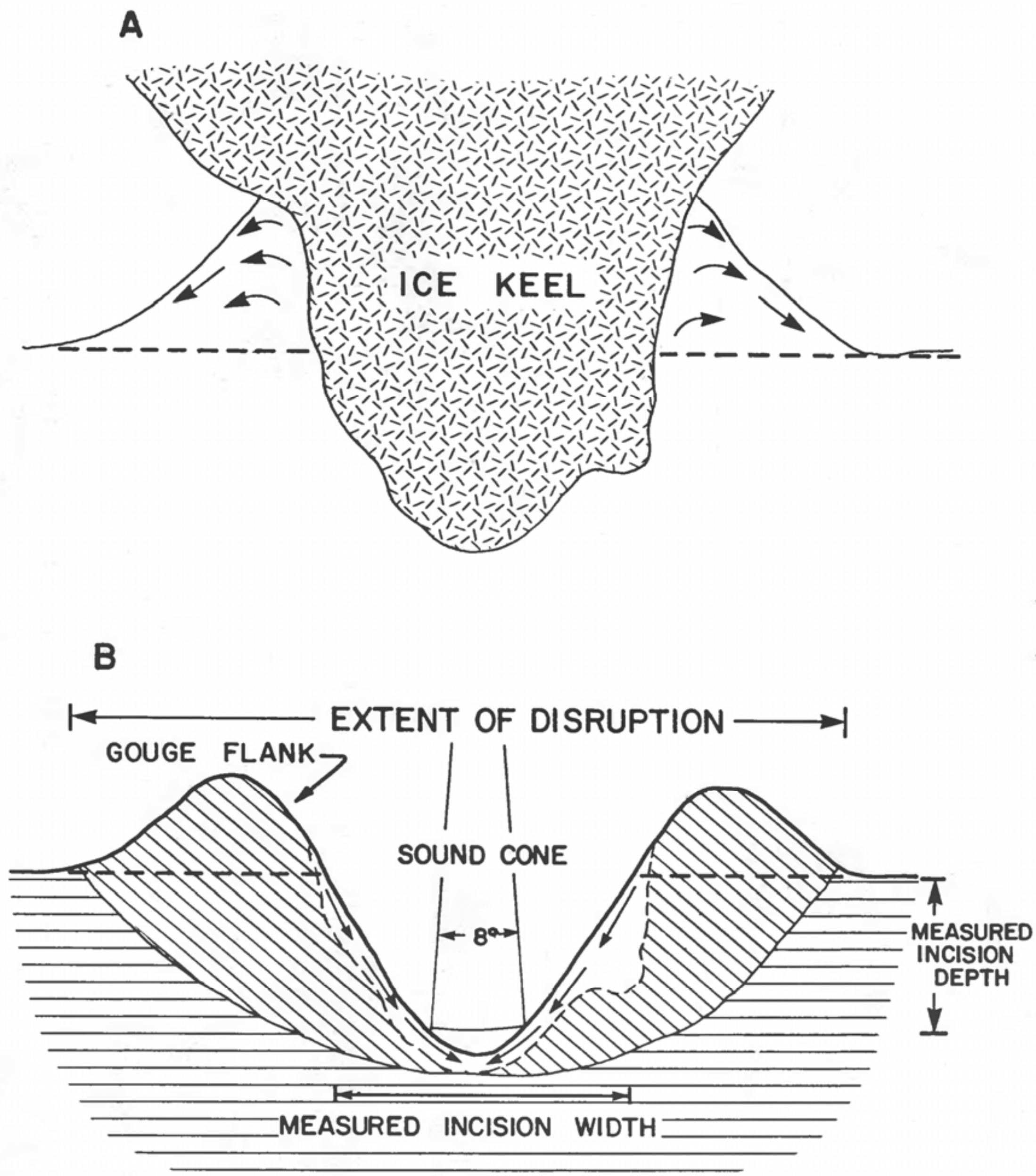

Figure 22: Idealized Single-Keeled Ice Gouge (Barnes et al., 1978).

6.2 Most Probable Ice Gouge Attack Angle

The ice gouge attack angle is the angle formed upon contact between the seabed and an impacting ice keel. A review of information has been conducted as part of the current project regarding the effect of varying ice gouge attack angles upon the seabed and the resultant gouge deformations. Although there is a potentially significant level of sensitivity to an ice gouge attack angle, no information or existing analysis regarding the most probable ice gouge attack angle or effect of varying attack angles has been found for use within the current project.

7. SUMMARY & CONCLUSIONS

Multiple years of existing ice gouge data was researched, reviewed and compiled for use within the current project. This data included ice gouge location, water depth, gouge depth, gouge width, dominant orientation, obliteration rate, and recurrence and / or crossing rate, among other pertinent parameters for offshore pipeline design. The data sets generated for use in future design have been subject to comprehensive review and analyses, and the quality and accuracy of the data assessed on the basis of the age of the data and the data collection technologies utilized, among other relevant factors.

Ice gouge data for the Alaskan Beaufort Sea was compiled and analyzed in the current study. The maximum ice gouge depth observed in analysis was 5.5m and corresponded to an ice gouge observation of unknown age and unknown width which was observed in 39.1m water depth. A general trend of increasing gouge depths with increasing water depths has been noted, with the deepest gouges commonly occurring beyond 20m water depths. Ice gouges of approximately 3.0m or less have been observed in the 0m – 20m water depth range, with gouge depths ranging from 0.1m – 5.5m beyond the 20m isobar. The deepest new gouge observed was 3.0m deep and occurred at water depths of 12.1m and 15.0m, with recorded gouge widths of 3.0m and 0.1m respectively. Analysis of only the combined new gouge data indicates no appreciable trend amongst ice gouge depths with increasing water depths.

As the ice regime is more active at and beyond the transition zone (located approximately at the 20m isobar), deeper ice gouges are to be expected. The 0m – 20m water depth range is characteristically an area of land fast ice which consequently shields the associated seabed areas from intrusion and gouging by large ice keels. Similarly, a general trend of increasing gouge width with increasing water depth has been observed, although maximum gouge widths were observed in the 10m – 60m water depth range due to significant scatter amongst the analyzed data sets. The maximum ice gouge width observed in analysis was 265m, which corresponded to a multiplet ice gouge of known age and gouge depth of 0.6m, and occurred at a water depth of 16.5m. The number of individual gouge incisions in this multi-keeled event was not specified. The widest observed gouge of unknown age was 67m and had a corresponding gouge depth of 2.1m and occurred at a water depth of 53.5m. New ice gouge depths ranged from 0.05m to 3.0m deep and were located in water depths ranging from 3.3m to 27.2m. New ice gouge widths ranged from 1m to 265m wide and were located in water depths ranging from 3.3m to 27.2m deep. The dominant ice gouge orientation exhibited in data analysis of combined new and unknown age gouges occurred in the 70° to 80° range, measured relative to true north, although this observation is based upon limited available data.

Analysis of ice gouge width/depth relationships and distributions was conducted for available data sets in order to evaluate relationships between the data which could then be used in pipeline design. A general trend of decreasing gouge width with increasing gouge depth was observed amongst plotted ice gouge width and depth data. Analyses does not support the presence of a conclusive relationship between ice gouge widths and depths, which subsequently indicates that ice gouge widths are not necessarily solely a function of the associated gouge depth. The apparent lack of correlation exhibited by the analyzed ice gouge width and depth data may also potentially be attributed to the inclusion of multiplet ice gouge widths in the analyzed data sets. Further data collection, review and analysis are required to provide a definitive conclusion regarding ice gouge width and depth statistical distributions.

Little information regarding the most probable ice gouge shape and ice keel attack angle was determined from the current study. The gouge shape and attack angle are of significant importance in pipeline design due to the significant effects these factors have on the forces required to create a gouge feature and on the associated subgouge soil deformations. It is recommended that further research be conducted in these areas so that the most probable ice gouge shapes and attack angles may be determined for use in pipeline design.

The episodic influence of waves and currents upon seabed sediment reworking procedures and immediate ice gouge infilling are presented, although no substantial analysis was conducted due to lack of available data. Long term infilling rates and ice gouge obliteration was analyzed for repetitive survey data, where available. The highest rates of long-term ice gouge infilling and obliteration are commonly observed in sandy seabed sediments. Areas of stiff silt sediments have generally displayed significantly lower gouge infilling rates. Long-term sediment infilling data was limited to one data set obtained from repetitive mapping surveys (Barnes et al., 1978) and thus requires additional investigation for conclusive pipeline design input. Additionally, it is recommended that further investigations be conducted to determine the immediate effects of gouge infilling and side berm slumping after ice gouge events. The extent of these immediate effects may lead to under-conservative measurements of the ice gouge events.

This report has presented an analysis of existing ice gouge parameters and data for use in pipeline design and burial depth determination within the Alaskan Beaufort Sea. Summary plots generated for preliminary statistical analyses in this project are provided in the Appendices of this report.

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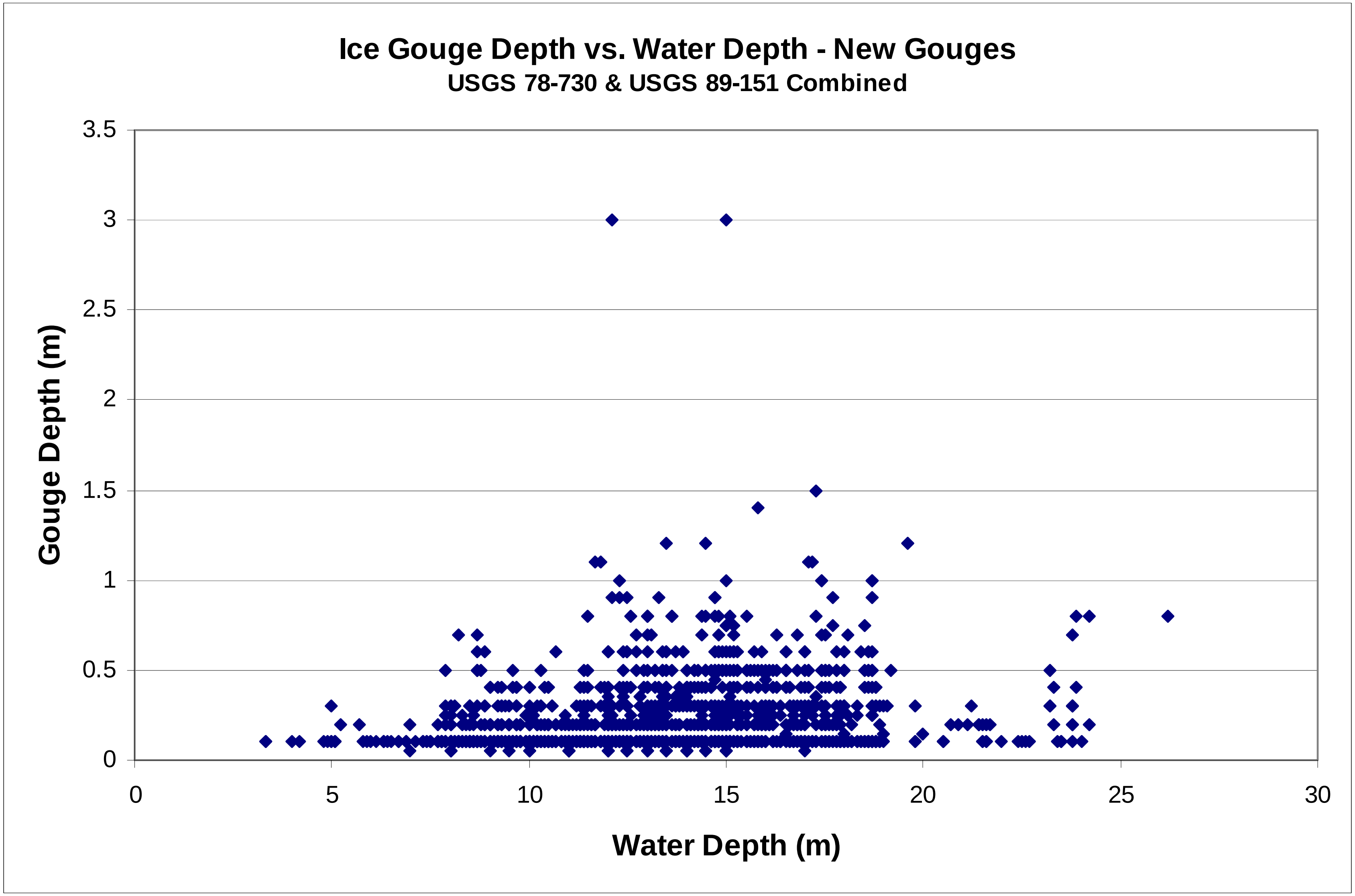
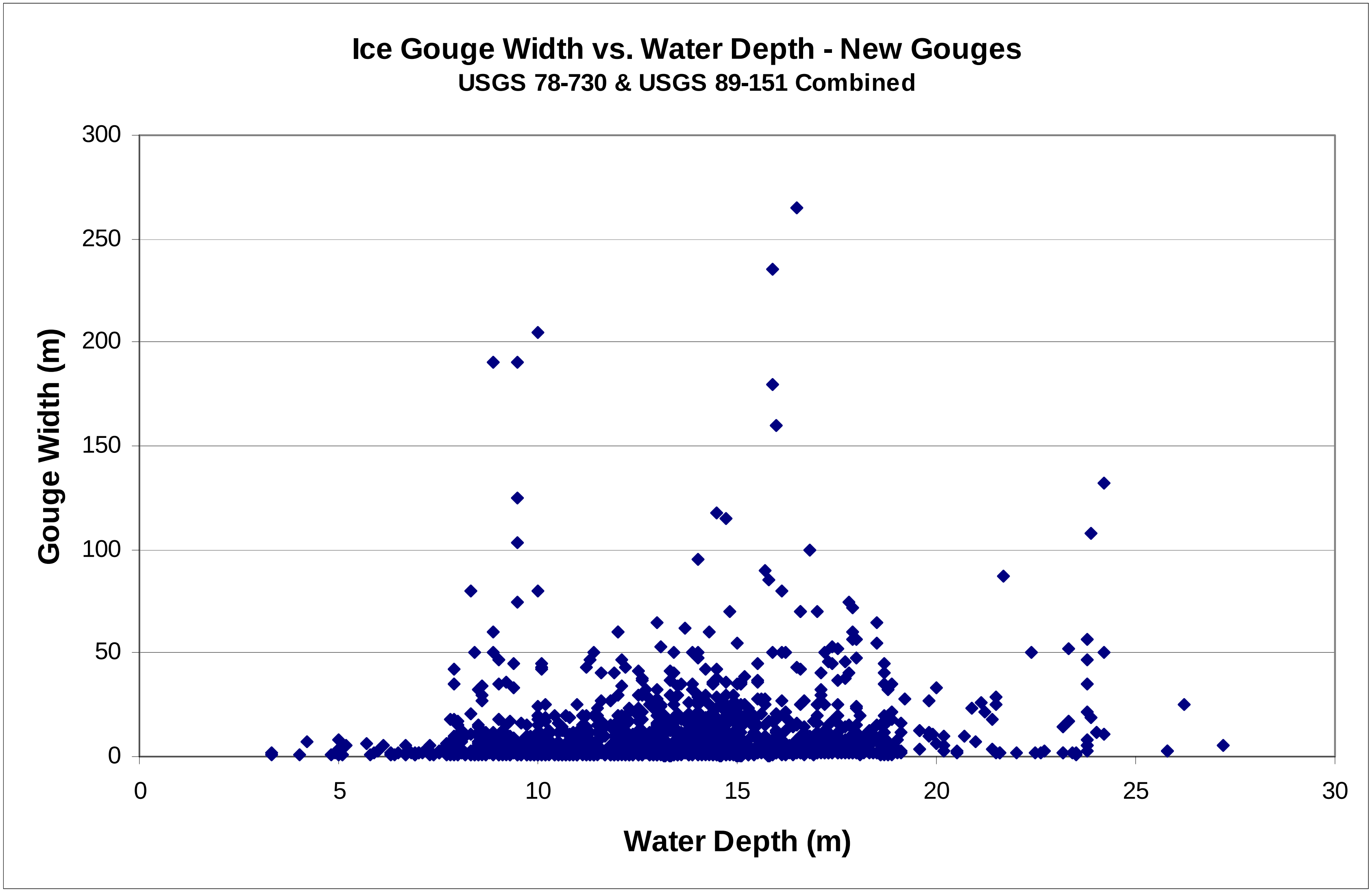
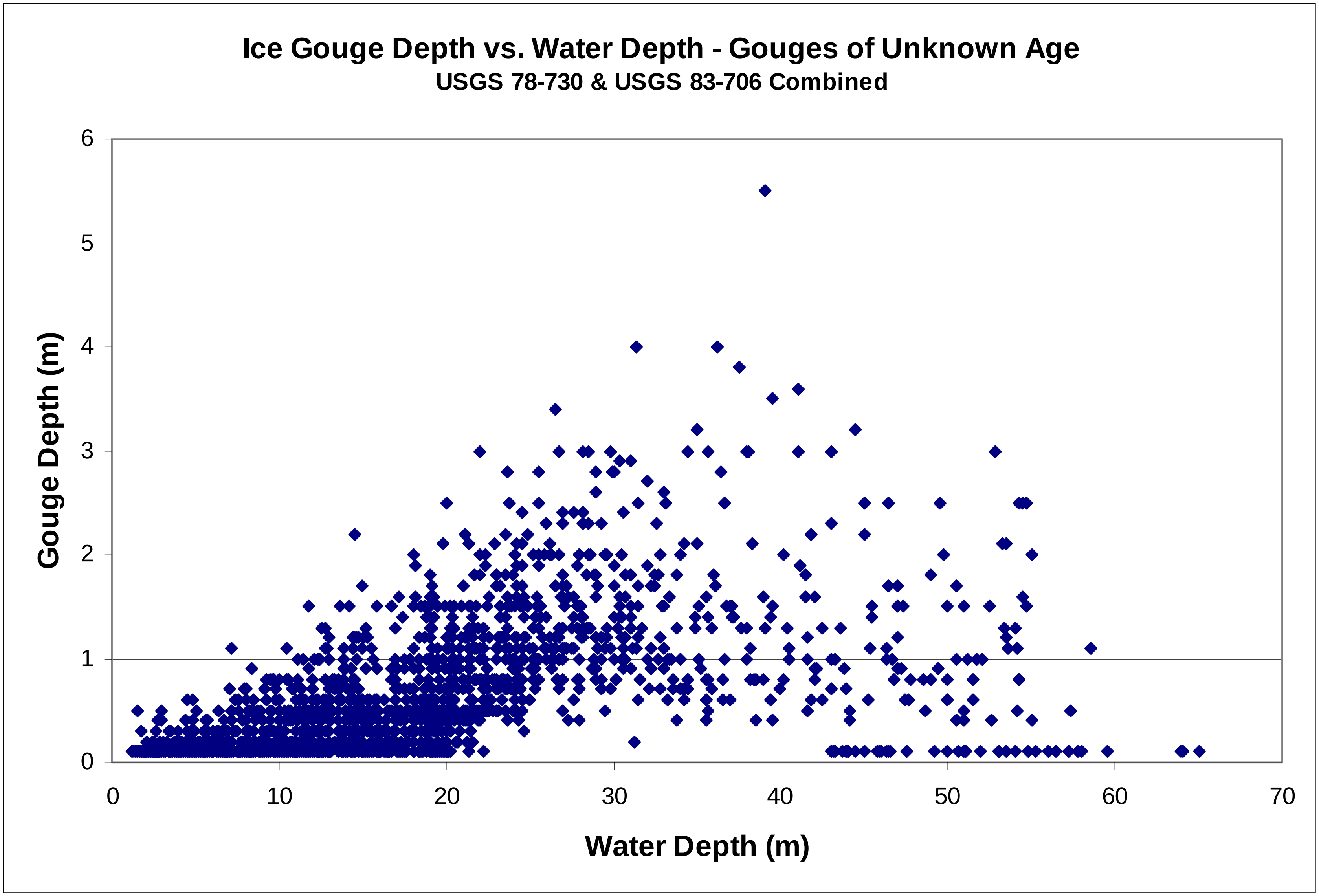
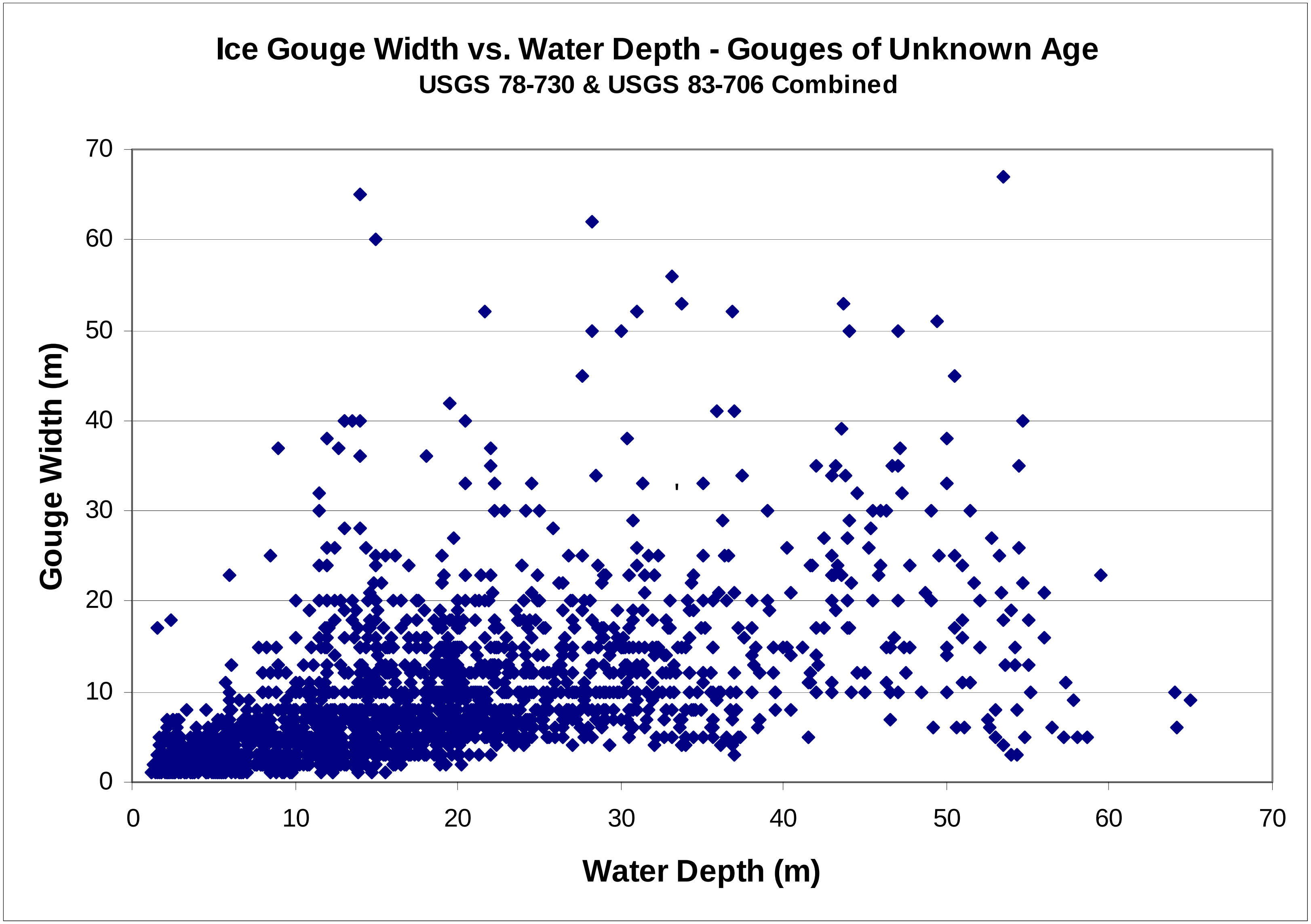
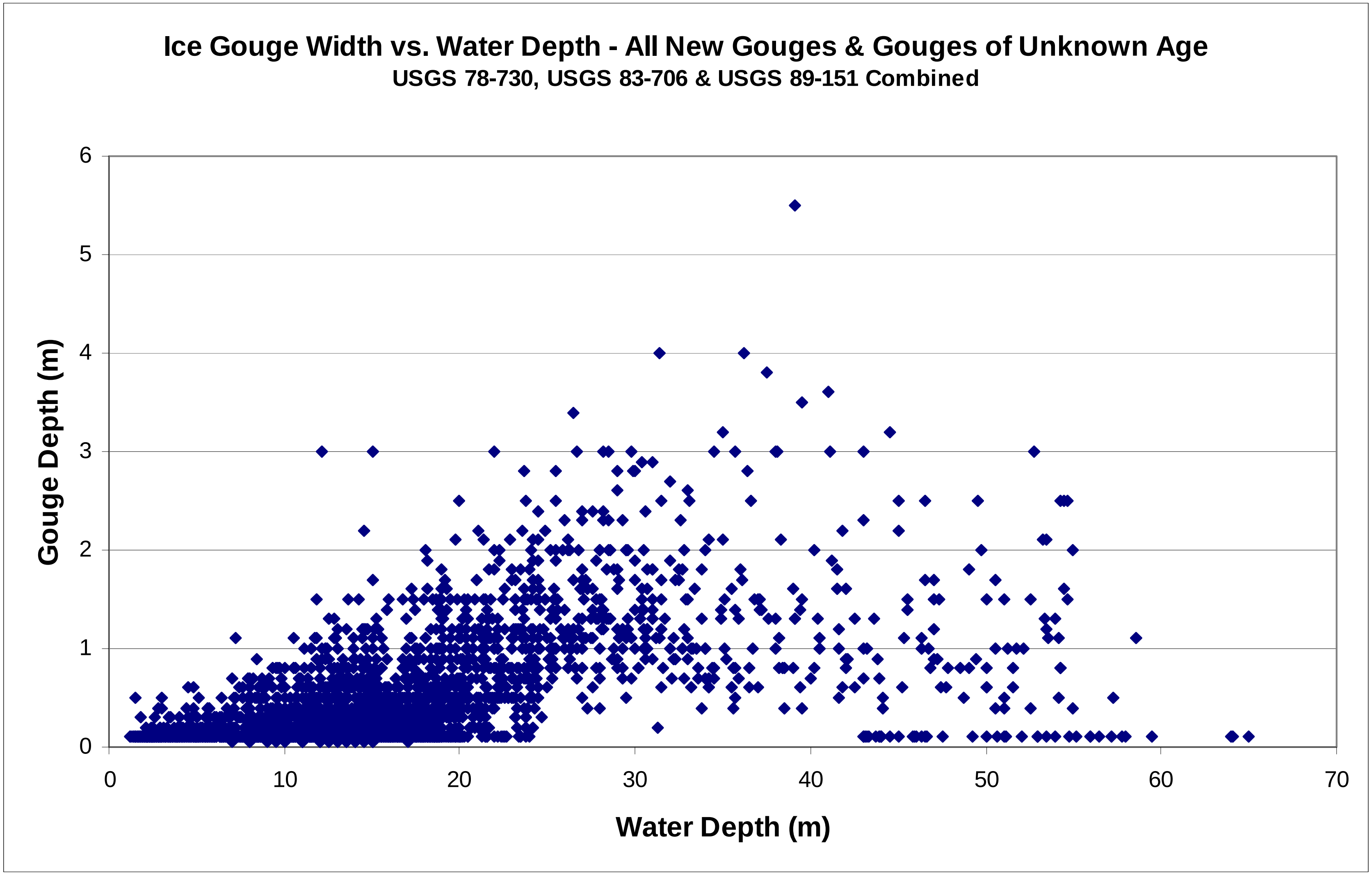
APPENDIX A1 – Summary Plots of Ice Gouge Data


Ice Gouge Depth vs. Water Depth - New Gouges
USGS 78-730 & USGS 89-151 Combined
Gouge Depth (m)
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
Water Depth (m)

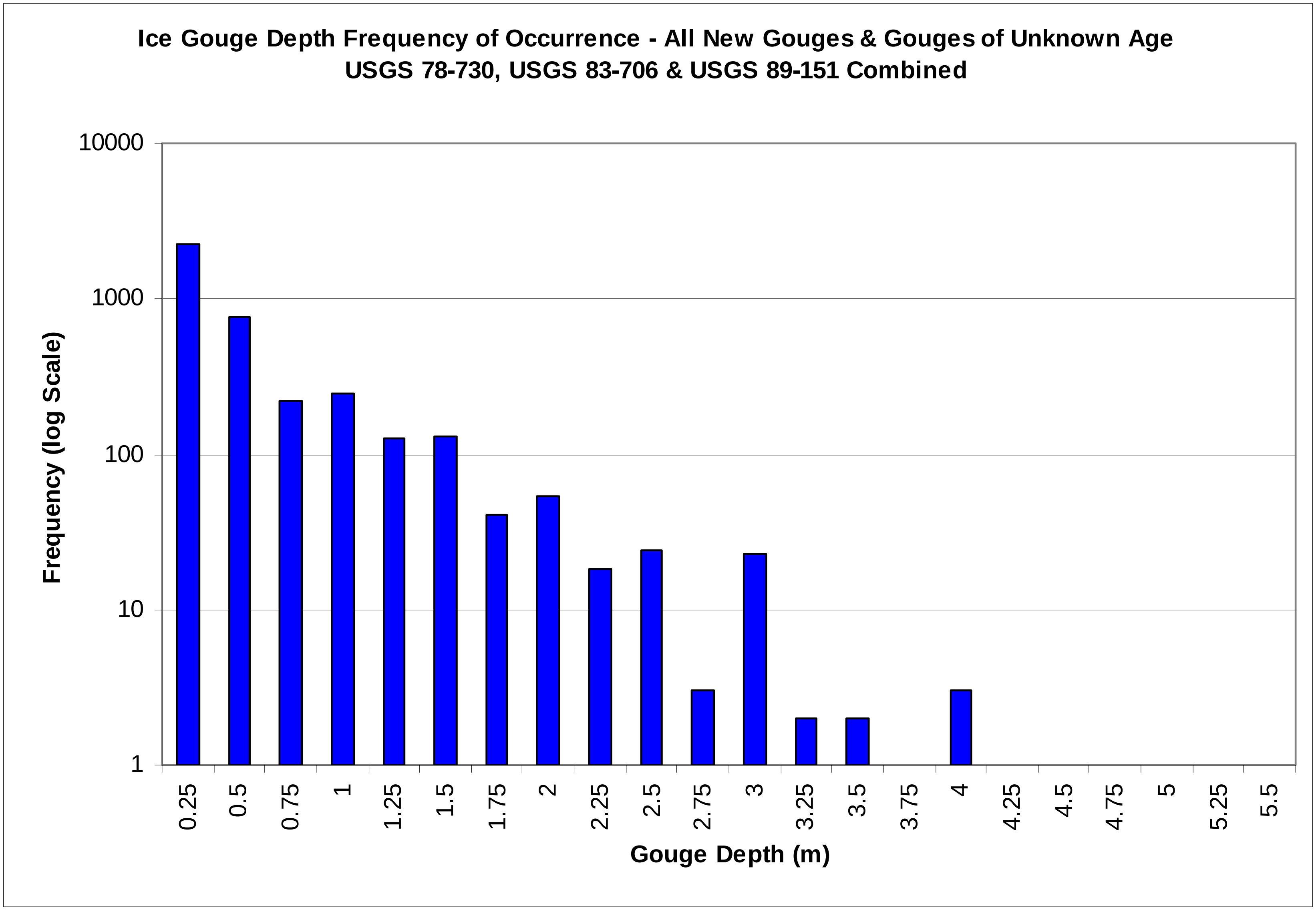

Ice Gouge Width vs. Water Depth - New Gouges
USGS 78-730 & USGS 89-151 Combined
Gouge Width (m)
300
250
200
150
100
50
0
0
5
10
15
20
25
30
Water Depth (m)

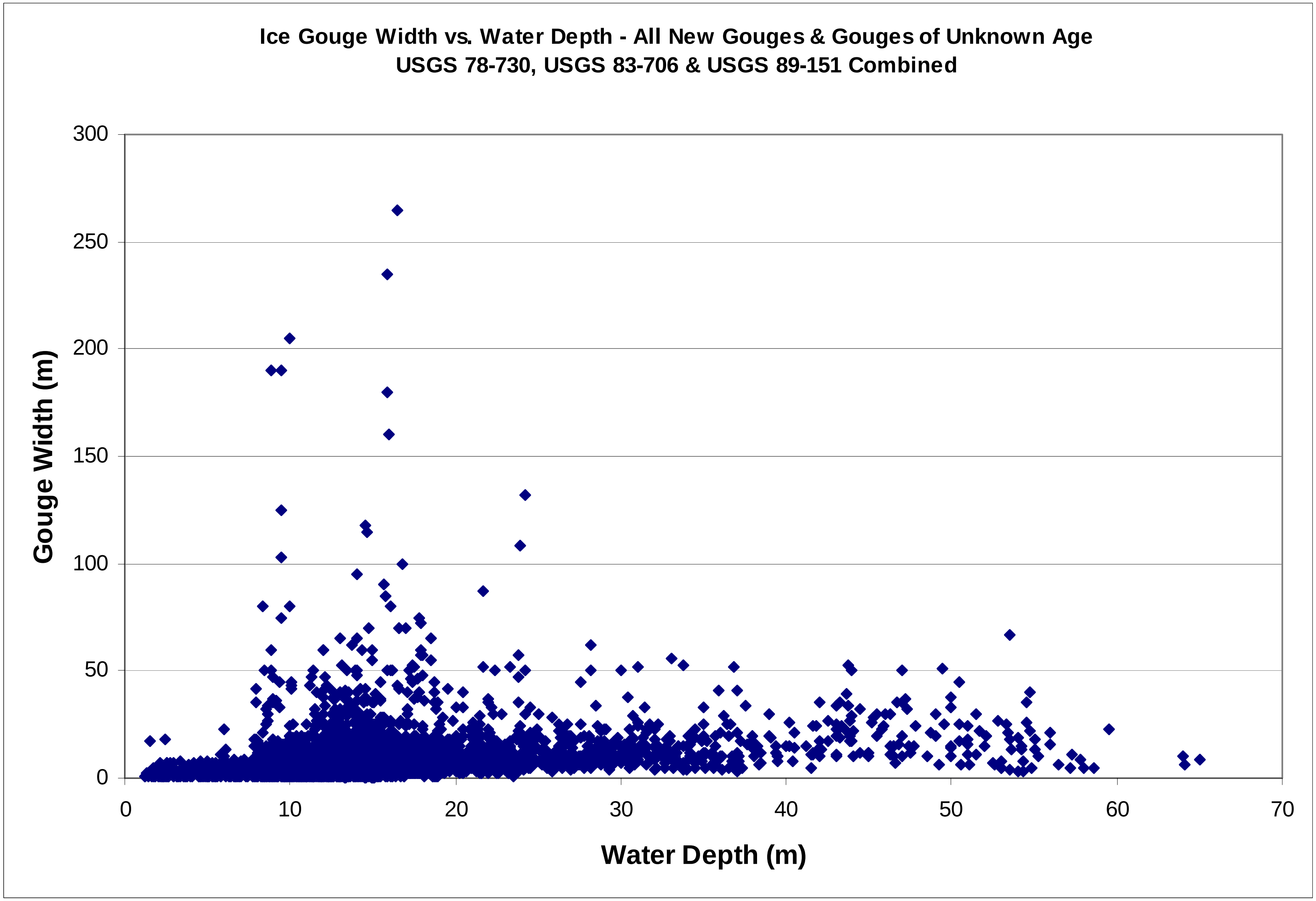

Ice Gouge Depth vs. Water Depth - Gouges of Unknown Age
USGS 78-730 & USGS 83-706 Combined
Gouge Depth (m)
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Water Depth (m)

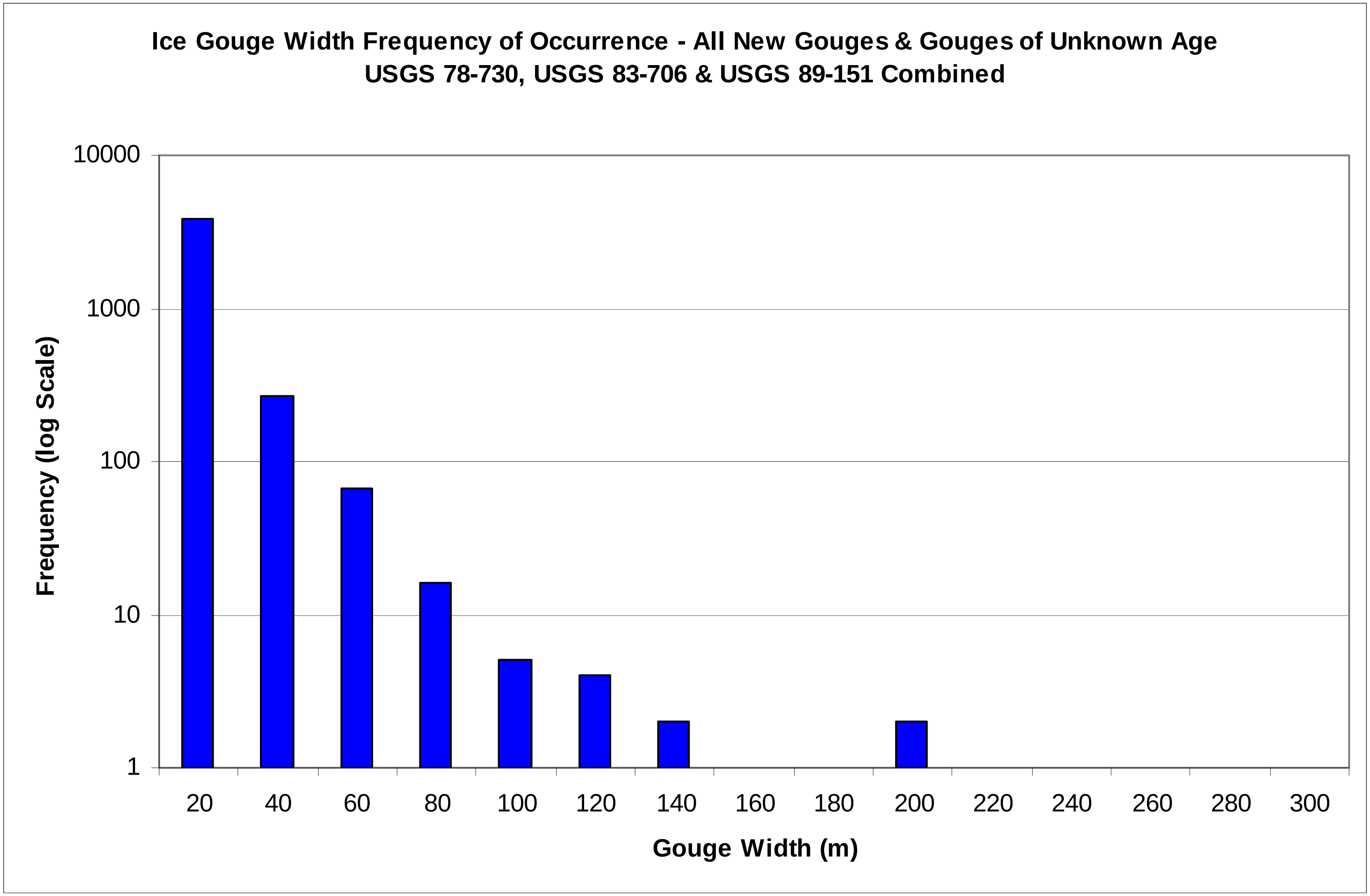

Ice Gouge Width vs. Water Depth - Gouges of Unknown Age
USGS 78-730 & USGS 83-706 Combined
Gouge Width (m)
Water Depth (m)
0
10
20
30
40
50
60
70
0
10
20
30
40
50
60
70



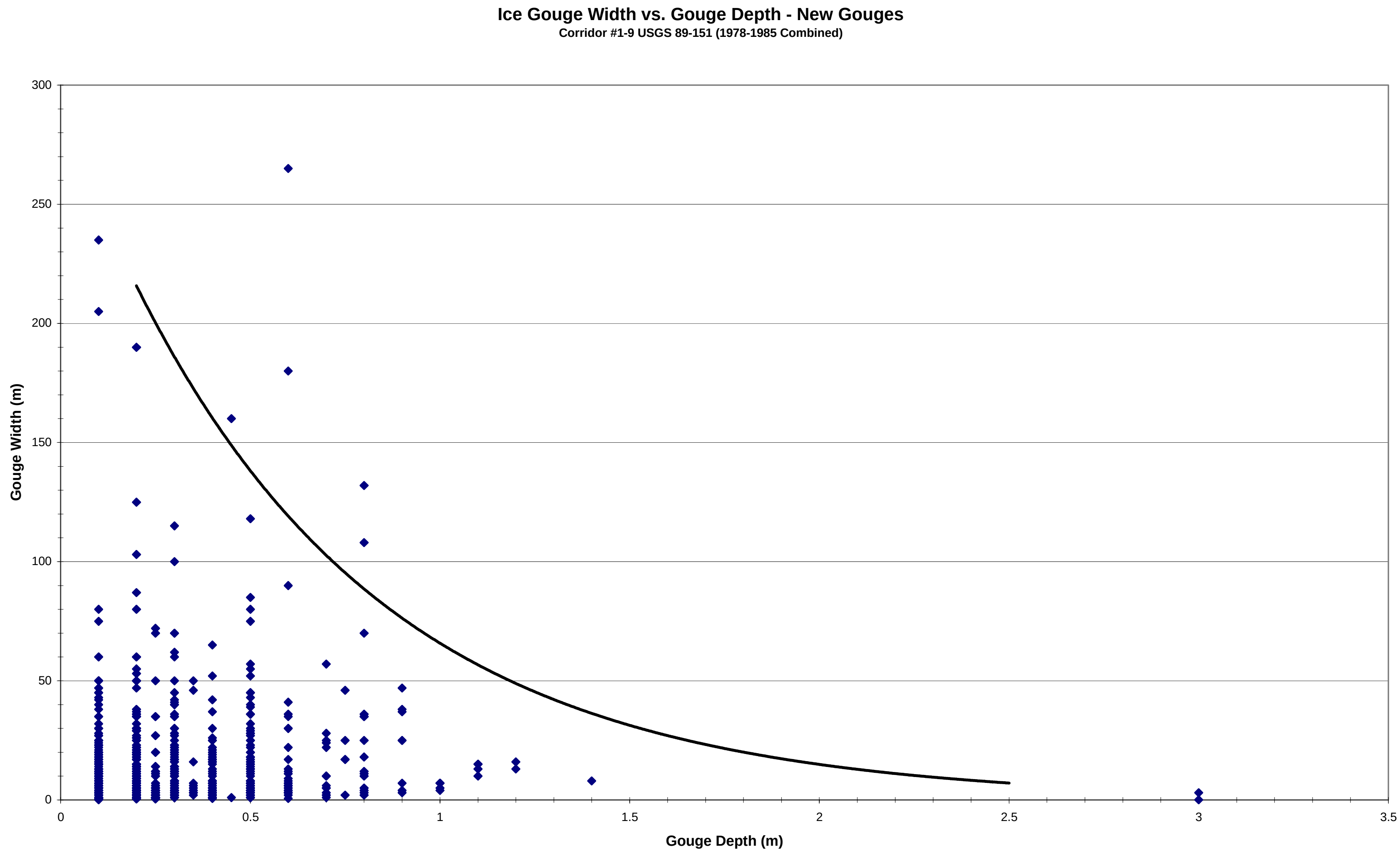
Ice Gouge Width vs. Water Depth - All New Gouges & Gouges of Unknown Age
USGS 78-730, USGS 83-706 & USGS 89-151 Combined
Gouge Depth (m)
0
1
2
3
4
5
6
Water Depth (m)
0
10
20
30
40
50
60
70

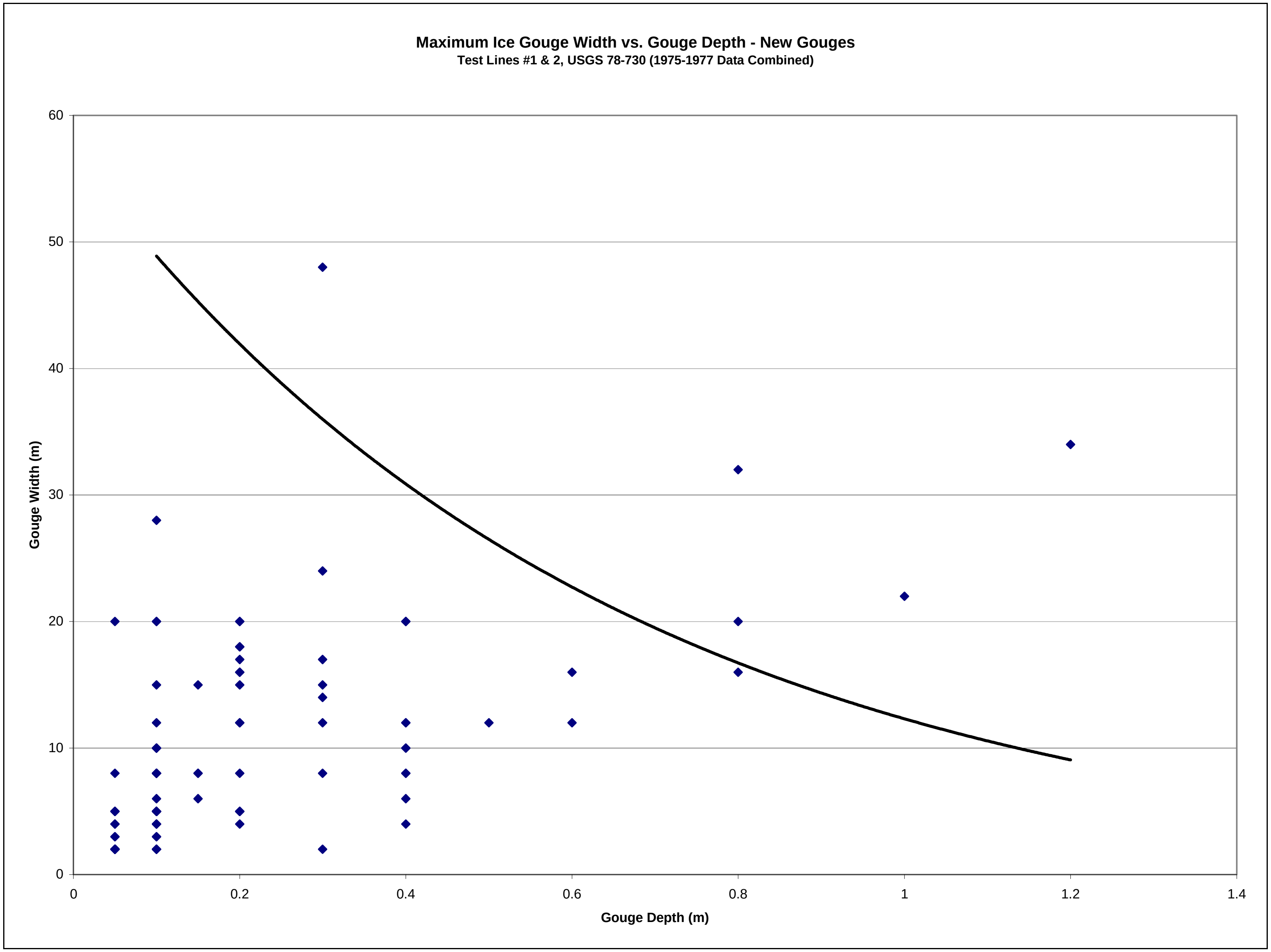

Ice Gouge Depth Frequency of Occurrence - All New Gouges & Gouges of Unknown Age
USGS 78-730, USGS 83-706 & USGS 89-151 Combined
10000
1000
100
10
1
Frequency (log Scale)
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
3.5
3.75
4
4.25
4.5
4.75
5
5.25
5.5
Gouge Depth (m)

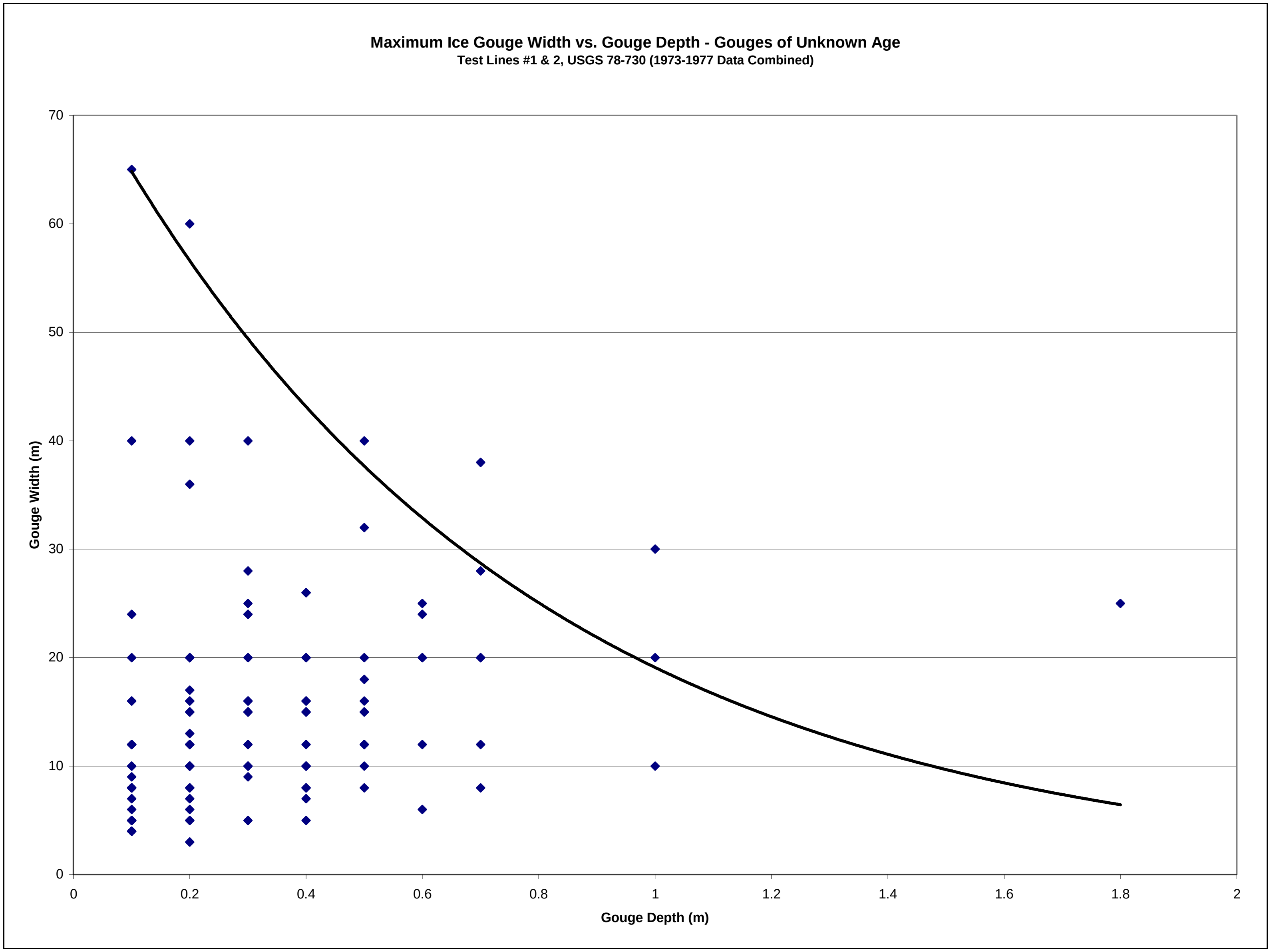

Ice Gouge Width vs. Water Depth - All New Gouges & Gouges of Unknown Age
USGS 78-730, USGS 83-706 & USGS 89-151 Combined
Gouge Width (m)
Water Depth (m)
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70

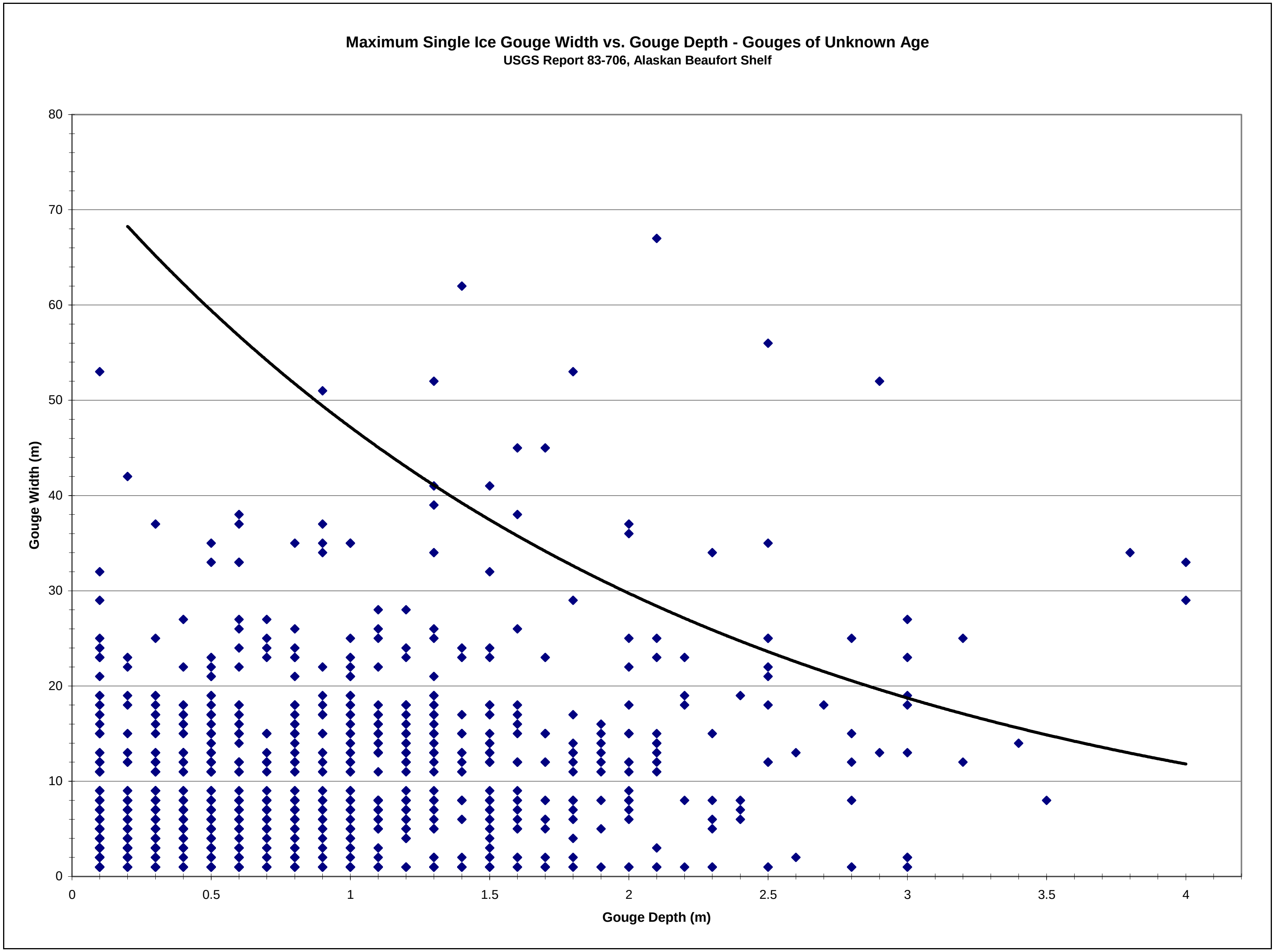

Ice Gouge Width Frequency of Occurrence - All New Gouges & Gouges of Unknown Age
USGS 78-730, USGS 83-706 & USGS 89-151 Combined
Frequency (log Scale)
10000
1000
100
10
1
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Gouge Width (m)

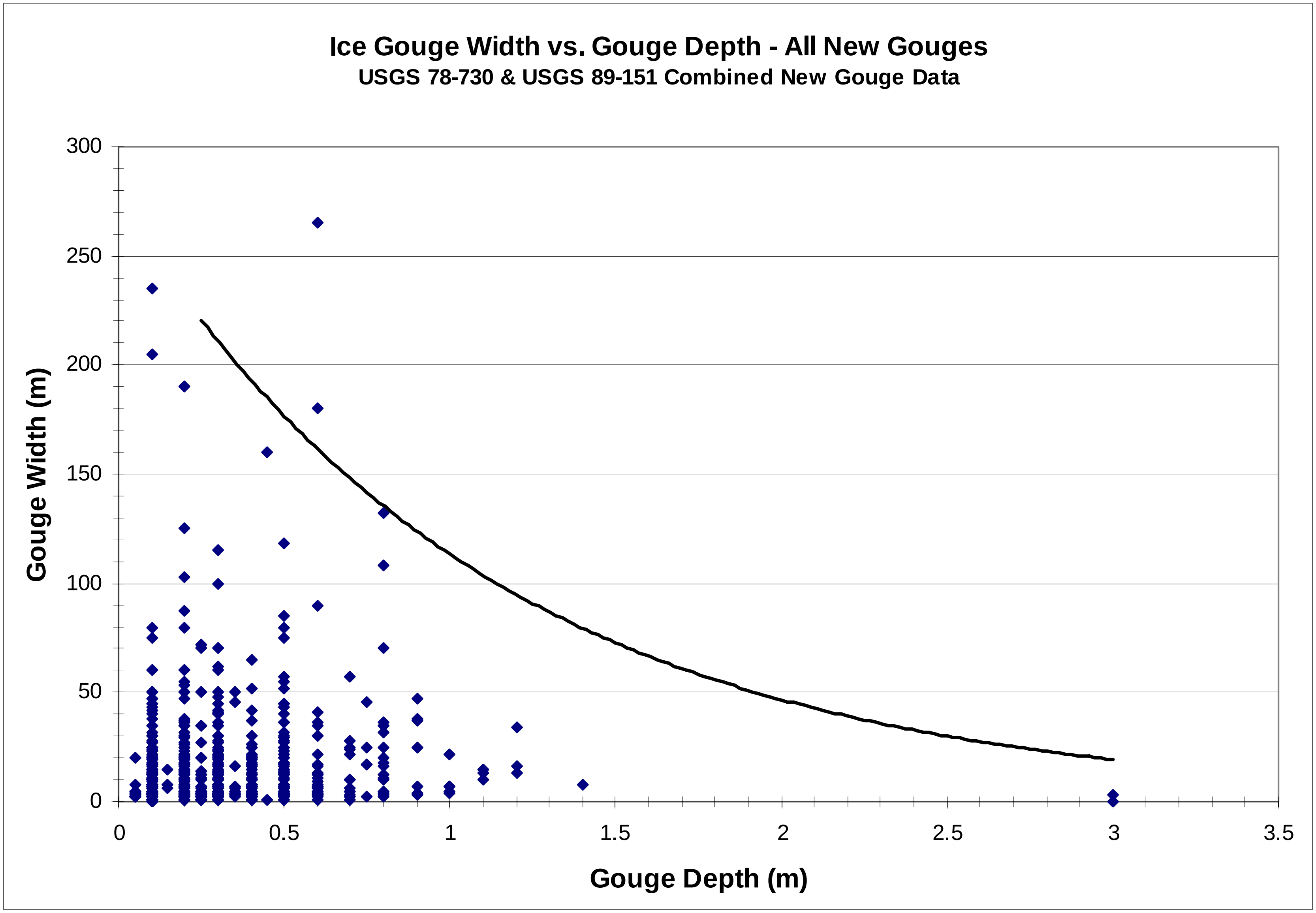
APPENDIX A2 – Ice Gouge Depth / Width Relationship


Ice Gouge Width vs. Gouge Depth - New Gouges
Corridor #1-9 USGS 89-151 (1978-1985 Combined)
Gouge Width (m)
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
Gouge Depth (m)

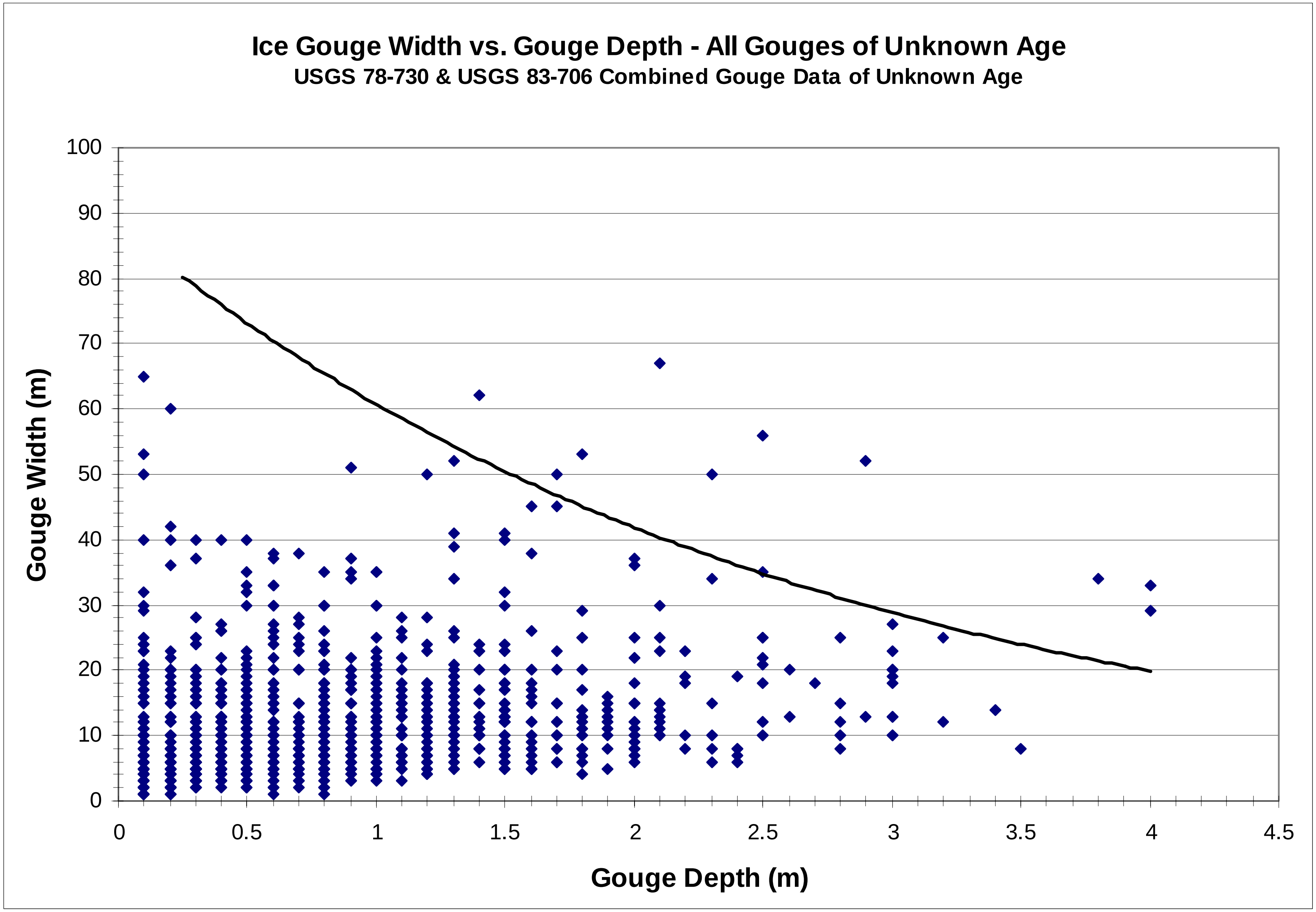

Maximum Ice Gouge Width vs. Gouge Depth - New Gouges
Test Lines #1 & 2, USGS 78-730 (1975-1977 Data Combined)
Gouge Width (m)
0
10
20
30
40
50
60
Gouge Depth (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4

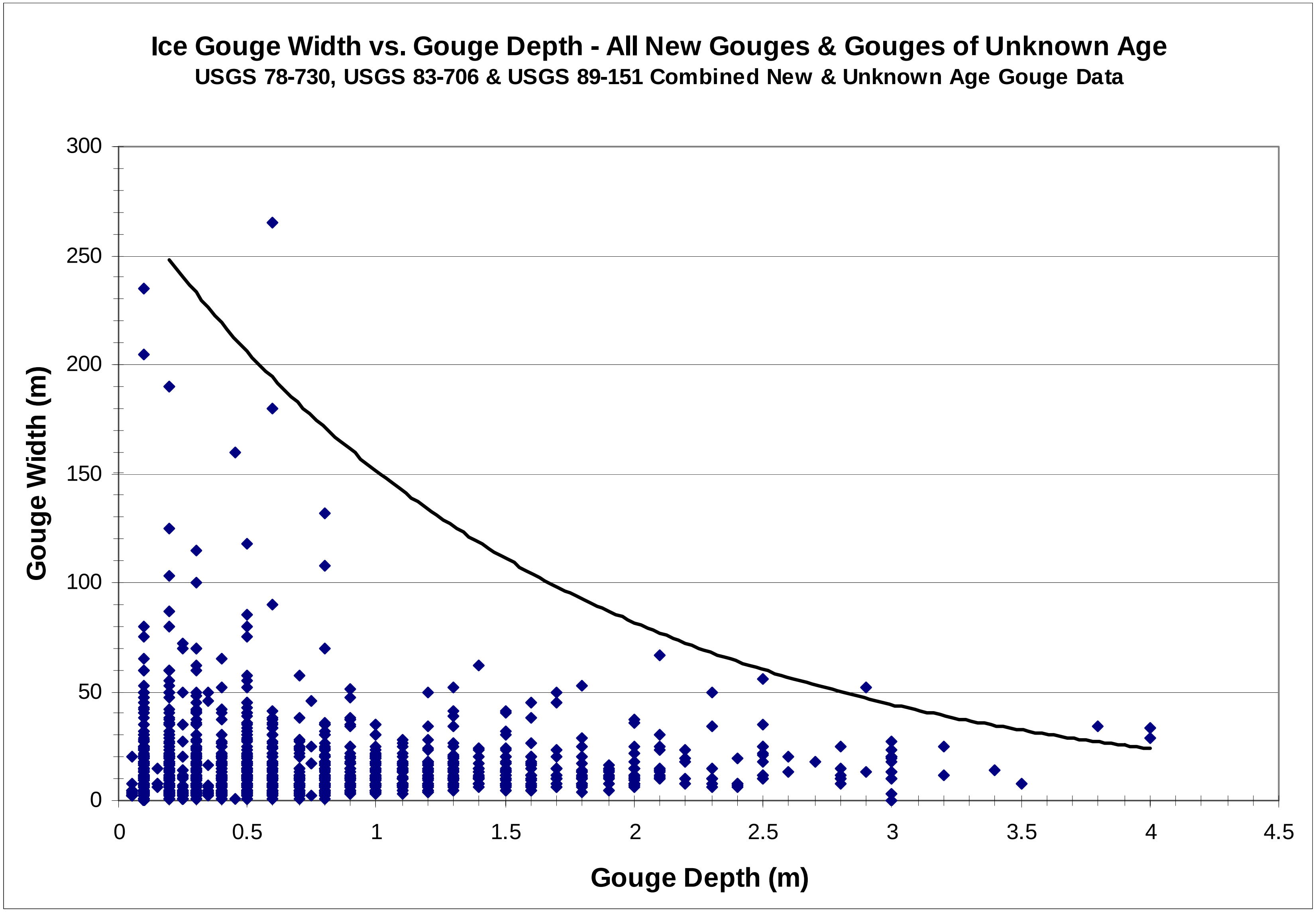

Maximum Ice Gouge Width vs. Gouge Depth - Gouges of Unknown Age
Test Lines #1 & 2, USGS 78-730 (1973-1977 Data Combined)
Gouge Width (m)
Gouge Depth (m)
0
10
20
30
40
50
60
70
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

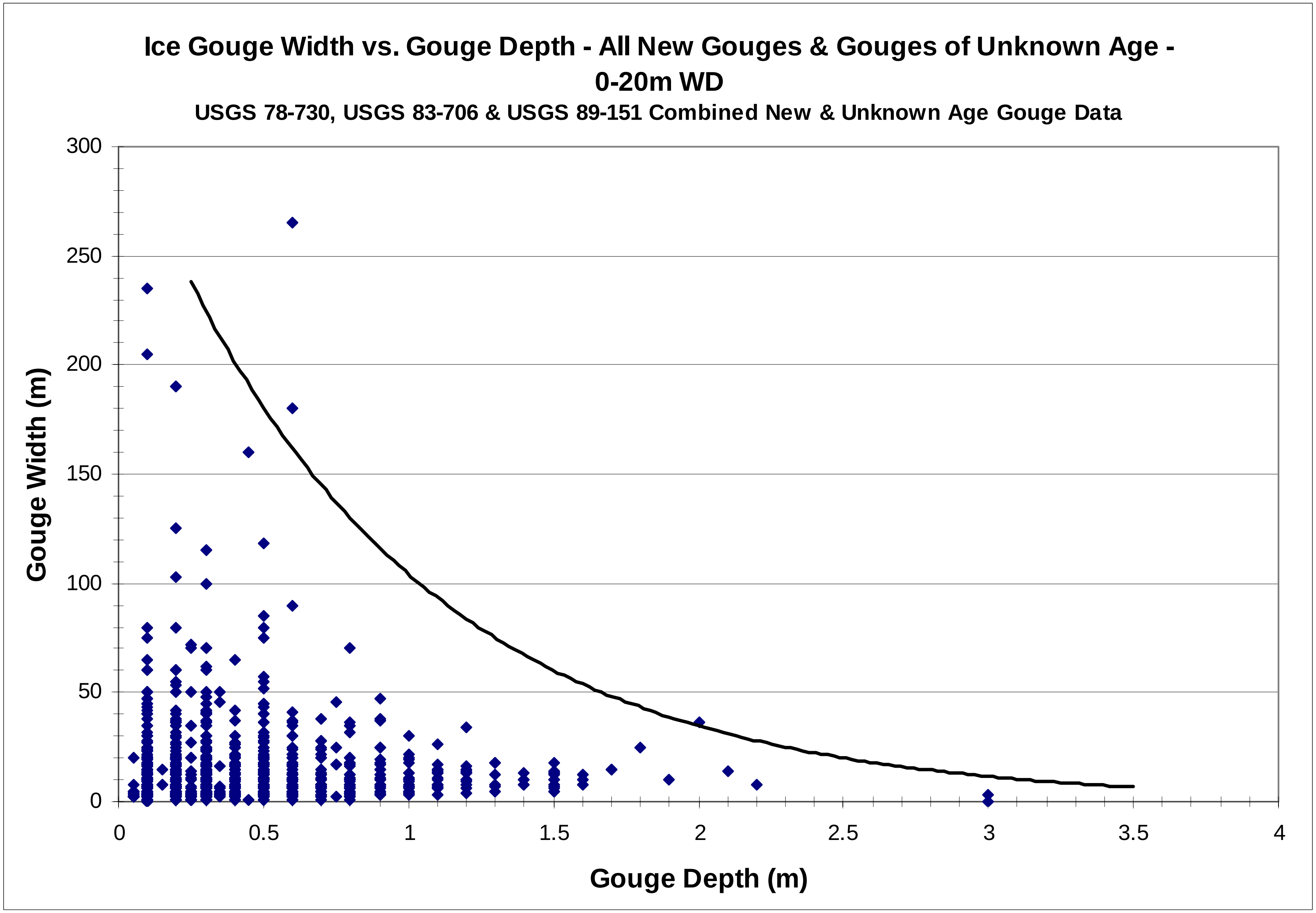

Maximum Single Ice Gouge Width vs. Gouge Depth - Gouges of Unknown Age
USGS Report 83-706, Alaskan Beaufort Shelf
Gouge Width (m)
Gouge Depth (m)
0
10
20
30
40
50
60
70
80
0
0.5
1
1.5
2
2.5
3
3.5
4

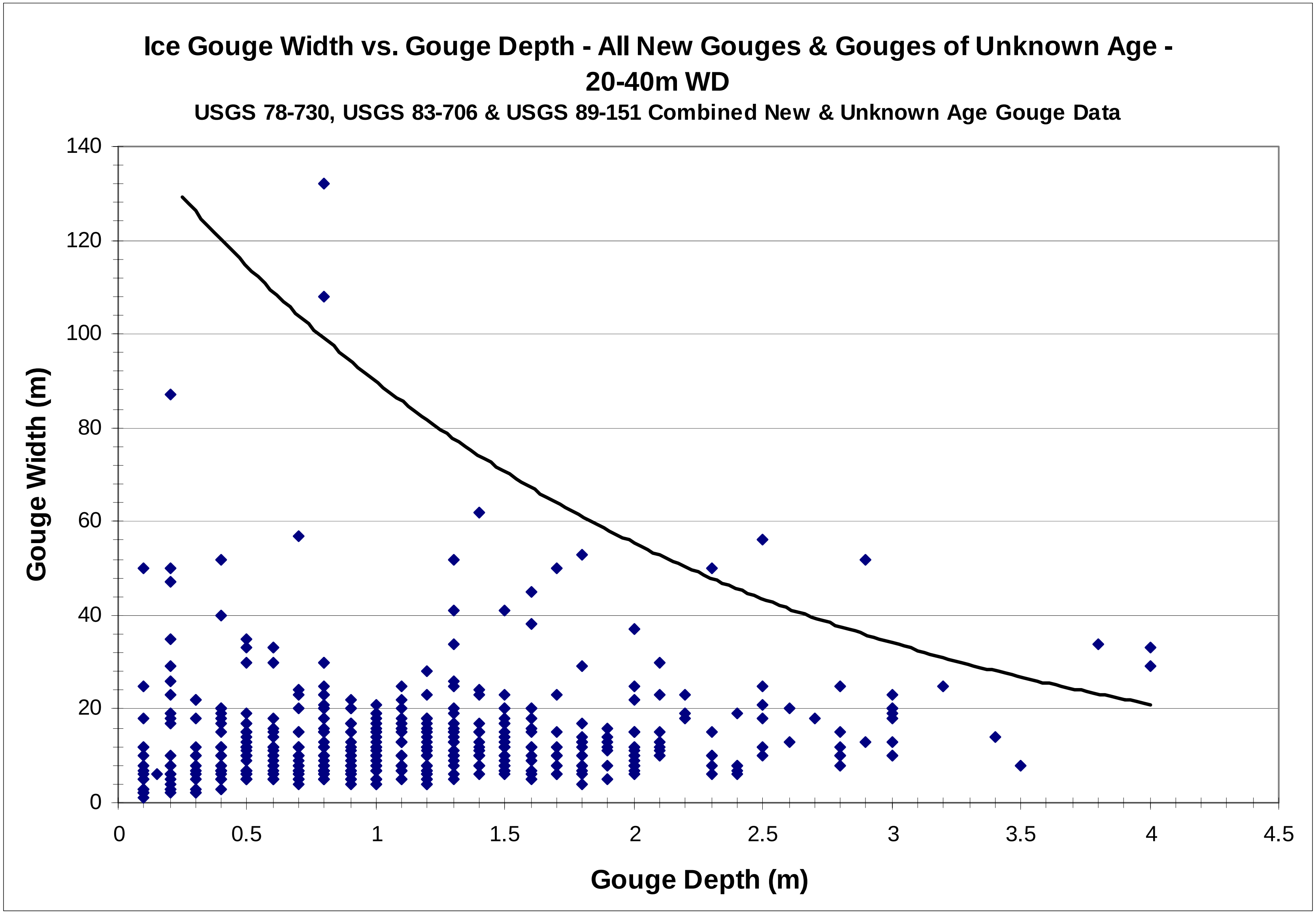


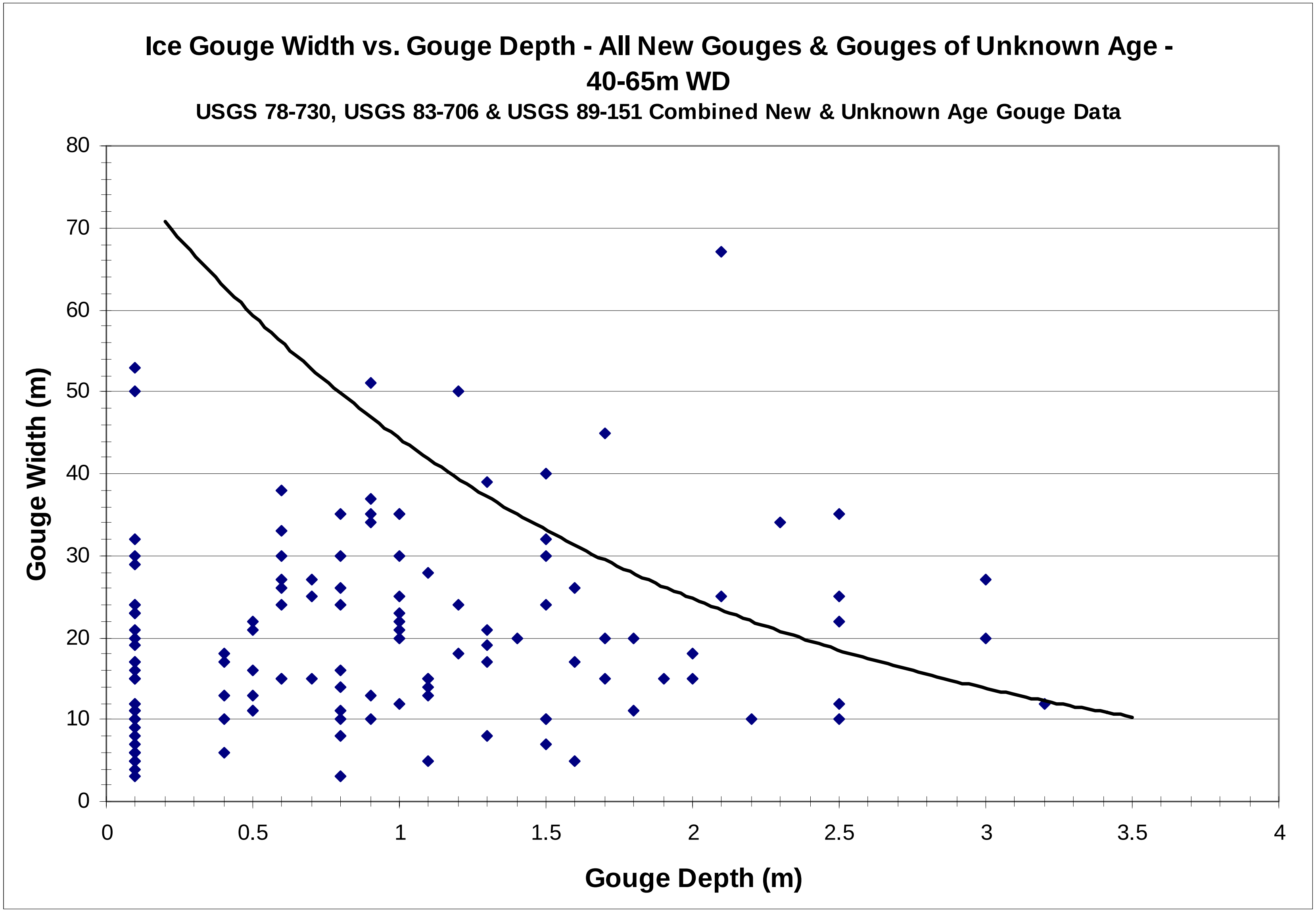
Ice Gouge Width vs. Gouge Depth - All New Gouges
USGS 78-730 & USGS 89-151 Combined New Gouge Data
Gouge Width (m)
Gouge Depth (m)
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5


Ice Gouge Width vs. Gouge Depth - All Gouges of Unknown Age
USGS 78-730 & USGS 83-706 Combined Gouge Data of Unknown Age
Gouge Width (m)
Gouge Depth (m)
0
10
20
30
40
50
60
70
80
90
100
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


Ice Gouge Width vs. Gouge Depth - All New Gouges & Gouges of Unknown Age
USGS 78-730, USGS 83-706 & USGS 89-151 Combined New & Unknown Age Gouge Data
Gouge Width (m)
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Gouge Depth (m)


Ice Gouge Width vs. Gouge Depth - All New Gouges & Gouges of Unknown Age - 0-20m WD
USGS 78-730, USGS 83-706 & USGS 89-151 Combined New & Unknown Age Gouge Data
Gouge Width (m)
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Gouge Depth (m)


Ice Gouge Width vs. Gouge Depth - All New Gouges & Gouges of Unknown Age - 20-40m WD
USGS 78-730, USGS 83-706 & USGS 89-151 Combined New & Unknown Age Gouge Data
Gouge Width (m)
0
20
40
60
80
100
120
140
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Gouge Depth (m)



Ice Gouge Width vs. Gouge Depth - All New Gouges & Gouges of Unknown Age - 40-65m WD
USGS 78-730, USGS 83-706 & USGS 89-151 Combined New & Unknown Age Gouge Data
Gouge Width (m)
0
10
20
30
40
50
60
70
80
Gouge Depth (m)
0
0.5
1
1.5
2
2.5
3
3.5
4