Mapping Sea Ice Overflood Along the Alaskan North Coast

David Dickins
DF Dickins Associates, LLC
La Jolla, California, USA
dfdickins@sbcglobal.net
Greg Hearon
Coastal Frontiers Corporation
Chatsworth, California, USA
ghearon@coastalfrontiers.com
Kim Morris
Geophysical Institute, University of Alaska Fairbanks
Fairbanks, Alaska, USA
kim.morris@gi.alaska.edu

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ABSTRACT

The U.S. Department of Interior, Minerals Management Service (MMS), Alaska OCS Region commissioned a study to map the extent of peak river overflooding onto the fast ice in the nearshore region of the Alaskan Beaufort Sea. River overflood constitutes a potential hazard to offshore oil and gas development, as it relates to facilities access, oil spill spreading, and the associated phenomenon of strudel drainage and potential seabed scouring. A primary goal of the study was to improve the knowledge of the spatial and temporal variability of overflooding and related hazards by mapping overflood boundaries for a 13-year period from 1995 to 2007, using a combination of helicopter surveys and satellite imagery.

KEY WORDS: Beaufort Sea; rivers; sea ice; overflood; strudel scour.

INTRODUCTION

River overflood on the sea ice occurs annually in the nearshore region of the Beaufort Sea during a brief period in the spring when river break-up precedes the break-up of the landfast sea ice. Upon arrival at the coast, the river water flows on top of the grounded and floating sea ice, spreading up to 10 km offshore. This brief but energetic phenomenon constitutes a potential hazard to offshore oil and gas development in that it can impede access to facilities, and expose buried subsea pipelines through strudel scouring.

The primary objective of this study was to map the maximum river overflood boundaries (peak seaward extent) on the sea ice along the Alaskan Beaufort Sea coastline between 1995 and 2007 using a combination of remote sensing and historical helicopter-based surveys. In addition, the hazards associated with the related phenomena of strudel scouring also were analyzed. The findings can be used for environmental assessment and hazard mitigation for present and future oil and gas facilities that may be located within or adjacent to the areas influenced by the overflood. Specifically, the study results can be used to assess strudel scour associated risks to prospective pipeline routes in different coastal areas of the Alaskan North Coast. The study area covered a 430 km stretch of shoreline between Smith Bay on the west and Camden Bay on the east (Figure 1).

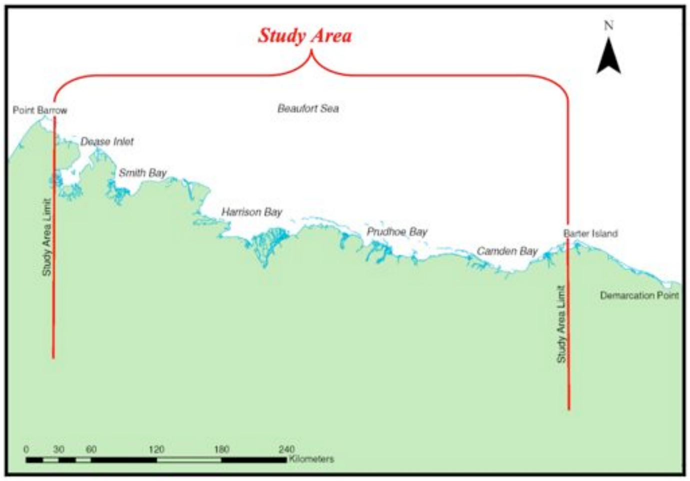


Figure 1. Project Location Map

BACKGROUND

Walker (1974) describes key features of the overflood process using the Colville River as an example. As the river stage rises, ice in the deeper channels fractures and lifts off the bottom on the rising flood. The overflood waters increase in area and in seaward extent over a period of ten to twenty days. Most of the initial floodwater moves out rapidly from the delta front over the nearshore bottomfast sea ice. As defined by Walker, the so-called "pre break-up" flooding continues until the river ice begins to move downstream. This period can be very short, lasting less than 2 days. While each river system has its own unique characteristics depending on the geometry of channels feeding the delta and flow characteristics, this general pattern of overflood stages is repeated at other drainages along the entire Alaskan Beaufort Sea Coast over a relatively short time window of a few weeks or less, from mid-May to mid- June.

The overflood layer can reach a depth of 1.5 m in places on top of the ice, however, depths of 0.6 to 0.9 m are considered more typical (Vaudrey 1984, 1985, 1986). Initially, the overflood waters pass over the region of bottomfast ice (typically extending to a water depth approaching 2 m). Farther offshore the overflood waters drain through holes and discontinuities in the floating fast ice, caused by tidal cracks, thermal cracks, stress cracks, and seal breathing holes. Figure 2 shows a representative circular drainage feature.

When the drainage rate is high, powerful strudel jets or whirlpools can develop at the drain sites and create large scour depressions on the sea floor. These sea floor craters were first documented in US Geological Survey investigations off the North Slope in the 1970's (*e.g.*, Reimnitz, *et al*., 1974; Reimnitz and Kempema, 1982). More recently, industry-sponsored studies conducted during the past two decades have greatly increased the knowledge base on strudel drains and scours at focused areas (see References listed under Coastal Frontiers). The processes of strudel drainage and sea floor scouring tend to be more severe in the floating fast ice zone than the bottomfast zone (Leidersdorf, *et al*., 2007).

Figure 2. Representative Circular Strudel Drain (Photo: D. Dickins)

Strudel scour can present a significant design consideration for subsea pipelines (Lanan, et al., 2008). While ice gouges from ridge keels often govern the depth of pipeline burial in deeper waters, strudel scours tend to govern in nearshore areas adjacent to river and stream mouths. Strudel scour concerns have resulted in the burial of the three existing subsea pipelines in the Alaskan Beaufort Sea (BPXA's Northstar, Pioneer's Oooguruk, and ENI's Nikaitchuq). An additional concern is that strudel drainage could provide a mechanism to transport spilled surface oil below the ice sheet in the spring (Dickins and Owens, 2002).

MAPPING METHODS

The early 1970's saw the first use of relatively high-resolution (100 m) Landsat imagery to document the overflood boundaries for some rivers in the study area, but the available record was limited by cloud cover and the long orbit repeat cycle of the satellites (16 to 18 days). More recently, Dickins and Oasis (2006) used all available visible imagery (Landsat and MODIS) to document patterns of ice clearing along the Alaskan Beaufort Sea Coast.

The database of peak overflood boundaries developed for this study was derived from a combination of historical helicopter-based surveys (1995-2007) and satellite image mapping. To gain an understanding of the accuracy and limitations of various image platforms, a field program off the Colville River was conducted in 2007 to compare the helicopter-derived overflood boundary in that year to boundaries mapped using images from three visible spectrum satellite platforms (Landsat 7, SPOT, and MODIS) and two SAR satellite platforms (ERS-2 and Radarsat). The findings suggested that satellite imagery could be used to derive overflood limits that approach the accuracy of helicopter-based results under favorable conditions. Additional details are provided in the final study report (Hearon, *et. al.*, 2009).

Helicopter-based mapping involves delineating the offshore boundary of the river overflood by recording successive positions with a GPS unit while flying at altitudes of 30 to 200 m, and at a speed of ~ 60 knots. The helicopter missions were conducted at the end of the overflood period rather than at the peak to insure that the absolute maximum seaward extent of the flood was documented. Evidence of the seaward extent of the overflood is usually characterized by sediment-laden water or discolored ice on the inshore side of the boundary. Evidence of strudel drainage also was frequently apparent inside the overflood boundary. In contrast, the ice offshore of the boundary generally was often a pristine white or blue color with areas of snow cover. See example in Figure 3.

Figure 3. Overflood boundary on Eastern portion of Kuparuk River Delta, 2006 (Coastal Frontiers)

A limited number of historical satellite platforms provide an archive of useful images that can be used to document peak overflood. The satellite platforms used as primary data sources for this study are: RADARSAT in Standard Beam and ScanSAR mode1 (SAR), ERS-1 and -2 (SAR), NASA MODIS (visible), NASA Landsat 4,5 and 7 (visible).

Cloud-independent SAR imagery was adopted as the primary satellite mapping data source, supplemented by Landsat 7 imagery where available. The relatively low resolution (250 m) MODIS imagery was used sparingly to fill in a few data gaps where no other imagery was available. The final selection of 64 images: 21 Landsat, 38 RADARSAT/ERS, four MODIS and one SPOT (ordered specifically for the 2007 field program). The selection was based on the probability of showing the most developed overflood extent and the field experience of the project team in being able to interpret differences between early, developed and late overflood stages.

Interpretation of overflood areas from SAR imagery can be complicated by different surfaces generating similar pixel values (brightness). Fetterer, et al. (1994), found that new ice and calm open water could exhibit very similar backscatter coefficients. Short-term variations in wind speed can quickly change the surface roughness of the overflood, leading to very different tonal values on images from day to day. The presence (or absence) of moisture affects the electrical properties of the target, which, in turn, influence the absorption, transmission, and reflection of the microwave energy. Barber, et al. (1995), demonstrated that the production of superimposed ice nodules in the snow early in the spring (increased roughness), followed by flooding (smooth surface) and then draining of the ice surface (renewed roughness) can lead to an increase, a sudden decrease and then another increase in backscatter, respectively. As a result, radar imagery during these different overflood phases can range from dark to bright white, back to dark and then light in texture over a matter of a few days. This phenomenon is illustrated in Figure 4, which shows the progression of the 2007 Colville River overflood through a series of RADARSAT and ERS images. While these ambiguities complicate the satellite interpretation during the overflood period, this study demonstrated that an informed interpreter is still able to map accurate overflood boundaries from the SAR imagery.

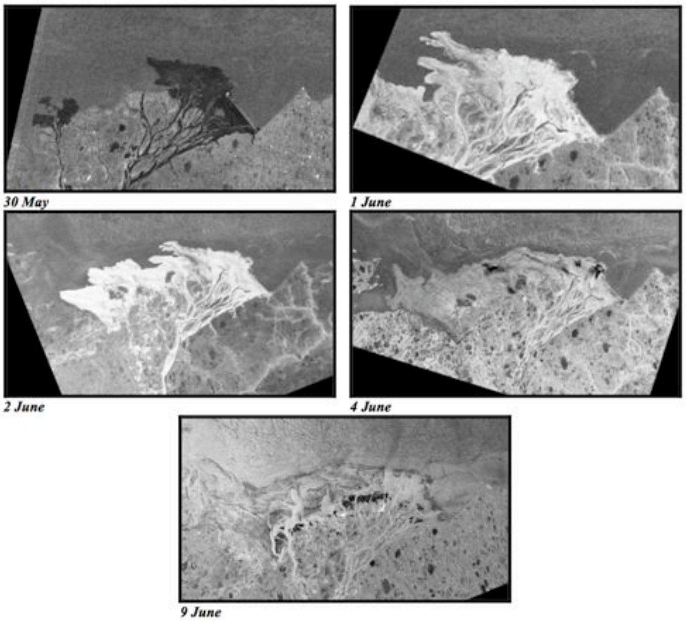

30 May
1 June
2 June
4 June
9 June

Figure 4. RADARSAT and ERS images showing the progression of the 2007 Colville River overflood

MAPPING RESULTS

Overflood limits were mapped for 129 out of 143 possible significant river and year combinations, equivalent to an overall mapping success of 90%. This result would not have been possible without having access to both the radar imagery and helicopter surveys. Figure 5 shows an example of the combined composite overflood boundaries for the West Study area for the complete period of interest, 1995-2007. Annual map sets and statistical characterizations of the overflood boundaries for each individual year are available in the final study report and GIS database (Hearon, *et al*., 2009).

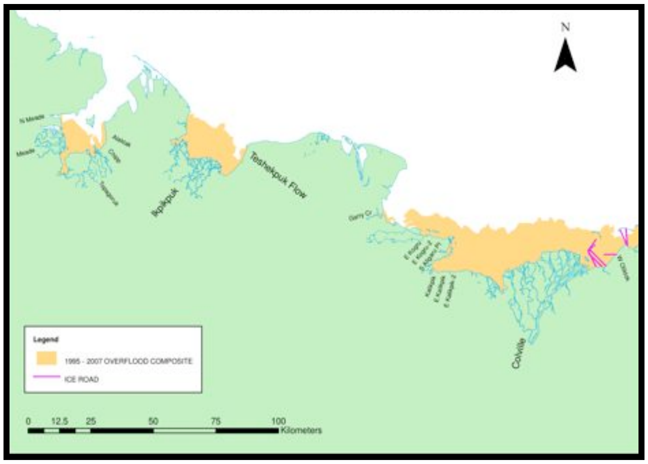


Figure 5. 1995-2007 Composite Overflood – West Study Region including the Colville Delta (East).

In terms of its contribution to the combined overflood area along the Alaskan Beaufort Sea Coast, the Colville River clearly dominates, with an annual average over 13 years of 717 km^2 (min. 485 km^2, max. 1011 km^2), more than three times greater in area than that of the second and third largest contributors (Kuparuk and Sagavanirktok). Outside of the "top three" rivers, the individual overflood areas drop by a further order of magnitude.

Man-made features such as ice roads and causeways play an important role in modifying or limiting the final distribution of the overflood. In some areas, such as off the Colville, Kuparuk and Sagavanirktok Deltas, winter ice roads and causeways significantly modify or limit the final configuration of the overflood waters. For example, during the construction of Northstar Island in the winter of 2000, the combination of the enhanced freeboard of the ice road, snow and ice berms along the road, and the through-ice trench used for pipeline installation established an artificial barrier that effectively restricted further spreading to the east during the spring overflood from the Kuparuk River. The effect is shown dramatically in Figure 6. More recently, in 2007, the ice road constructed along the Oooguruk flowline prevented the overflood waters from spreading farther east and created a sharp transition.

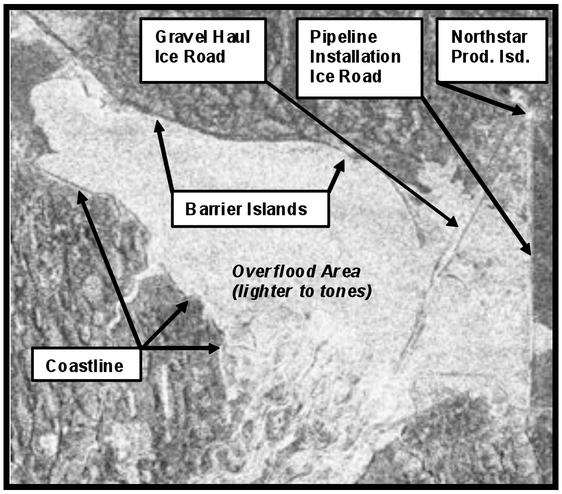


Figure 6. Impact of the Northstar ice road in containing overflood waters on June 11, 2000. Image: RADARSAT

APPLICATION OF RESULTS

Strudel scours constitute the most significant hazard associated with river overflood. A sufficiently deep strudel scour may expose a buried pipeline and lead to an unsupported span. The removal of backfill material needed to help prevent upheaval buckling and protect against ice keels also is a concern.

Leidersdorf, *et al.* (2007), classified the zone of bottomfast ice as the "Secondary Strudel Zone" and the zone of floating fast ice immediately seaward of the Secondary Strudel Zone as the "Primary Strudel Zone". The Primary Strudel Zone was defined as the region between the 1.5-m and 6-m isobaths, with the Secondary Strudel Zone located landward of the 1.5-m isobath. Based on the recognition that the potential for strudel scour formation diminishes in water depths beyond approximately 6 m, a third zone (the "Tertiary Strudel Zone") was defined for the purposes of this study as the region offshore of the Primary Strudel Zone.

The strudel scour potential in the study area was assessed by segregating the annual composite overflood limits into the three zones defined above, using the bathymetric contours developed by the National Oceanic and Atmospheric Administration (NOAA). The strudel scour zones developed in this manner for the western portion of the study area for 2001 are shown in Figure 7 as an example. The full map set and statistical characterizations of each strudel zone for each river and year are presented in Hearon, *et al.,* (2009). These data can be used to assess the risk to prospective pipeline routes posed by strudel scouring.

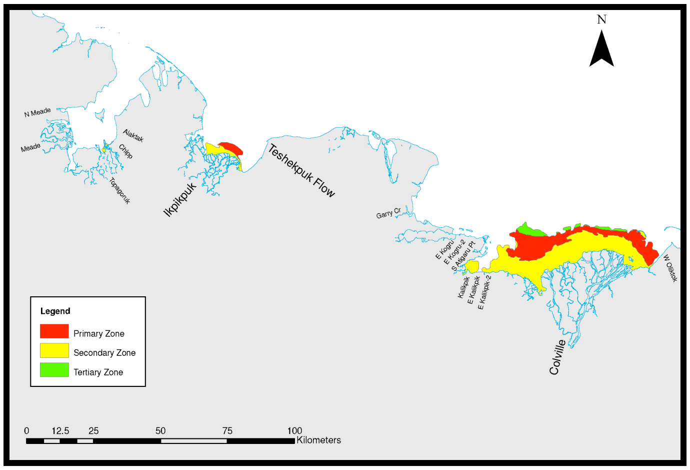


Figure 7. 2001 Strudel Zones in Western Portion of the Study Area

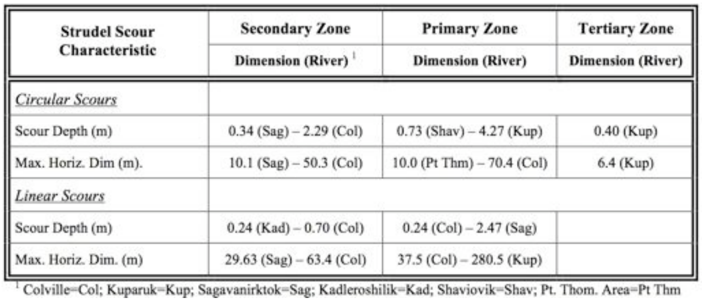
An analysis of the strudel zone areas for the eleven major river systems located between the Colville and Okpilak Rivers showed that the Secondary Strudel Zone accounts for the greatest portion of the overflood, representing, on average, 66% of the total overflood area. The Primary Strudel Zone accounts for 32%, while the Tertiary Zone accounts for a mere 2%.

Strudel drain and strudel scour data obtained from petroleum industry studies were analyzed to characterize the frequency and severity of strudel scouring in each of the strudel zones. The underlying studies tended to focus on mapping drains and scours in the vicinity of proposed or existing subsea pipelines, and did not necessarily attempt to locate all such features within the overflood boundaries of a specific river. The density of strudel drains (number of drains per square kilometer of area searched) varies substantially from river to river in any given year, and from year to year off any given river. For example, off the Kuparuk River, the drain density ranged from 0.6 to 7.1 drains/km^2. As in the case of river overflood itself, the factors that influence the occurrence and distribution of strudel drains are complex and poorly understood.

A majority of the strudel scours was located in the Primary Zone (ranging from 64% of the total number of scours in the Pt. Thomson Area to 100% in the Shaviovik River). Strudel scours were found in the Secondary Zone of each river except for the Shaviovik. Two scours were mapped in the Tertiary Zone of the Kuparuk River, while no scours were located in this zone in the other overflood areas. It is noteworthy that although 101 drainage features were mapped in the Tertiary Zone of the Kuparuk River overflood (Fig. 16), only two strudel scours were discovered in this region.

Table 1 summarizes the maximum strudel scour dimensions over the full 12-year period covered by the industry studies (see Coastal Frontiers – various years in References). Because the characteristics of circular and linear scours are distinctly different, statistics are provided according to scour type. In the case of circular scours, the term "maximum horizontal dimension" refers to the largest horizontal extent measured at the elevation of the surrounding sea bottom (i.e., the diameter of a perfectly circular scour or the major axis of an oblong scour). In the case of linear scours, the "maximum horizontal dimension" represents the length measured parallel to the scour orientation. The "scour depth" is measured as distance from surrounding sea bottom to the deepest point in the scour depression.

Table 1. Summary of all Strudel Scour Characteristics Measured during Industry Studies, 1996-2007



Strudel Scour Characteristic	**Secondary Zone**	**Primary Zone**	**Tertiary Zone**
	Dimension (River) [1]	**Dimension (River)**	**Dimension (River)**
Circular Scours			
Scour Depth (m)	0.34 (Sag) – 2.29 (Col)	0.73 (Shav) – 4.27 (Kup)	0.40 (Kup)
Max. Horiz. Dim (m).	10.1 (Sag) – 50.3 (Col)	10.0 (Pt Thm) – 70.4 (Col)	6.4 (Kup)
Linear Scours			
Scour Depth (m)	0.24 (Kad) – 0.70 (Col)	0.24 (Col) – 2.47 (Sag)	
Max. Horiz. Dim. (m)	29.63 (Sag) – 63.4 (Col)	37.5 (Col) – 280.5 (Kup)	

[1] Colville=Col; Kuparuk=Kup; Sagavanirktok=Sag; Kadleroshilik=Kad; Shaviovik=Shav; Pt. Thom. Area=Pt Thm

SUMMARY AND CONCLUSIONS

This study produced the first consistent database of overflood extent and strudel drains and scours for Alaskan North Coast Rivers. Understanding the frequency and severity of strudel scouring according to water depths (*i.e.*, strudel zones) will aid in risk analysis for future seabed installations and pipelines within the nearshore area covered in fast ice each year from October to June. Key conclusions are summarized in the following below.

1. *Comparisons of Mapping Techniques*: Helicopter-based surveys can be used to map maximum annual overflood limits with the highest level of confidence and greatest accuracy under favorable conditions. Helicopter-based surveys remain as the only reliable means of comprehensively mapping strudel drainage features within the overflood boundary. Under favorable conditions, satellite imagery can be used to derive overflood limits that approach the accuracy of helicopter-based limits. Late in the overflood period and under unfavorable conditions, overflood

limits derived from satellite-based imagery can differ materially from those derived from helicopter-based mapping. Satellite imagery is potentially more cost-effective over large areas (assuming that SAR imagery is available at reasonable cost through research channels) and provides the possibility of acquiring data on historical events. Notable disadvantages include timing and availability of suitable images, and somewhat lower accuracy of results relative to helicopter-based surveys.

2. *Historical Overflood Boundary Mapping*: River overflood boundaries were mapped with an overall success of 90% in covering the 11 major rivers systems in the study area over the 13-year period from 1995-2007. This was achieved by using a combination of historical helicopter surveys and satellite images to create a composite overflood limit that used all available data sources.
3. *Hazards Related to Strudel Scours*: Strudel scouring can constitute a significant design consideration for subsea pipelines in nearshore areas adjacent to river and stream mouths. Strudel scour concerns have resulted in the burial of the three existing subsea pipelines in the Alaskan Beaufort Sea (BPXA's Northstar, Pioneer's Oooguruk, and ENI's Nikaitchuq). In the event that a strudel drain is located directly above a buried subsea pipeline, a sufficiently deep strudel scour may expose the pipeline and lead to an unsupported span. A strudel scour that forms directly over a buried pipeline also can remove the backfill material that is needed to prevent damage from ice keels and forestall upheaval buckling.
4. *Strudel Scour Zonation:* Strudel scouring typically is most common and severe in the Primary Strudel Zone, which extends offshore from the bottomfast ice edge at approximately 1.5 m to approximately 6 m water depth. In the zone of bottomfast ice (the "Secondary Strudel Zone") and offshore of the Primary Zone (the "Tertiary Strudel Zone"), scouring tends to be more modest and occur less frequently. Strudel zone information from this study can be used to assess the risk to prospective pipeline routes posed by strudel scouring in different coastal areas off the North Coast of Alaska.

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REFERENCES

Barber, D.G., Papakyriakou, T.N., LeDrew, E.F., Shokr, M.E., "An Examination of the Relation Between the Spring Period Evolution of the Scattering Coefficient and Radiative Fluxes over Landfast Sea-ice",. *Int. J. Remote Sens.* 16, 3343-3363, 1995.

Coastal Frontiers Corporation, "Northstar Development Pipeline Route Surveys 1996 to 2007", individual reports for BPXA, Chatsworth, CA, 1997, 1998a to 2001a, 2002, 2003a, 2004 to 2005, 2006a to 2008a.

Coastal Frontiers Corporation, "Liberty Development Pipeline Route Surveys 1997 to 1999" individual reports for BPXA, Chatsworth, CA, 1998b to 2000b.

Coastal Frontiers Corporation, "2003 Liberty Development River Overflood Reconnaissance", Memorandum Dated July 18, 2003 to BPXA, Chatsworth, CA, 2003b.

Coastal Frontiers Corporation, "Oooguruk Development Bathymetric Surveys 2005 and 2006", individual reports for Pioneer Natural Resources, Chatsworth, CA, 2006b and 2007b.

Coastal Frontiers Corporation, "Sivulliq Development Nearshore Survey Programs 2006 and 2007", individual reports for Shell Exploration and Production, Chatsworth, CA, 2007c and 2008b.

Dickins (DF Associates) and OASIS Environmental, "North Slope Nearshore and Offshore Breakup Study", Report prepared for the Alaska Department of Environmental Conservation, Anchorage AK. 19 pp, 2006.

Dickins, D.F. and Owens, E,H., "Annual Ice Cycle at the Mouth of the Colville River and Implications for Oil Transport", *Proceedings 2002 Arctic and Marine Oil Spill Conference*, 2002.

Dickins, D.F., Hearon G. and Vaudrey, K., "Sea Ice Overflood in Stefansson Sound, Alaskan Beaufort Sea", *Proceedings 16th International Conference on Port and Ocean Engineering Under Arctic Conditions*, Ottawa, pp. 193-202, 2001.

Fetterer, F. et. al.. 1994. Sea ice type maps from Alaska Synthetic Aperture Radar Facility imagery: An assessment. JGR, Vol. 99, No. C11, pp. 22443-22458.

Hearon, G., Dickins, D.F., Ambrosius, K., and Morris, K., "Mapping Sea Ice Overflood Using Remote Sensing: Smith Bay to Camden Bay", Report prepared by DF Dickins Associates, Coastal Frontiers Corporation, Aerometric, and the Geophysical Institute, University of Alaska for US Department of Interior, Minerals Management Service, Alaska OCS Region under Contract M06PC00034, 2009.

Lanan, G.A., Maguire, D.H., Hazen, B., Hall, J.D. and Perry, C.J., "Oooguruk Offshore Arctic Flowline Design and Construction", *Proc., 2008 Offshore Technology Conference*, OTC-19353. 2008.

Leidersdorf, C.B., Hearon, G.E., Vaudrey, K.D. and Swank, G., "Strudel Scour Formation off Arctic River Deltas", *Proc., 30th International Conference on Coastal Engineering,* Vol. 5, World Scientific, Hackensack, New Jersey, p. 5312-5324, 2007.

Reimnitz, E.C. and Kempema, E.W., "High Rates of Bedload Transport Measured from Infilling Rate of Large Strudel-scour Craters in the Beaufort Sea, Alaska", U.S.G.S. Professional Paper, Menlo Park, CA, 1982.

Reimnitz, E.C., Rodeick, C.A. and Wolf, S.C., "Strudel Scour, a Unique Arctic Marine Geologic Phenomenon", Journal of Sedimentary Petrology, 44(2); 409-420, 1974.

Vaudrey, K., "Breakup Study of the Alaskan Beaufort and Upper Chukchi Seas", separate reports for 1983 to 1985 seasons, AOGA Projects 224, 274 and 319, Vaudrey & Associates, Inc., San Luis Obispo, CA, 1984/85/86.

Walker. H.J., "The Colville River and the Beaufort Sea: Some interactions", The Coast and Shelf of the Beaufort Sea, *Proceedings of a symposium on Beaufort Sea Coast and Shelf Research.* Eds., J,C. Reed and J.E. Sater, The Arctic Institute of North America, pp. 513-540, 1974.

Email to: **secretariat@icetech10.org**