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BEAUFORT SEA RUBBLE FIELDS: CHARACTERISTICS AND IMPLICATIONS FOR NEARSHORE PETROLEUM OPERATIONS

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KEYWORDS: Rubble field, Beaufort Sea, ice, offshore, operations

HIGHLIGHTS:

1. Analysis of the formation, decay, shape and size of ice rubble fields
2. Large grounded rubble fields have formed in water depths up to 32 m
3. Grounded rubble fields in the Beaufort Sea can have areas up to 1 km^2
4. Their implications on offshore petroleum operations are described

ABSTRACT

Experience with past offshore platforms in the Beaufort Sea has shown that in some regions, a stable rubble field of ice may surround the platform during the winter months. These rubble fields can influence marine operations, emergency evacuation systems and can reduce ice loads on the platform. This paper analyzes the historical rubble information that has been collected pertaining to the nearshore Beaufort Sea and it examines potential empirical relationships between rubble field characteristics and a variety of ice and environmental parameters. Historically, offshore structures in this region were in open water for approximately 100 days. During the remaining time, quasi-stable, grounded rubble could be present around a

structure for extended periods – for example, on average 65% of the time that there was moving pack ice in the autumn. Rubble fields formed between 76-87% of the time when a drilling structure was in water depths from 5 to 32 m. This review shows that grounded rubble fields in the Beaufort Sea can be extensive with areas up to 1 km^2 with maximum sail heights up to 14 m. The extent and shape of each field is interdependent upon a number of factors, such as water depth, number of days the site is in moving ice, and the size and shape of an island, caisson or a submarine berm. But no one factor could guarantee the formation of grounded rubble. Upper bounds to the size of a rubble field are proposed based upon three separate data sets. The potential presence of rubble to such a great degree indicates that operators should clearly identify the strategies to be used to either manage grounded ice rubble or account for its presence with respect to marine operations and emergency evacuation methods. However, the data also shows that rubble fields often don't form, even if conditions seem to be favourable for their formation.

1. INTRODUCTION

Broken ice is common in Arctic waters. Moving pack ice often fractures when it interacts with a stationary structure or ice floes with a differential speed. Ice pile-ups have been observed around offshore drilling platforms, along shorelines, and in the form of ice ridges. All of these broken-ice features can cause problems for offshore operations. This paper focuses on the ice pile-ups surrounding offshore petroleum platforms, and at sites where these platforms used to be located, in the shallow waters of the Canadian and American Beaufort Sea. These pile-ups can be floating or grounded. In most cases, floating rubble piles do not persist for any length of time since changing environmental forces and directions can move these broken ice piles away from the platform. However ice that is grounded persists (see Figure 1) and can remain around the platform well into the spring break-up. These pile-ups can impact operations in several ways. For example, they restrict access to the platform for marine vessels. This can affect marine operations for both re-supply and petroleum offloading to tankers. Further, these grounded rubble fields can hinder emergency evacuation in the event that helicopters cannot be used for personnel movement during an emergency. But they do offer the advantage that they tend to "shield" the platform from oncoming ice movement and this shielding results in significantly lower ice loads (Croasdale et al., 1994; 1995; Timco and Wright, 1999). All of these issues must be considered and addressed by careful planning. To do this reliably, quantitative information about the formation, size, characteristics and duration of these rubble fields is essential for proper engineering design and operations in nearshore waters. This paper investigates these aspects of grounded rubble fields in the Beaufort Sea based upon a large amount of historical data and new field observations, in an effort to present reasonable relationships and some upper-bound envelopes. As the mechanics of rubble field formation has been examined elsewhere (see, for example, Canatec (1994)), this is not re-examined here. The present paper summarizes the lessons learned about past grounded rubble fields in the Beaufort Sea, as these features relate to offshore exploration and production considerations.

Figure 1: Photograph of the Caisson-Retained Island (CRI) at the Kaubvik I-43 site, showing its extensive surrounding ice rubble field (photograph courtesy Imperial Oil Ltd.).

2. TYPICAL SHALLOW-WATER BEAUFORT SEA STRUCTURES

Various types of systems were used as shallow-water (<100 m) drilling platforms in the Beaufort Sea during the 1970s to 1990s, including floating drill-ships in marginally deeper waters, bottom-based caisson structures in more moderate water depths (from 15 to 30 m), and artificial sand/gravel islands and grounded ice pads in shallower waters (see e.g. Timco and Frederking, 2008, 2009 for a detailed review). This paper examines only sites that had bottom-founded structures or artificial sand/gravel islands. There are three structural configurations that were investigated in this study. The first two represent situations where the rubble was generated at a location while exploration drilling operations were taking place. The third situation is post-drilling and there was no drill rig present. All three configurations are outlined below and shown in Figure 2 through Figure 4.

A large number of natural shoals and artificial islands were used in the Beaufort Sea for exploration activities. The islands were made of either dredged material or granular fill that was trucked from shore and dumped on site. These islands generally had a low freeboard. Additionally, they could have a sandbag-retained or sacrificial beach design (see Exxon, 1979). Figure 2 shows an example profile of an island configuration. The surface area of these artificial islands could be quite large, with diameters in the order of 100 m with much larger submarine berms. In the 1970s and 1980s, this type of drilling platform was thought to be the most cost effective in shallower water depths (<20 m). Note that in the 1990s, spray ice pads proved to be a much more effective exploration alternative in shallow water (see Weaver and Poplin, 1997).

The second configuration was one that used a caisson platform. Figure 3 shows a schematic of a typical caisson cross-section arrangement. An exploration platform with this type of configuration would generally consist of an outer concrete caisson (Tarsiut caissons, Concrete Island Drilling Structure (CIDS)) ring which was back-filled with sand for stability, or a steel structure (Molikpaq, Caisson Retained Island (CRI), Single Steel Drilling Caisson (SSDC),) which could have sand or water fill for added stability. Caisson structures were typically set down upon a sand or gravel berm (or for one structure (SSDC), a fabricated, removable berm was employed). Typically, the caissons had a surface length around 100 m, with freeboards that varied from 5 m to about 20 m. The sides of these structures were generally vertical, but some had slight inclinations depending upon their set-down depth. These types of platforms would typically be used today in water depths of approximately 15 m to 30 m, with an upper limit depth dictated largely by cost and ease of construction/use. When the drill rigs were removed after the drilling was complete, the islands and submarine berms for caissons were left to erode from wave action. However they did not completely erode to the seabed and this presents a current-day situation of submerged, remnant berms (see Figure 4). Thus, unlike the previous two types of configurations, which had surfaces or structures that were above the water-line, the remnant berm sites are not surface-piercing. Note that the remnant berms from island sites are generally substantially larger in aerial extent than those from caisson sites. These berms erode down over time, and also slightly migrate horizontally due to local water currents and tidal effects. Several of these sites were examined in four separate field programs by the authors (in conjunction with Brian Wright) from 2006 to 2010 (see e.g. Barker et al., 2006a, 2007, 2008, 2009a, 2009b; Spencer et al., 2007; Timco and Barker, 2015). These sites are referred to as the Barker field sites in this paper.

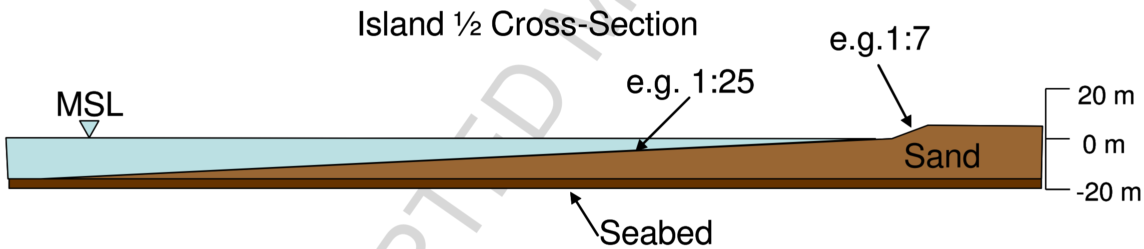


Figure 2: Example of a half-island cross-section along one direction of a sand island. A drilling rig would have been located on the top surface.

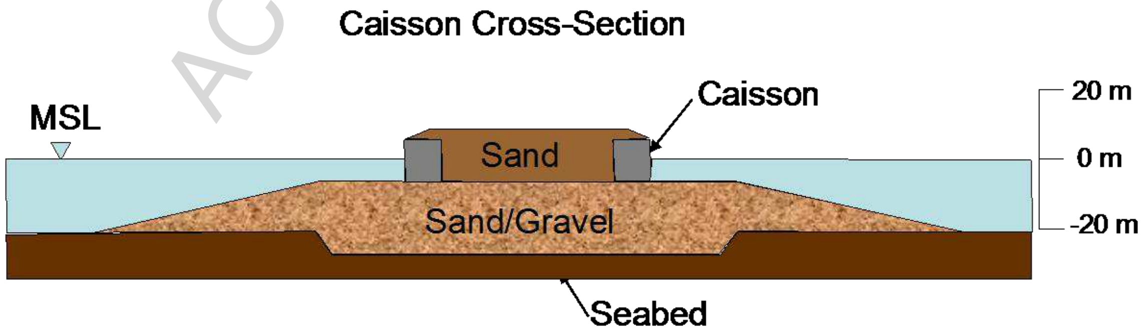


Figure 3: Example caisson cross-section. A drilling rig would have been located on the sand fill or steel deck of the caisson.

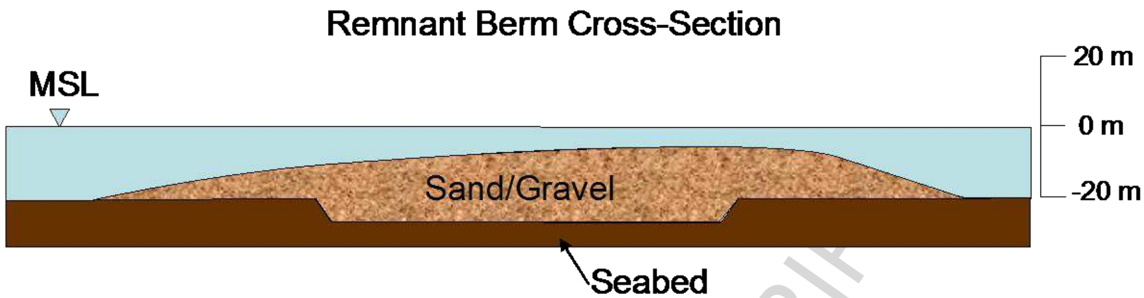


Figure 4: Example remnant berm cross-section. Note that the berm is not surface-piercing, as there is no drilling structure anymore. A remnant berm can be affiliated with either an island or a caisson site; the latter remnant berms are smaller than the former.

Thirty-seven locations were examined in this study. Eighteen of these locations were examined in detail, with source information from historical documents contained in the NRC Centre of Ice-Structure Interaction (Timco 1996) for each site [see Barker and Timco (2006) for a detailed overview of the rubble sites]. The comprehensive reports on grounded rubble fields prepared by Canatec (1994) and Spedding (1987) also provided valuable information. In addition to this historical information, data collected from recent field programs (Barker field data) at Minuk I-53, Tarsiut N-44, Issungnak O-61 and Kadluk O-07 provided additional information. The Spedding (1987) report was particularly useful for this analysis since it documented changes at remnant drill sites for as many as ten years. Dates of landfast ice and length of time in moving ice, rubble area, maximum length and width were reported, as well as sketches of the rubble field. However, data on rubble formation and disappearance for these sites were not available. The locations of the Canadian and American sites from Barker and Timco (2006) and the Barker field data set are shown in Figure 5 and Figure 6 respectively. These were all used to assess relationships between a number of parameters and rubble field area to attempt to address the following questions:

1. Is it possible to predict if a rubble field will form based on historical data?
2. If it forms, how does it develop?
3. Once formed, how long does a rubble field stay on site?
4. What are the characteristics of the rubble field and can characteristics such as their size and shape be predicted?

5. What are their implications in terms of marine operations, emergency evacuation and ice load reduction?

These questions are addressed in the following sections.

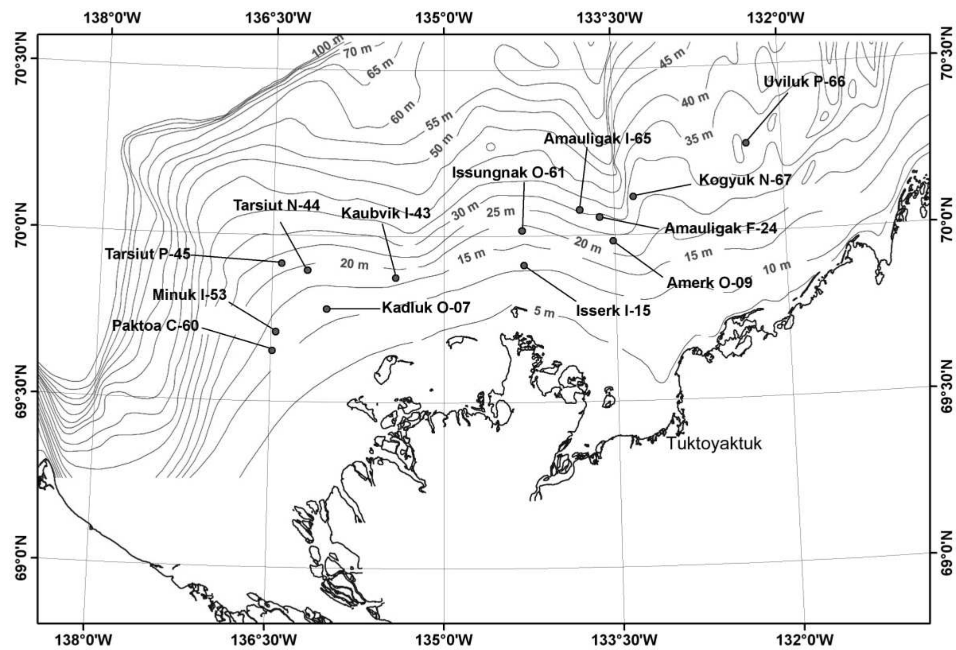


Figure 5: Location of some of the key Canadian Beaufort Sea sites examined in this paper.

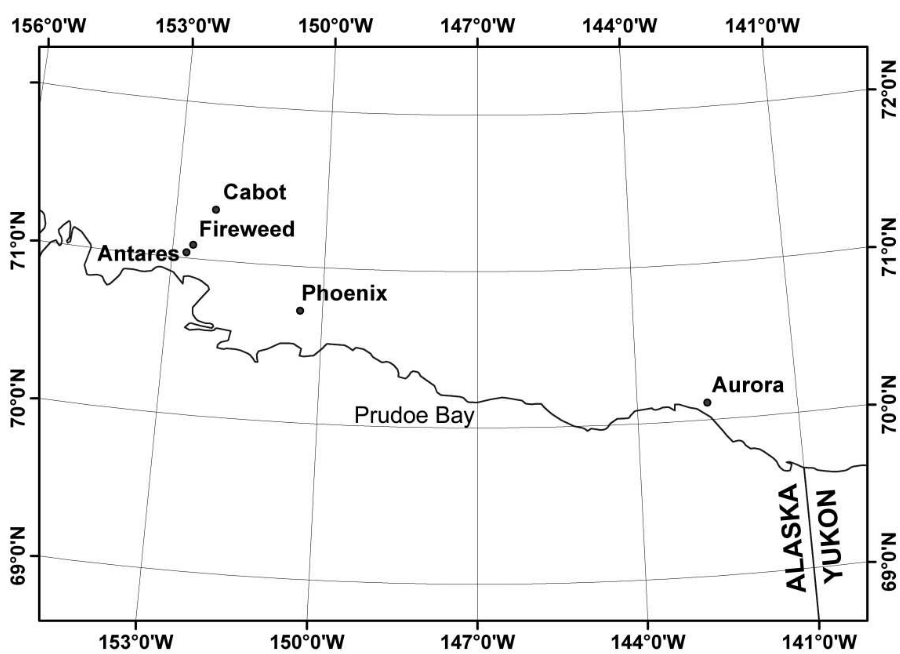


Figure 6: Location of the American Beaufort Sea sites examined in this paper.

3. WILL A GROUNDED RUBBLE FIELD FORM?

From an engineering and safety standpoint, it would be useful to know whether or not it is possible to predict the likelihood of the formation of a rubble field. That is, what is the probability of occurrence for rubbled ice at a particular location? And if it does form, how large will the rubble field be at that location?

Intuitively one would think that several factors affect the formation and size of a rubble field. These might include the necessity for an obstacle such as either a large ice feature grounding on the seabed or a surface piercing structure for the moving ice to pile on, a sufficient amount of moving ice to generate the rubble field, a water depth that is not too deep so that the ice can ground, and a sufficient build-up of ice to "stabilize" the grounded rubble so that moving pack ice cannot displace it.

How do these parameters relate to the Beaufort Sea? If one considers the ice regimes of this region, the ice begins to initially form in late September and spreads seaward from the coast. The ice in the shallower waters (say less than about 10 m) is relatively stable since there are several small islands in this region that act to limit the ice movement. This ice soon becomes landfast with little movement other than thermal effects. In water deeper than 10 m, the ice can be quite dynamic and is almost always highly rafted and ridged. But through the winter months the extent of the landfast ice continues to spread seaward to the region with about 20 m water depth. For deeper waters, the sea ice remains active throughout the winter months. The landfast ice remains in place well into the summer months with breakup dates as late as mid-July in a cold summer along the coastline.

If one combines this ice regime scenario with the parameters that intuitively one might expect to influence the formation and growth of a rubble field, it is possible to speculate on the formation of a grounded rubble field, but not on its size. For example the stable landfast ice in shallow waters less than 10 m suggests that the lack of moving ice would not favour the formation of a rubble field. Seabed gouges have shown that the majority of ice-induced scours occur in water depths from 10 to 30 m in the Beaufort Sea (Blasco et al., 1998, 2011; Wadhams, 2012). For water depths greater than 20 m there is certainly sufficient moving ice and evidence from the scour profiles that large features can reach the seabed there. But the dynamic ice movement in these deeper waters with thicker ice (including multi-year ice) might more easily displace any grounded ice that forms. This leaves the region of water depths between 10 to 20 m which should have the necessary conditions for the generation of stable grounded rubble. But is this assessment correct? Grounded rubble fields are not observed at a large number of sites in the Beaufort Sea, and in fact are often observed at the same locations. Then the question is: What factors dictate the actual location of a rubble field and how will it form?

Clearly, the availability of data at particular locations, or lack thereof, can make this a challenging assessment. However, from a monitoring perspective, this task is becoming much easier to accomplish compared to even twenty years ago. With far more frequent, repetitive remote sensing coverage, especially in polar regions, this task can be accomplished with less effort and cost than before. This is especially true when using a remote sensing platform such as RADARSAT-2, which is not limited by weather conditions or darkness for repetitive monitoring. However, a limitation to the ease of monitoring is that a location must be targeted in order to order and obtain the correct type of imagery. As described in Barker et al. (2008), searching for a rubble feature using the necessary higher-resolution settings on various satellites can be both unrealistically time-consuming and costly.

The first step is to look at the overall likelihood of rubble formation in the data investigated here. Table 1 summarizes the data. Thirty-seven sites were compiled with a total of 167 yearly observations. Of these observations, 110 contained rubble fields giving an overall 66% chance that a rubble field would develop. The maximum water depth for this data is 32 m. Of the 37 sites, 12 had only a single observation over the years, generally the one year where exploration drilling occurred, and therefore one would record a 0% (no rubble field) or 100% (rubble field formed) chance of occurrence for those single observations.

However, this is an unrealistic and too broad of a grouping, given the diversity of locations, water depths and ice conditions. The right-hand side of the table examines the data by more practical groupings. For example, for sites with 8 or more years of observations (10 of the 37 sites), the average occurrence was 69%, similar to the overall average. Locations in water depths less than 5 m are less likely to experience large fluxes of moving ice, due to either bottom-fast or landfast ice formation before a rubble field would form. Further refinement to eliminate sites with water depths less than 5 m (5 of the 37 sites) gives a greater average occurrence of 80%. For sites in water depths greater than 10 m, it increases again to 90% (4 sites). This grouping does not take into account ice conditions such as days of moving ice, the height of a submarine berm, etc., although the former is somewhat reflected in the water depth. The more important factor, clearly, is whether or not there was a surface-piercing presence, either a berm or a drilling rig, at the time of rubble formation. Not surprisingly, the presence of any surface-piercing object, be it a berm or a caisson, makes the chance of rubble formation at a particular site far greater than if there are only submerged features. Grouping the data in this manner, there is a greater distinction – when a surface piercing structure was present, the likelihood of rubble forming was between 76% (caisson) to 87% (island), while when there was no surface piercing structure present, the likelihood dropped considerably to between 52% (island site) to 69% (caisson site).

Spedding (1987) concluded that for locations in the landfast ice, where a submarine berm had eroded to 2.5 – 5 m below sea level, the probability of rubble field formation was reduced significantly. He felt that that was why rubble field formation ceased after a period of years, and why no rubble fields were observed at a number of berm sites while they were under construction. However, given the relatively regular rubble formation observed at Tarsiut N-44 in the Barker field data, where the berm is likely below that 5 m depth, this is perhaps not entirely the case. Most likely this is because the formation of the rubble field is dependent upon so many other factors other than water depth alone. The frequency of ridging in an area, the amount of ice flux past a site, etc. will all play potentially large roles in determining whether a rubble field will form. In any event, the data clearly show that in the Beaufort Sea for water depths between 5 m and 32 m, during years where drilling takes place, there is a high likelihood (on the order of 80% or greater) that a rubble field will form.

Table 1: Summary of rubble field occurrences

	Water Depth (m)	Count	Rubble Count	Probability of occurrence
All		167	110	66%
Adgo C-15	2	5	1	20%
Adgo H-29	2.8	2	2	100%
Adgo J-24	1.4	1	0	0%
Adgo J-27	2	5	3	60%
Adgo P-25	2	12	2	17%
Alerk P-23	11.6	6	6	100%
Amauligak F-24	32	1	1	100%
Amauligak I-65	31	1	0	0%
Amerk O-09	26	3	1	33%
Antares	15	1	1	100%
Arnak K-06	7.2	1	1	100%
Arnak L-30	8.5	10	7	70%
Aurora	21	1	1	100%
Cabot	16.764	1	0	0%
Fireweed	15.24	1	1	100%
Ikatok J-17	2	4	2	50%
Immerk B-48	3	11	4	36%
Isserk E-27	13	9	7	78%
Isserk I - 15	11.5	1	1	100%
Issungnak O-61	18.6	11	11	100%
Itiyok I-27	14	4	4	100%
Kadluk H-08	13.6	5	4	80%
Kannerk G-42	8	4	2	50%
Kaubvik I-43	17.9	1	1	100%
Kogyuk N-65	31	2	1	50%
Kugmallit D-49	5.2	9	5	56%
Minuk I-53	14.7	8	8	100%
Netserk B-44	4.6	12	7	58%
Netserk F-40	7	10	8	80%
Nipterk L-19	11.6	2	2	100%
Paktoa C-60	13.5	1	0	0%
Phoenix	17.5	1	1	100%
Sarpik B-35	3.5	5	2	40%
Tarsiut N-44	22	10	9	90%
Tarsiut P-45	25.5	1	0	0%
Uviluk P-66	31	2	2	100%
West Atkinson L-17	7	3	2	67%

All data - 8 or more obs.	69%
All data - water depth>5m + >8 obs.	80%
All data - water depth>10m + >8 obs.	90%
All islands, including remnant sites	67%
All caissons, including remnant sites	73%
Surface piercing	84%
Not surface piercing	54%
Surface piercing islands	87%
Surface piercing caissons	76%
Remnant Island Berms	52%
Remnant Caisson Berms	69%

4. DEVELOPMENT OF GROUNDED RUBBLE FIELDS

A grounded rubble field forms when broken ice, driven by wind or currents and through the interaction with a structure, berm or a submarine feature, becomes so thick that it touches the seabed bottom. Additional ice moving into this region continues to pile-up on this initial formation, and the rubble can become firmly grounded to the seabed. With submerged berms, the initiation of the grounded rubble likely occurs when a deep ridge interacts with the berm and this interaction stops its movement. Subsequent ice piles up behind it and on top of it forming a stable pile-up. In shallow waters (< 5 m), the level ice usually freezes in place early in the winter with little movement, so rubbling is not usually observed. Canatec (1994), in a very comprehensive analysis, examined the mechanics of the formation of rubble fields and the reader is referred to it for details.

With these simple scenarios it is clear that many factors can influence rubble development: *viz.*, water depth, the existence (or lack of) landfast ice at a site, ice drift, storm severity and duration, level ice thickness, freezing degree days, structure shape and rubble volume/area. With so many parameters and such limited data, it is not reasonable to develop a single quantitative expression for rubble development. Canatec (1994) also examined these factors and others for a number of Beaufort Sea locations, including most of the sites examined here. The Canatec report examined the relationship between rubble field formation and ice thickness. Their results showed that most of the analysed rubble field forming events involved ice less than 0.3 m thick, with 90% of the events involving ice less than 0.8 m thick. Canatec (1994) felt that this indicated that most rubble fields formed before January 1.

Rubble development and characteristics will vary between sites, and for the same site, will be different each year. The amount of time of moving pack ice compared to the time the site is in landfast ice would be expected to control the growth, size and duration of any rubble that may develop at the site. Rubble can form during pack ice intrusions but once a location is within landfast ice, further growth of the rubble field is effectively halted. The rubble that had developed is then stabilized against further significant movement and may endure past the break-up of the surrounding ice. Locations not within the landfast ice zone can expect continual movement of pack ice past the platform. This often results in the clearing of rubble, especially floating rubble, which may have developed. However, this is not always the case. Periods of little or no pack ice movement can occur in this region and rubble piles can become relatively stable and last throughout the winter season (at Amauligak F-24, for example).

Barker and Timco (2006) and Barker et al. (2006b) examined timelines of rubble field development for exploration locations throughout the Beaufort Sea. Four distinct rubble "seasons" could be established that are applicable to marine operations and evacuation and rescue concerns. These are:

- open water;
- pack ice and rubbling;
- quasi-stable rubble;
- stable ice.

Analysis of the timelines showed that there were typically slightly more than 100 days of open water surrounding an offshore structure in the Beaufort Sea. Note that these are not necessarily ice-free conditions since ice in concentrations of 1/10 to 2/10 may be present. In this case the ice concentration is so low that no rubbling would occur.

The periods of pack ice and rubbling, is part of the shoulder season, or freeze-up and/or break-up, and is characterized by moving pack-ice in the near-shore region. Floating ice rubble may accumulate at a structure. During freeze-up, the ice is thin and this “season” lasts until the initiation of grounded rubble formation. For deeper-water locations, pack ice and rubbling interaction could continue throughout the winter, with much thicker ice, with no further transition to a different “season” if stable grounded rubble does not form.

The quasi-stable rubble interaction period is also part of the shoulder season. It is the time from the formation of grounded rubble at a structure in the autumn or early winter until the rubble is stabilized by landfast ice (i.e. during this time the rubble becomes consolidated through thermal consolidation). This is the period of large rubble field growth. The rubble may or may not form a complete annulus around the structure. In the spring, this period is marked by the disappearance of the rubble field such that the season runs from break-up of the landfast ice until the disappearance of the rubble field. Not every location will have the grounded rubble that forms around it stabilized by landfast ice. For example, in the transition zone, quasi-stable rubble may last through much of the winter, from its formation until its disappearance in the spring, never becoming stabilized by landfast ice. As a result, this interaction period duration could vary considerably, from a few days to never reaching a particularly stable state, even though the rubble may have been grounded. Quasi-stable rubble was present, on average, for 65% of the time that moving ice was also present in the autumn, for those locations that had grounded rubble. It should be noted that this value only accounts for grounded rubble that formed and remained at these sites. There may have been periods when grounded rubble had formed, but was subsequently removed by further pack ice interaction. If this was the case, then the 65% value could be conservative for these locations. This can be a substantial amount of time for a production platform and is a very useful piece of information for operators of both exploration and production platforms, especially with respect to marine operations during that time of year.

The stable ice season can mean one of two things depending upon the ice regime outside the rubble field and how "stable" rubble is defined. In the *landfast* ice zone, this means that the rubble is in fast ice and is quite secure from any large-scale movements. For locations in the *transition zone*, the rubble field may be essentially stable, but it is surrounded by moving pack ice. Determining rubble stability is not straightforward, but calculations based upon the sliding resistance of grounded rubble may help determine stability. However there is always the potential for sections of the rubble to be swept away by moving pack ice. Note that there is inconsistency in the literature regarding the definition of ice rubble stability (see Barker and Timco, 2010 for further discussion regarding the term "stable rubble"). Therefore, for simplicity, here the rubble is defined to be stable only with the presence of surrounding landfast ice. During the stable ice season, the rubble is locked by the landfast ice surrounding it and other than slight movement from thermal expansion, it remains locked in place around the platform. As will be discussed later (for example, in Figure 11), the rubble does generally remain in place well after the disappearance of the surrounding landfast ice, even though it is no longer constrained by the surrounding fast ice.

5. RUBBLE FIELD DURATION

The duration of the rubble field was calculated as the number of days between the initial formation of grounded rubble and the date that the rubble disappeared at the site. Where appropriate dates were available from Barker and Timco (2006) and the Barker field data, the analysis showed that overall, the duration of the grounded rubble at the sites studied ranged from 136 to 288 days, with a mean of 219 days and a standard deviation of 42 days. Note, however, that those values include locations such as Uviluk P-66, where spray ice was used to enhance the existing rubble around the structure. Nonetheless, as previously indicated, this is a substantial amount of time that rubble may surround a structure. Figure 7 shows the time-lines for 13 sites in the Canadian Beaufort Sea. The sites are ordered by increasing water depth from top to bottom of the figure. There are several things to note. First, there is a wide variation in the length of time that each season persisted for these sites. Some sites exhibited large time spans of stable rubble/ice whereas in other sites, this was not observed throughout the season. Second, comparing the time-lines for Tarsiut N-44 and Tarsiut N-44 TIRP (the latter was a research program at the drill site, after drilling equipment had been removed) allows an indication of the variation in time-lines for one site for two consecutive years. The comparison shows that there can be a large difference between the relative times for each of the "seasons" at a site. Third, no definitive trends were evident between the duration of the rubble field and water depth. Naturally, however, the longer a rubble field remains within landfast ice, the more likely it is to remain for a longer period of time. This implies that rubble fields in deeper water, where the landfast ice often breaks up first, are more likely to disappear earlier than those in shallower water. For example, Figure 8 plots the duration of the stable rubble field versus the water depth. As previously mentioned, "stability" is defined here as time within landfast ice; hence this plot essentially reflects the duration of the landfast ice at a particular location in a particular year. Nonetheless, it is interesting to examine the data in this form. Generally, as shown in Figure 8 the rubble remained later into the summer months at shallower water depths, with an average around the middle of July, but there was a standard deviation of 24 days. A polynomial upper bound line for rubble field duration versus water depth, as shown on the plot, is defined as:

$$\boldsymbol{D_R = -0.25\, d_w^{2} + 0.92\, d_w + 277 \quad \text{for } 10 < d_w < 33} \qquad \textbf{[1]}$$

where D_R is duration in days and d_w is water depth in metres. This line does not take into account factors regarding rubble field formation that have been examined elsewhere, such as the likelihood of formation in very shallow water (see Canatec, 1994, where the maximum rubble formation efficiency was found to be in water depths between 8 and 14 m), the use of spray ice, etc. The effective water depth was also plotted against duration (not shown here). While there was no apparent trend for effective water depth, unlike what is shown in Figure 8, it was noted that rubble could ground at relatively deep effective water depths, of up to 20 m. However, given the mobility of the surrounding pack ice for much of the season at locations in deep water, it is possible that the rubble at those depths was not very well-grounded.

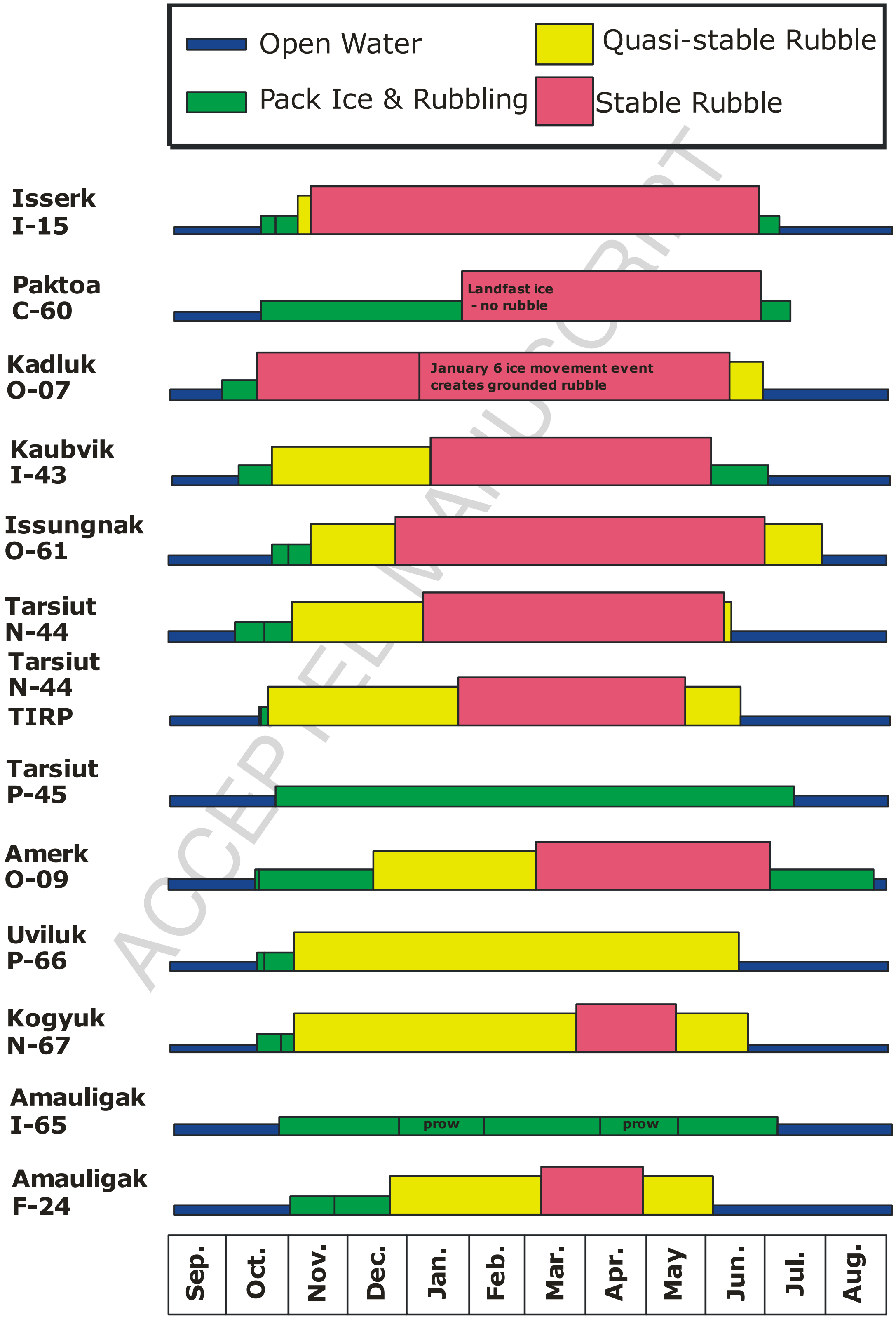


Figure 7: Time-lines for each of the four seasons for several locations in the Canadian Beaufort Sea. Note the wide variation in the length of seasons amongst these sites. The water depth at the sites increases from top to bottom in the figure.

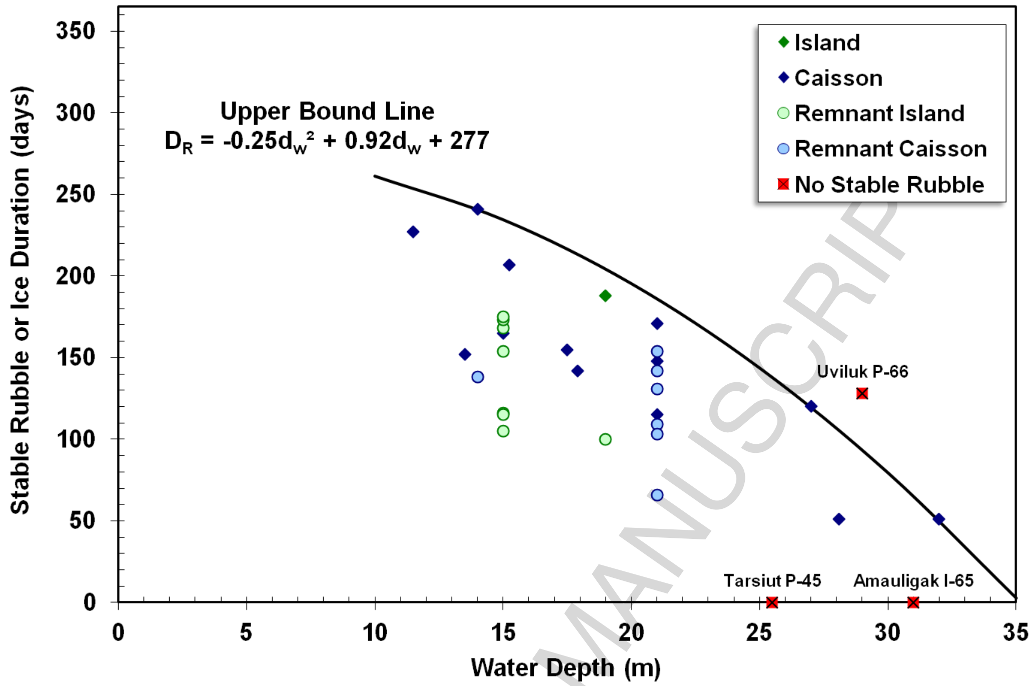


Figure 8: Plot of rubble field duration versus water depth. An upper bound line has been fit through the data. Note that the Uviluk P-66 site was left as an outlier, due to the lack of landfast ice at this site. The application of spray ice at this site largely contributed to the build-up of artificial rubble, which appeared to enhance the ability of this site to capture further naturally-forming rubble.

Once break-up of landfast ice has occurred in the spring, there are similar issues as experienced in the autumn with quasi-stable grounded rubble. Additionally, not only is the rubble field exposed to moving pack ice, but the ice is also deteriorating, primarily through thermal processes (see Figure 9). Melting and ablation of ice rubble in the Arctic landfast ice zone begin well before the break-up of any surrounding fast ice. These thermal processes weaken the ice (see e.g. Leppäranta et al. (1995)) so that by the time break-up has occurred in this zone, the rubble has lost a considerable amount of its previous strength. Pack ice interacting with the rubble after break-up may further decrease the size of a rubble field, removing weaker and less well-grounded sections of the field. Rubble fields have also been known to grow due to this interaction. However, the rubble that is created is loose and unconsolidated compared to that which formed in the autumn since the ice is warm with low strength and the air temperature is close to the melting point of the ice. The wave climate during the spring quasi-stable rubble season is minimized in the presence of pack ice, so it is generally not until fairly open water conditions exist that waves truly impact the rubble field. At that point, through undercutting and other processes, wave-induced removal of the rubble field occurs, acting along with the aforementioned thermal processes.

Figure 9: Tarsiut caissons (Tarsiut N-44 TIRP research program) in the spring, showing the decaying, quasi-stable grounded rubble field (photo courtesy Gulf Canada Resources Ltd.)

For the Barker and Timco (2006) data set, some locations may have had quasi-stable rubble in the spring, but information concerning the disappearance of the rubble was not available. For most of the examined locations, detailed information concerning the deterioration of the rubble fields was not readily available, as drilling activities had generally ceased by that time. With the exception of some existing ice observer record sheets, it was not possible to determine the level of direct ice interaction with the structures. Typically, the landfast ice surrounding a very well-grounded rubble field site is among the last to break-up, with the rubble field remaining until it has lost sufficient buoyancy through solar or physical deterioration to be swept away. In general, many extensive rubble fields did not disappear until July in any given year. For the seventeen sites where sufficiently detailed information about the rubble deterioration was available, rubble fields disappeared on average seven days after open water conditions (not break-up) began (see, for example, Figure 10), with a standard deviation of eighteen days. This can be a significant observation, as it means that in the spring, the quasi-stable season effectively "erased" much of the spring pack ice season. That is to say, because rubble fields generally remained in place until there was mainly open water, any moving pack ice during spring break-up did not directly contact the platform, and interacted with the rubble field instead. In practice, however, the non-symmetry of the rubble fields and the varying degrees of deterioration of a surrounding rubble field could mean that some sides of a structure were indeed exposed to moving pack ice while other sides were still afforded some degree of protection from the moving ice. For locations where the grounded rubble disappeared after open water conditions began, the disappearance of the rubble ranged from 3 to 39 days after open water conditions began (fourteen sites). For the remaining three sites, the rubble disappeared during spring break-up, when mobile pack ice was present and before open water conditions began.

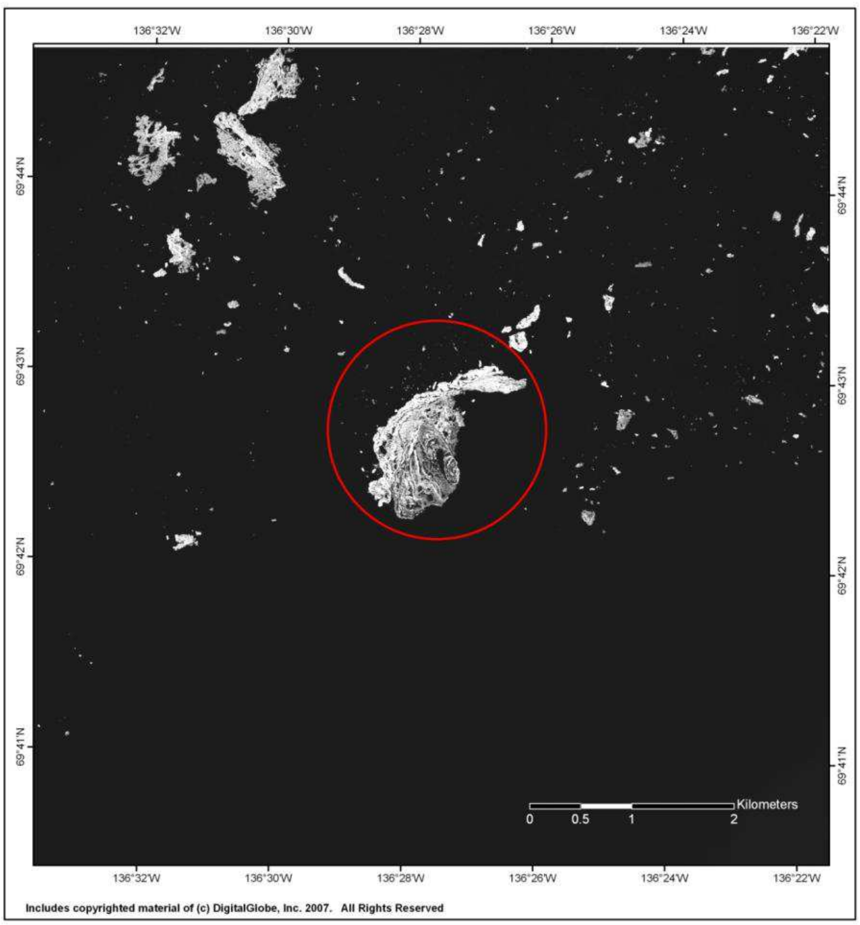


Figure 10: QuickBird satellite image of the Minuk I-53 rubble field (circled in red) in the process of deteriorating on July 10, 2007. The ice outside of the red circle is primarily low concentration mobile pack ice, from the deteriorating landfast ice.

Figure 11 plots the Julian date of rubble field disappearance versus the break-up date for the landfast ice in the situation where a rubble field formed. It can be seen that the disappearance of the rubble field generally lags the break-up of the surrounding landfast ice by about 30 days. The lag is smaller if the break-up date of the landfast ice occurs later in the year, and vice versa. A reasonable upper bound equation of the form

$$RDD = 0.8\ BUD + 70 \qquad [2]$$

fits most of the data where *RDD* is the Julian Day of the rubble field disappearance date and *BUD* is the Julian Day of the break-up date at the site. The two outliers were due to either extensive spray ice applications at a site that was built upon grounded multiyear ice floes (Antares drill site) or a particularly durable rubble field with little ice movement after break-up (Fireweed).

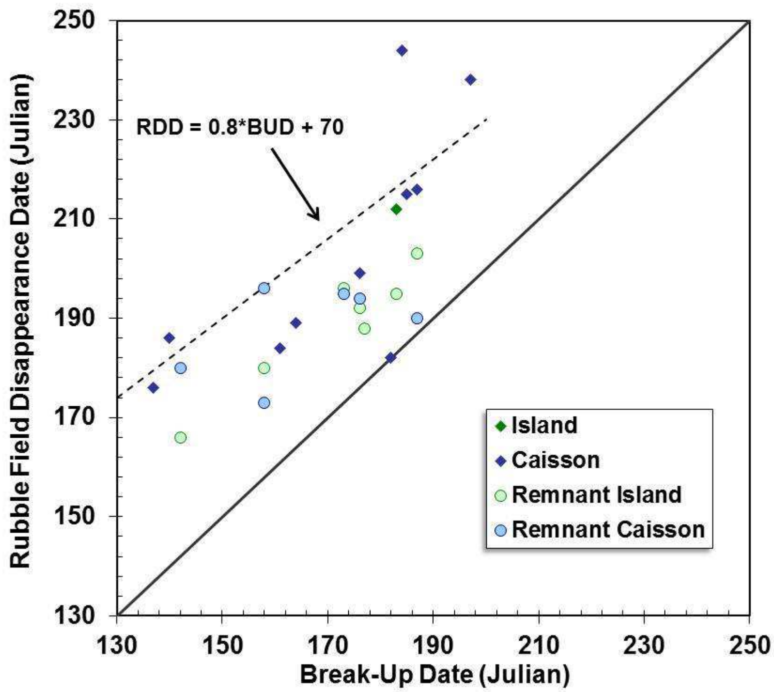


Figure 11: Plot of rubble field disappearance date versus the landfast ice break-up date. The 1:1 line is shown as a solid line in the plot. The number of days above the line for each site is the number of days that the rubble field was not surrounded by landfast ice. A reasonable upper-bound line is presented.

Figure 12 shows the Julian date of the rubble field disappearance date (RDD) versus the thawing degree days (TDD). A linear relationship was found such that:

RDD = 152 + 0.113 TDD **[3]**

For this, the thawing degree days were calculated from all positive Celsius degree days from April 1 each year. The values were calculated based upon hourly temperature data, averaged for each day, from the Environment Canada Historical Climate Data archive for Tuktoyaktuk Airport (http://climate.weather.gc.ca/index_e.html#access), which in the past has been found to have an acceptable agreement with the nearshore exploration drilling regions. Negative values were skipped. Note that this plot does not take into account the many other factors associated with ice melting and disintegration, such as solar radiation, water currents and velocities, etc.

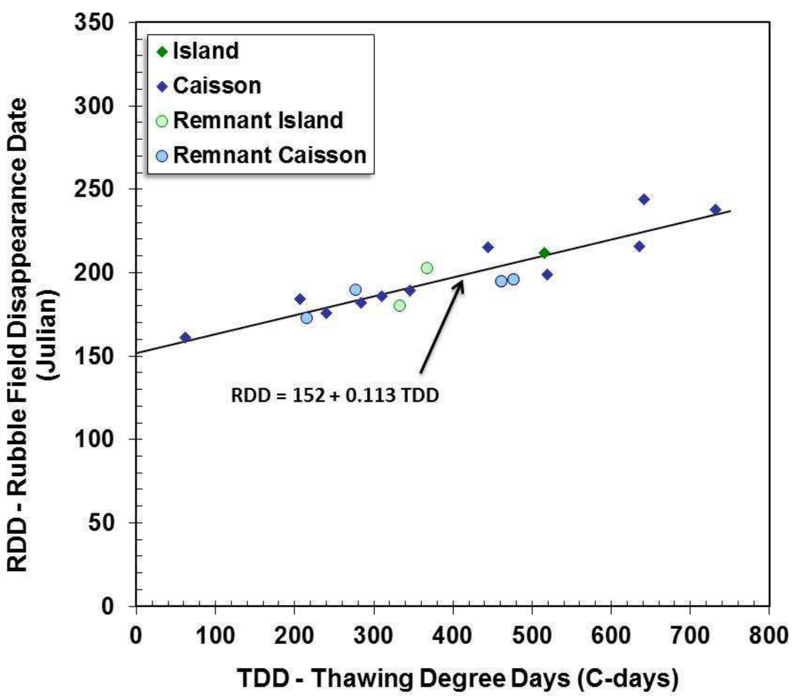


Figure 12: Rubble field disappearance date versus the thawing degree days.

6. RUBBLE FIELD CHARACTERISTICS

6.1 Sail Height in the Rubble

Sail height has been examined in Canatec (1994), and will not be covered in detail here. Figure 13 shows the ice thickness at formation plotted against maximum observed sail height. Canatec (1994) derived an expression for the maximum sail height (H_{sm}) in the rubble as a function of the ice thickness (h_i) at formation. They found that $H_{sm} = 14.5\ (h_i)^{0.5}$ where both H_{sm} and h_i are in meters. The plot shows that for thinner ice, the upper bound calculation underestimates the heights that have been observed around offshore platforms. This would largely be of consideration in the early winter, as a rubble field is being formed. This data clearly shows that the sail heights in the grounded rubble can be quite high – on the order of 10 to 14 m. The present data, in contrast to the Canatec equation does not show any systematic relationship between sail height and ice thickness.

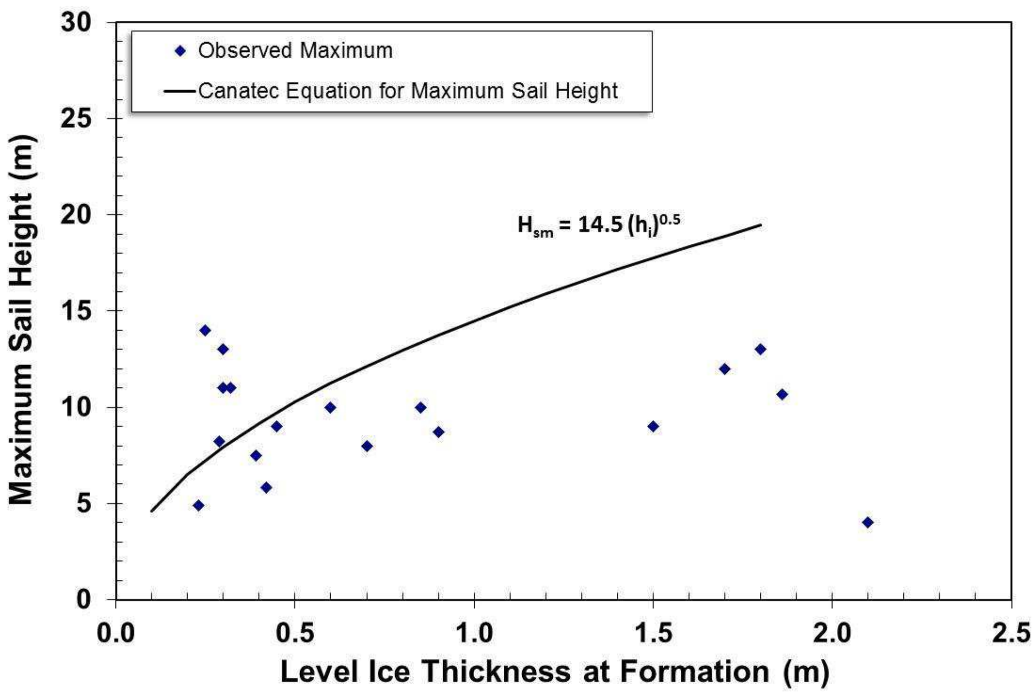


Figure 13: Plot of level ice thickness against maximum observed sail height within a rubble field. The calculated maximum upper envelope line for grounded rubble from Canatec (1994) is also shown.

6.2 Rubble Field Size and Anisotropy

The size and anisotropy of a rubble field are very important parameters. There are many factors that contribute to the size and shape of the rubble, such as the presence of sub-sea berms, ice drift direction, amount of moving ice, structure shape, removal of rubble by icebreaking vessels, and the influence of spray icing at the site.

Figure 14 shows a compilation of several rubble fields that were observed around islands or caisson structures in the Beaufort Sea. The photographs clearly show that rubble fields can be quite large and rarely have a uniform shape around a structure; i.e. they are usually highly anisotropic. Further, a number of structures had locations where one side of the structure may have had no rubble at all or where there was very little rubble formation. Figure 15 and Figure 16 show quantitative information on the size and anisotropy of some of the rubble fields. These figures show the maximum rubble extent along the longest length of the rubble field (Figure 15) and across the longest width of the rubble field (Figure 16), taken from aerial imagery of the sites. The data are plotted centred on the island or berm and the rubble fields were measured from the edge of the caisson or island. The data are plotted with increasing water depth from left to right. The plots show that the ratio of the maximum longer diameter to the maximum shorter diameter of the rubble ranged from a value of about 1 (indicating that the axes were roughly equal) to 2 values of four and two sites with rubble fields only off of one side of the structure. These latter four sites had long rubble fields that formed in the predominant ice drift direction, up-drift of the structure. The median ratio of maximum longer diameter to maximum shorter diameter was approximately two, meaning that the perpendicular width was half that of the longest length of rubble.

Figure 17 plots the maximum rubble field length (L_{max}) against maximum rubble field width (W_{max}). In this plot, both the available Spedding (1987) and Barker field data have been combined (92 data points). A linear best-fit line through the data gives the equation (R^2=0.6)

$$\boldsymbol{L_{max} = 1.7\ W_{max} + 65} \qquad \textbf{[4]}$$

where L_{max} and W_{max} are in meters. Figure 18 presents a probability of exceedence plot, based upon the entire data set as well as for only years when a rubble field was present, for the maximum total length of the rubble field. Note that for Figure 17 and Figure 18, the data include the length/width of the structure, if one was present. The latter plot shows that rubble fields with lengths greater than 1 km are not uncommon in the Beaufort Sea, whether or not a structure is present. Analysis of the sites from the three data sources (Spedding 1987; Barker et al. 2006; Barker field data) indicated that the average maximum rubble extent was approximately 490 m, including years without rubble fields, with a large standard deviation of 518 m. Excluding the years when no rubble field formed, the average maximum rubble extent was approximately 740 m, with a standard deviation of 467 m.

For some locations, the progressive growth of the rubble field was available. Figure 19 shows an example of the growth progression at the Issungnak O-61 during the winter of 1979-1980. The figure shows rubble field development (and decay) based upon analysis of available air photo images. The plot shows that extensive rubble fields may be generated very early in the season. It also demonstrates that a significant amount of rubble may be present well into the summer months at some sites.

Spedding (1987) examined the directional distribution of 56 rubble fields. The most prominent directions of the major axes with respect to True North were 100-280° (10 observations) and 140-320° (9 observations), followed by 120-300° (8 observations) and 110-290° (7 observations). Those values intuitively make sense, given the predominant direction of ice motion in this region. For the Barker field data, the two most predominant axes for the Minuk I-53 and Tarsiut N-44 rubble fields were 120-300° (3 observations) and 130-310° (3 observations), similar to the Spedding data. The Minuk I-53 site in particular does often have other rubble-forming events that occur after the core rubble field has formed. These subsequent build-ups may be in very different directions, such as 30-210°, depending upon the pack ice drift events in a given year.

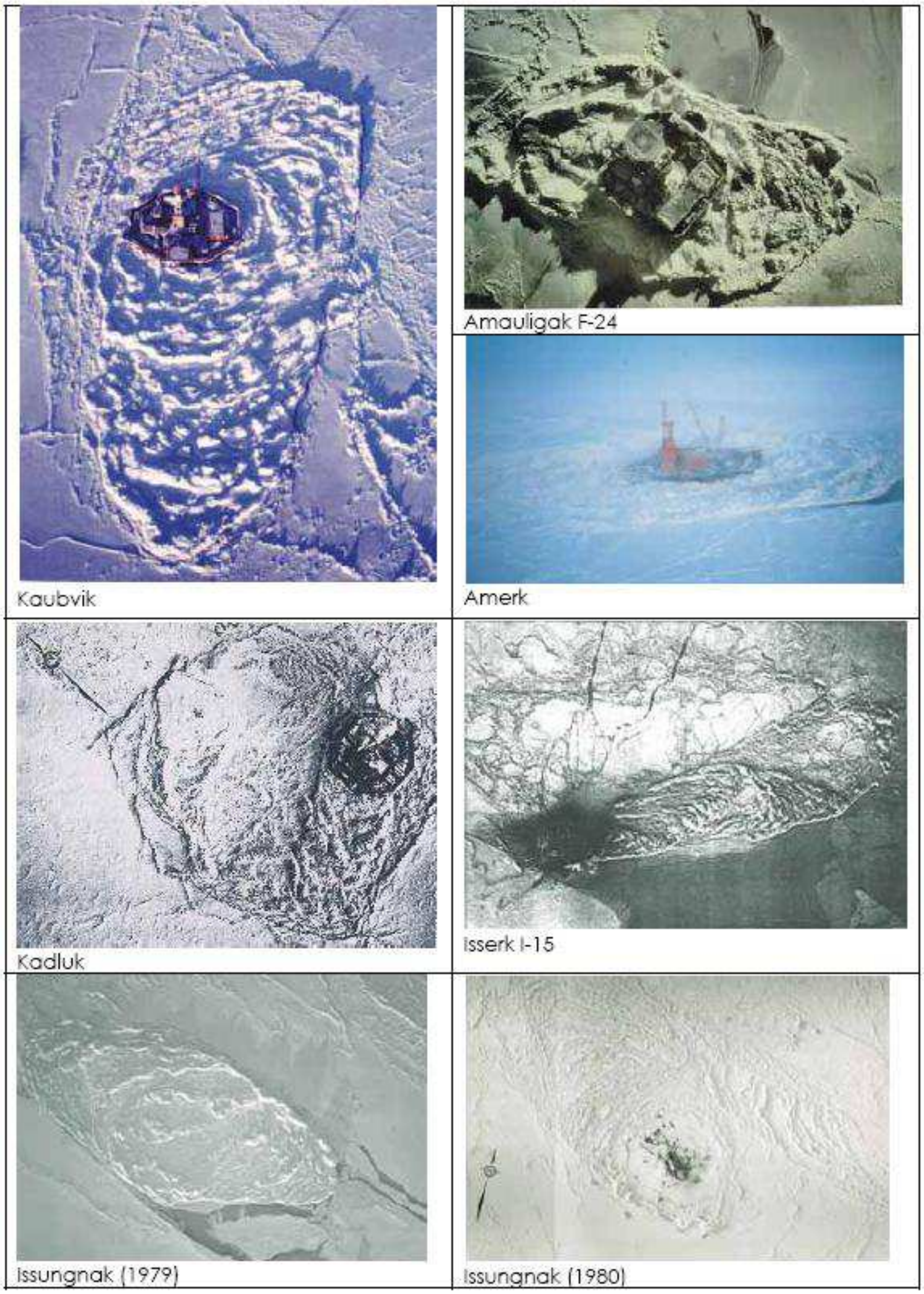


Figure 14: Photographs demonstrating anisotropy of rubble fields. (photos courtesy Gulf Canada Resources Ltd., Imperial Oil, Dome Petroleum).

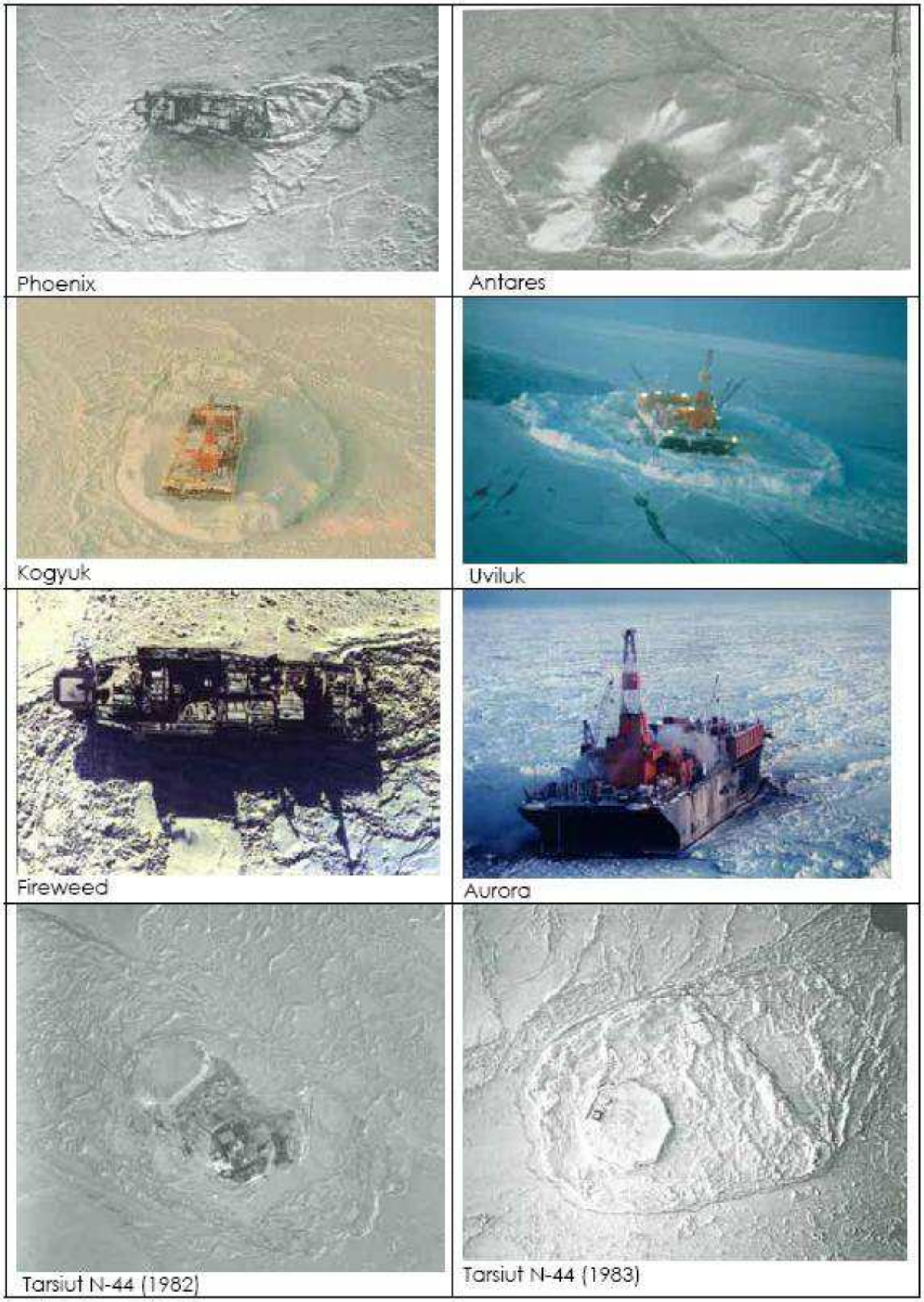


Figure 14: (continued) Photographs demonstrating anisotropy of rubble fields. (photos courtesy Gulf Canada Resources Ltd., Imperial Oil, Dome Petroleum).

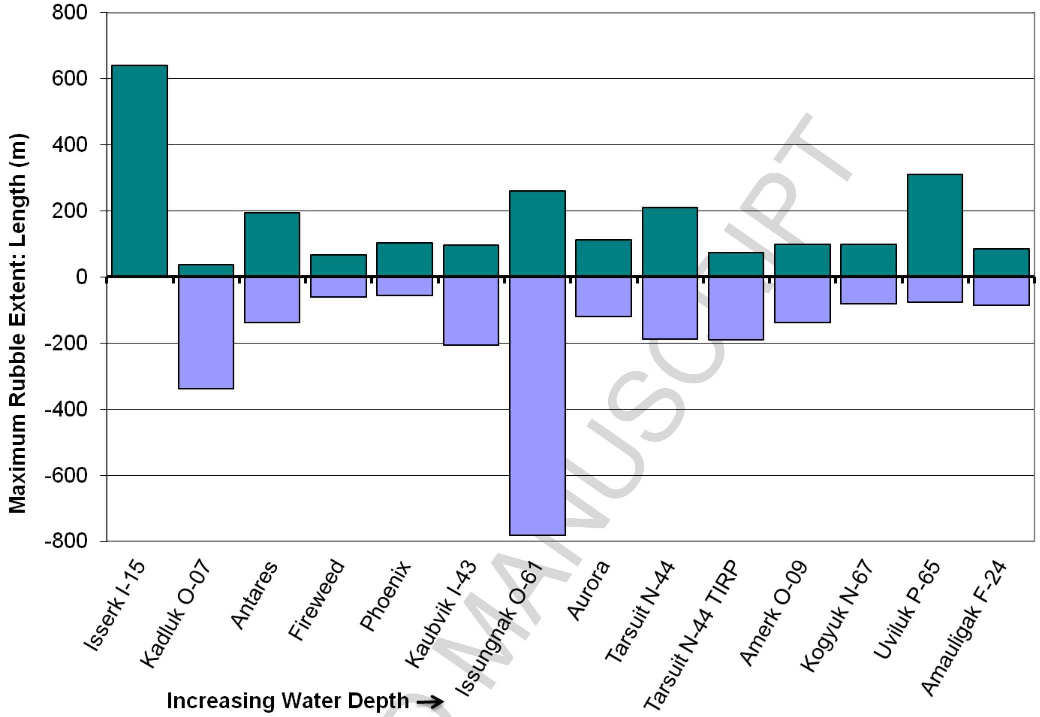


Figure 15: Anisotropy of rubble fields, as distance from structure along the longest length axis (historical data). Note that the y-axis ranges from -800 m to 800 m.

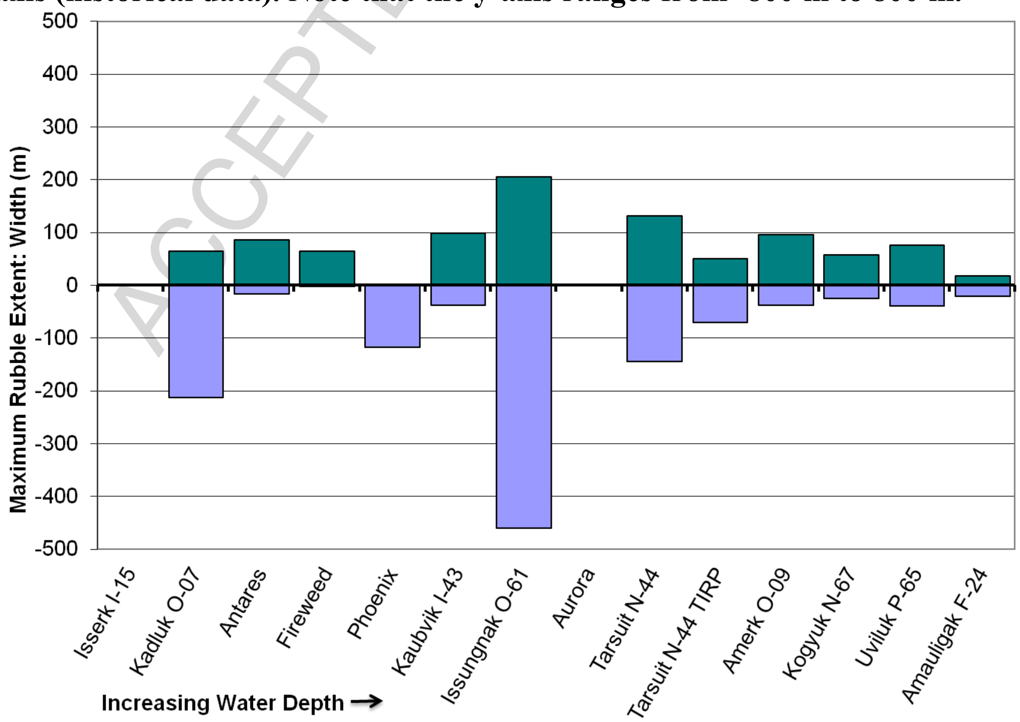
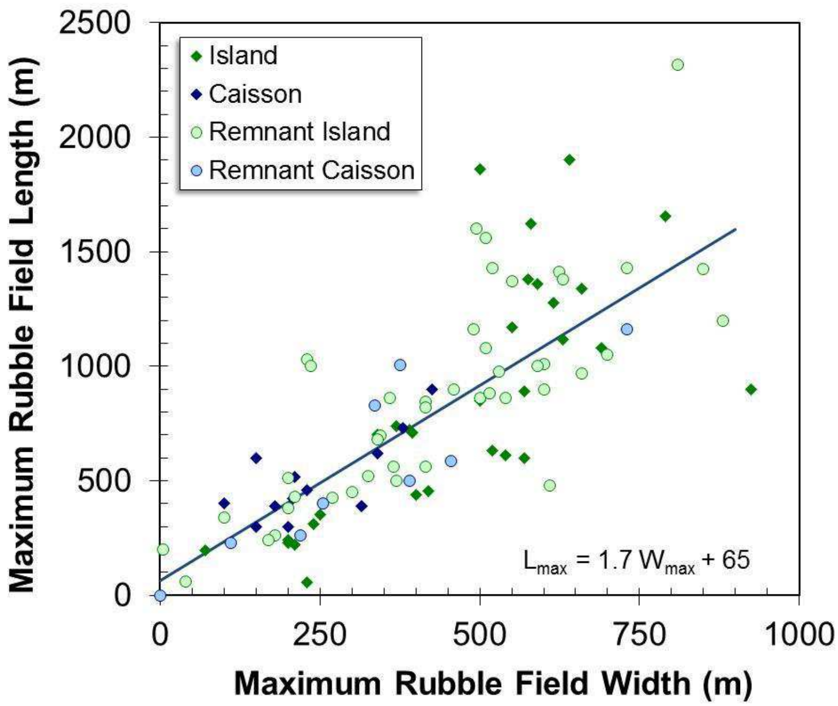


Figure 16: Anisotropy of rubble fields, as distance from structure along the longest width axis (historical data). Note that the y-axis ranges from -500 m to 500 m.



Island
Caisson
Remnant Island
Remnant Caisson
Maximum Rubble Field Length (m)
Maximum Rubble Field Width (m)
L_{max} = 1.7 W_{max} + 65
2500
2000
1500
1000
500
0
0
250
500
750
1000

Figure 17: Plot of maximum rubble field length versus width.

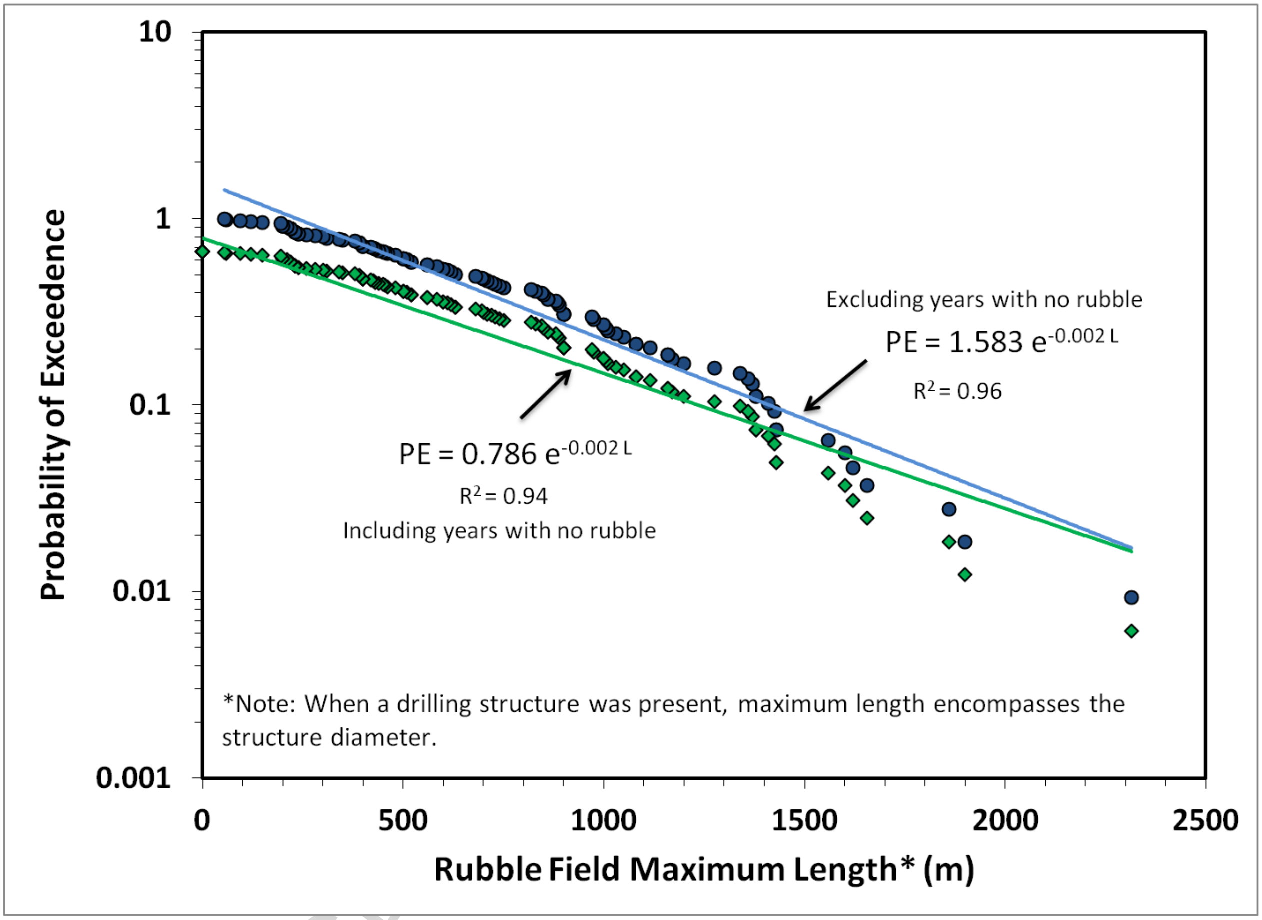


Figure 18: Probability of exceedence plot for rubble field maximum length, based upon (green) the entire data set, whether or not a rubble field was present, and (blue) only years in which a rubble field formed. Exponential fit lines of the data for lengths up to 2300 m are shown. Note that rubble fields greater than 1 km total length are not uncommon.

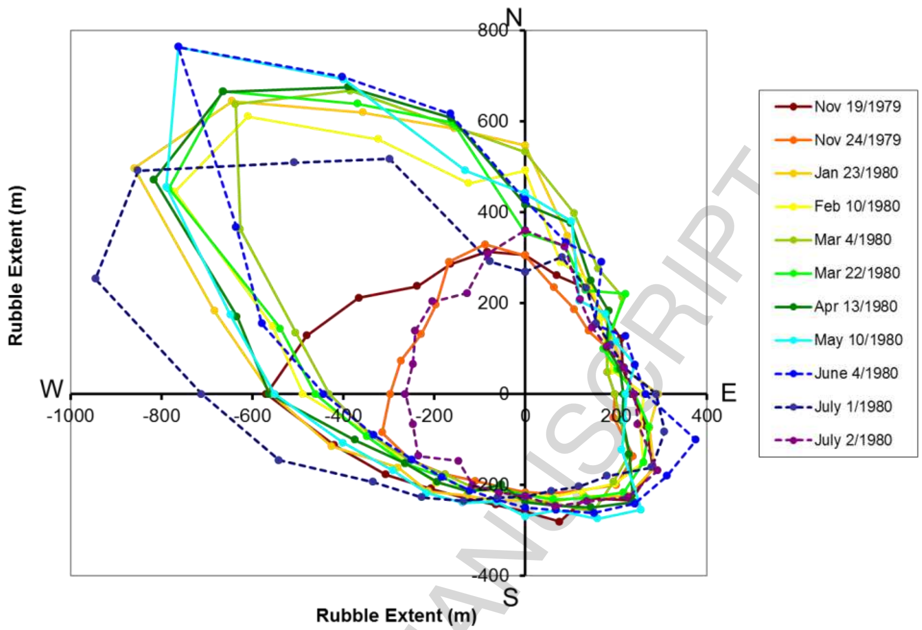


Figure 19: Rubble field development and decay at Issungnak O-61 (winter of 1979-1980) showing the rapid growth in the early winter (into January) followed by a relatively static shape for remainder of the winter. The solid lines show the rubble field growth whereas the dashed lines indicate the rubble field decay in the spring. The contour lines include the island area which was centred at (0,0).

6.3 Rubble Field Area

The preceding rubble field characteristics are all factors that make up the overall rubble field area. Previous attempts at defining relationships between rubble field area and a variety of ice and environmental parameters have been done by other authors, notably Spedding (1987). His report primarily examined island sites (and remnant island sites), as limited caisson data were available at that time. He evaluated the relationship between rubble field size and water depth, days in moving ice and berm size. For all three cases, there was a great deal of scatter in the data. A relationship between rubble field size and water depth was indicated for the island sites, with increasing rubble fields with increasing water depth. No such relationship was evident for the caisson sites. With respect to days of moving ice, there was a trend of larger rubble fields with greater time in moving ice, but the correlation was poor.

Analysis of the data has indicated that rubble field areas ranged from 0 km² (where no rubble field formed) to 0.97 km², with an average of 0.17 km² and a standard deviation of 0.24 km². Sometimes grounding occurred almost exclusively on the submarine berm, if one was constructed, while at other locations, the rubble field was extensive enough that it progressed past the edge of the submarine berm to ground in the original water depth or deeper. This has been further explored in Barker et al. (2009a).

Figure 20 shows a plot of the average rubble field area for the four Barker field sites, including historical data on these sites from Spedding (1987), along with bars indicating each site's standard deviation. The sites have been grouped by similar water depth / exposure to moving ice. That is, the Minuk I-53 and Kadluk O-07 sites are similar, while the Issungnak O-61 and Tarsiut N-44 sites are similar. In each group, one site was originally an island (Minuk, Issungnak), while the other was originally a caisson site (Kadluk, Tarsiut). These data include both the original site and seasons where there was no surface piercing structure. A simple examination of this data shows that the two factors of water depth and exposure to moving ice alone cannot readily explain the differences in both the average values and the standard deviations. Other factors, such as the size, slope and shape of the berm (which are inter-related with water depth) must come into play when it comes to the ultimate size of a rubble field. This was also briefly examined in Spedding (1987).

Figure 21 shows a histogram analysis of the data, using both the Spedding and Barker field data sets. The data set is made up of 121 rubble observations (62 in water depths less than 10 m, 42 in water depths greater than 10 m and less than 20 m, and 17 in water depths equal to or greater than 20 m), is naturally non-negative, and is also left-skewed. Note that the data set includes null values for years when no rubble field formed at a site, and includes the structure area, when one was present. The lack of formation of a rubble field was more common in water depths less than 10 m or greater than 20 m, as would be expected. Figure 22 is a probability of exceedence plot for the same data set, as well as showing the impact of excluding the years when rubble did not form.

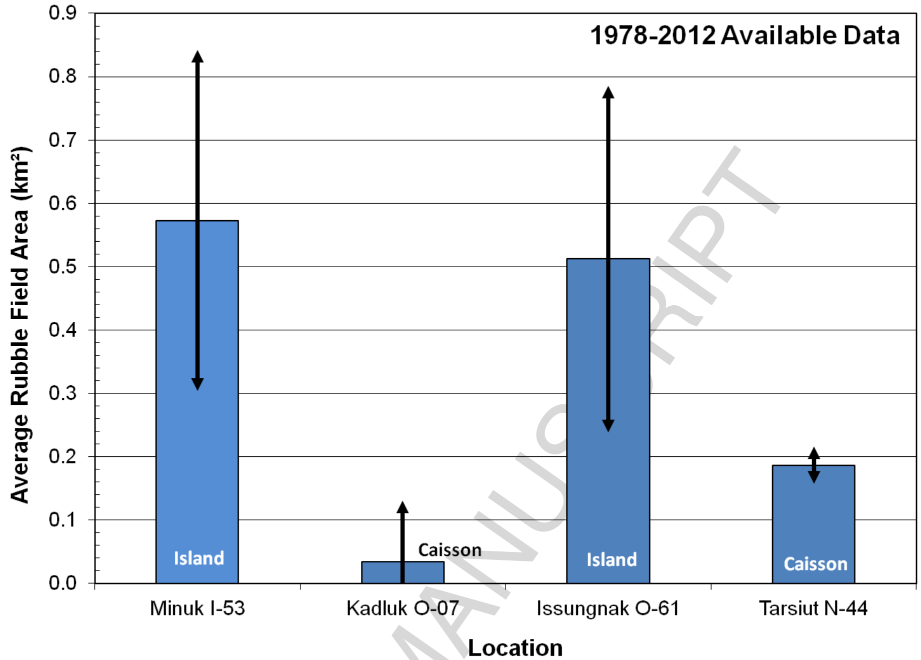


Figure 20: Average rubble field area and standard deviation for four sites. Minuk and Kadluk had similar water depths and ice exposure. Issungnak and Tarsiut had similar water depths and ice exposure but different than those of Minuk and Kadluk. The data shows that the two factors of water depth and exposure to moving ice alone cannot readily explain the differences in rubble field area.

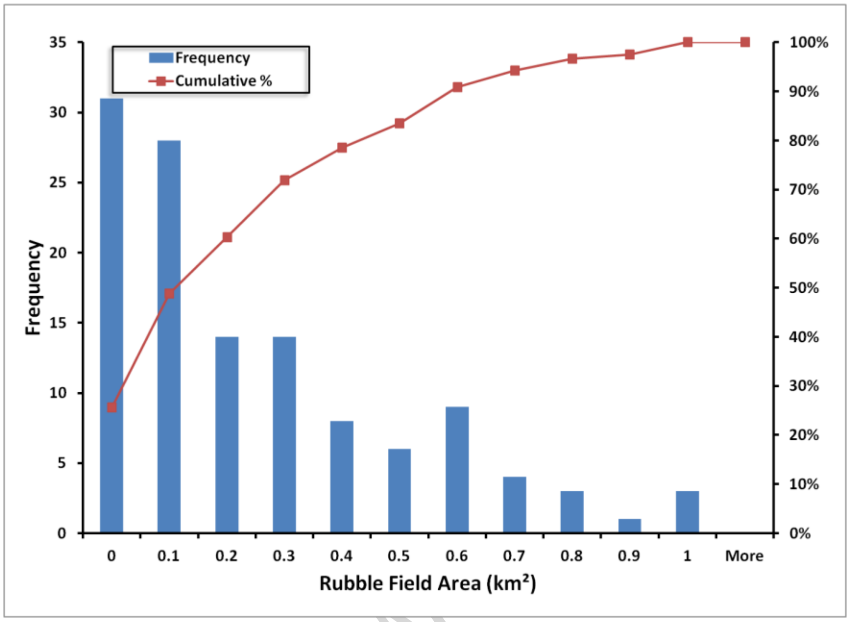


Figure 21: Histogram of 121 rubble field areas which contains historical data as well as the more recently collected Barker field data. Note that rubble fields with areas of 1 km^2 are possible.

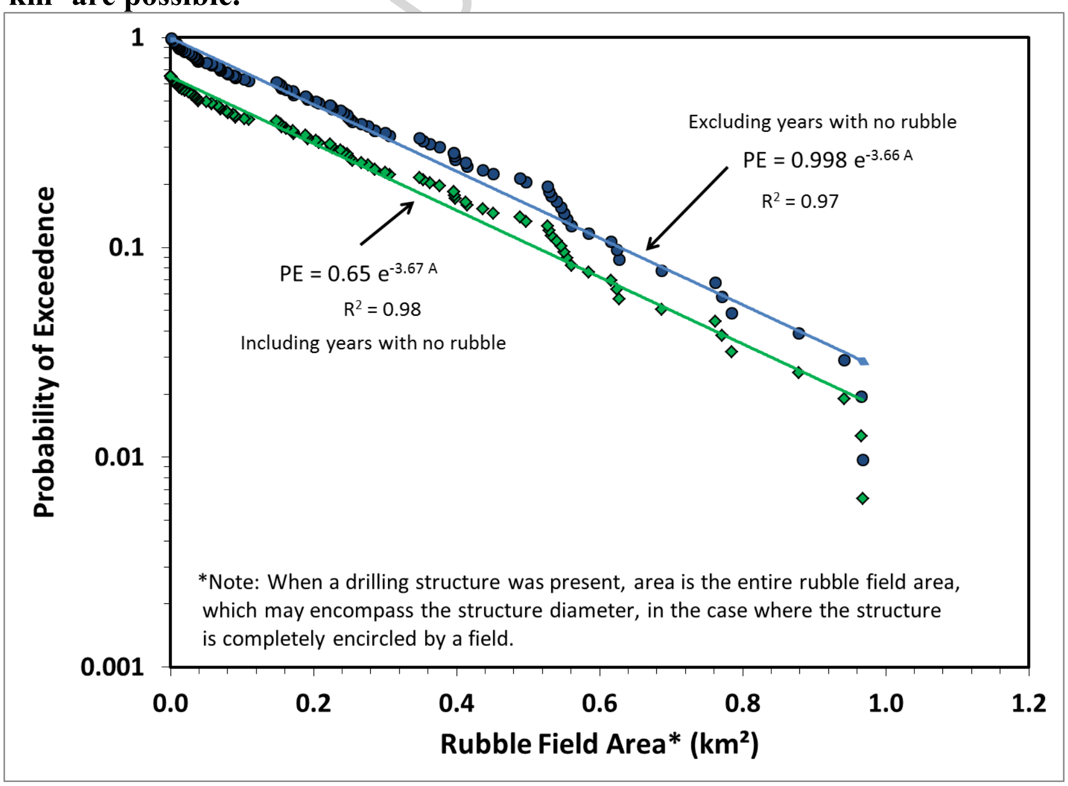


Figure 22: Probability of exceedence plots for rubble field area, based upon (green) the complete data set and (blue) only years during which a rubble field formed. Exponential fit lines of the data for areas up to 0.95 km^2 are shown.

The data were examined to try to determine a relationship between the area of the rubble field with a variety of parameters. No definite relationships were found. Further, all data plots exhibited considerable scatter. Analyses that were made included trying to correlate the rubble field area to the freeze-up date of the surrounding landfast ice, the number of days of moving ice, and the ice flux past the site. The discussion below focuses on a few parameters to illustrate the scatter and highlight potential upper bounds of the data.

Figure 23 examines the relationship between the area of a rubble field and the water depth at the site. Note that in this plot, the water depth is the site water depth, not the berm (or effective water) depth. Approximate upper bound lines for the available data are given by the equation:

$$\begin{aligned} A_{max} &= -0.0034\, d_w^2 + 0.12\, d_w + 0.068 && \text{for } 2\text{m} \le d_w \le 20\text{m} \quad [5] \\ &= .3 && \text{for } 20 \text{ m} \le d_w \le 32 \end{aligned}$$

where A_{max} is the maximum rubble field area in square kilometres and d_w is the original water depth in metres. There is clearly a great deal of variability in the data: some fields are extensive, while in many years, little or no rubble exists. There is the additional question of whether rubble fields of larger extent may exist at deeper water depths, but there haven't been a sufficient number of bottom-founded structures at these depths to see this. Or, the observed upper bound of 0.3 km^2 at deeper water depths may reflect the fact that the rubble field extent is smaller for these water depths due to factors such as increasingly dynamic ice, berm size and soil strength. If the former is true (with more observations, one would observe more, larger rubble fields at deeper depths), this could mean that there could be larger rubble fields in deeper waters than shown here (i.e. maximum area of 0.3 km^2). This could potentially alter the upper bound for water depths above 20 m. The presently available data are not sufficient to determine this. It could also be possible that there would be different upper bounds depending upon the platform type (island or caisson). Regardless, Figure 23 does give a rough idea of the potential maximum size of a rubble field at a particular water depth.

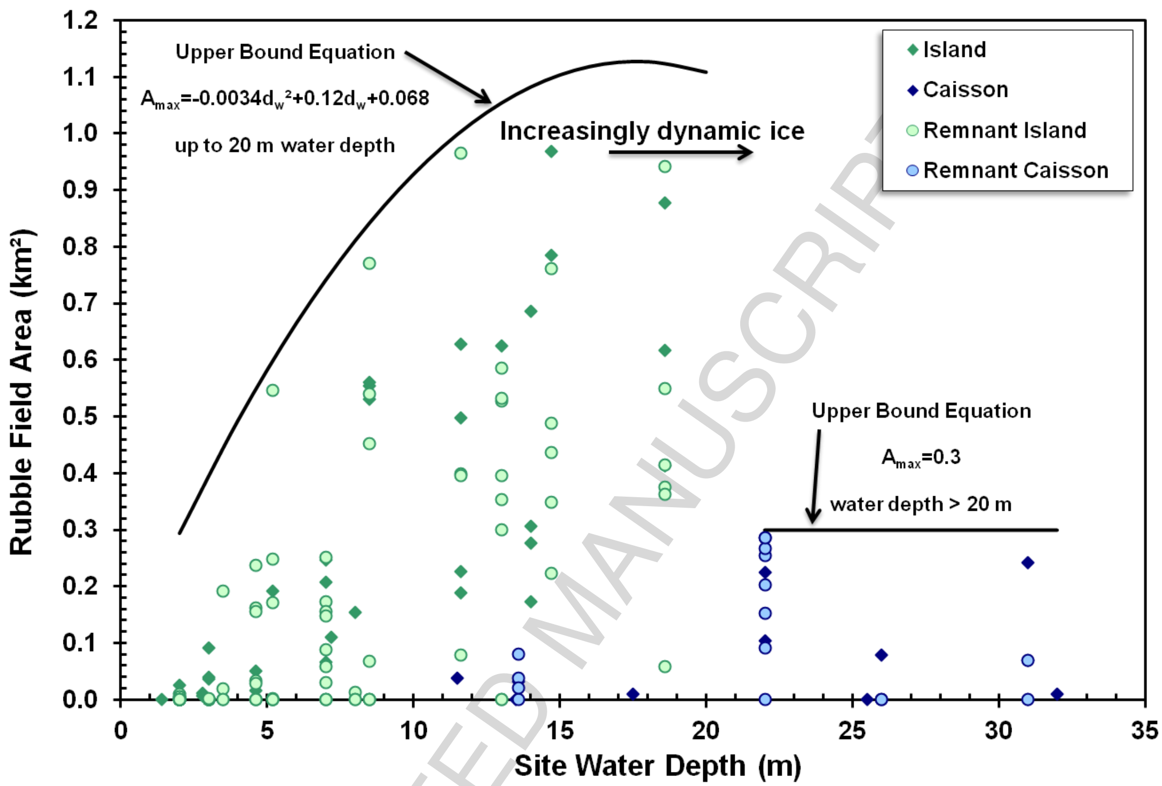


Figure 23: Plot of maximum area versus water depth. The water depth is the original site depth and does not account for the presence of any underwater berms. The upper bound equation is an approximation that is mainly applicable for water depths less than 20 m.

Barker et al. (2009a) examined the relationship between rubble field area and berm area. Figure 24 shows these areas plotted together, with 1:1 and 1:2 lines indicated on the plot. The results of that study showed that the average relationship between berm area and rubble field area is highly variable. The plot indicates that the smallest rubble fields were associated with the small footprint area of the remnant sites. This seems reasonable since these sites no longer have a surface-piercing element so rubbling would only begin once large ridge keels would interact with the berms. Figure 24 also suggests that caisson sites generally (but not always) have rubble field areas smaller than their berm, and island sites generally (but not always) have rubble field areas greater than their berm area. These trends again seem reasonable since the islands were very large in extent and as they pierced the water line with a slope, ice pile-ups would begin very early in the year. Furthermore, less ice would be required to ground on the seabed since the effective depths were considerably smaller, and over a greater area, than those of the caisson sites. Spedding (1987) also found that there was a poor correlation between rubble field size and berm size, although he suggested a trend, with rubble fields generally 2 to 3 times the berm area. Spedding (1987) also suggested that water depth and ice sheet movement were more important factors in controlling rubble field size. However, as shown in Figure 20 and discussed previously, these are such inter-related factors, it is not possible to separate them.

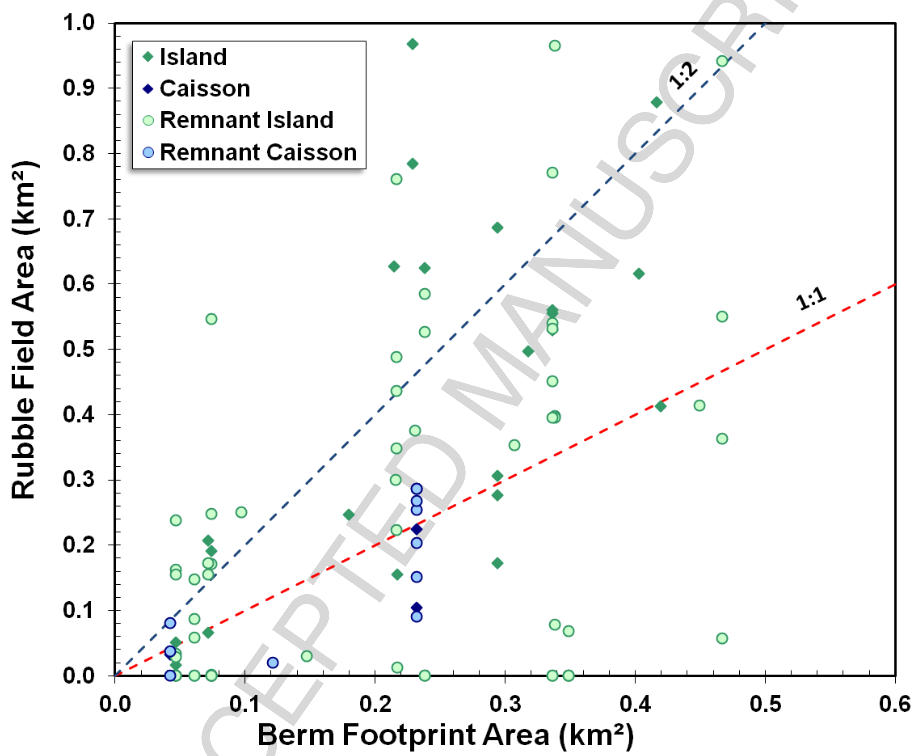


Figure 24: Plot of rubble field area versus berm area, where berm area is the maximum footprint area of the submarine berm or island on the seafloor. The dotted lines indicate 1:1 and 1:2 ratios.

While berm area does indicate a highly-scattered relationship between that value and rubble field area, it is possible that a more important factor, which also relates to the potential stability of grounded rubble, is the slope of the berm. As suggested in Spedding (1987), steeper berm slopes, associated with caisson berms, would lead to smaller rubble fields. Figure 25 shows a plot of the rubble field area as a function of the steepest underwater slope angle of the berm (as-built). Note that for island locations in particular, a variety of underwater slopes were used to construct the berm at the site. An exponential upper bound line has been fit to the data, given by the equation:

$$A_{max} = 1.5\ e^{(-0.11\alpha)} \qquad [6]$$

where A_{max} is the maximum rubble field area in square kilometres and α is the steepest berm slope, in degrees. The caisson data set within this group may not follow the same apparent trend as the island sites.

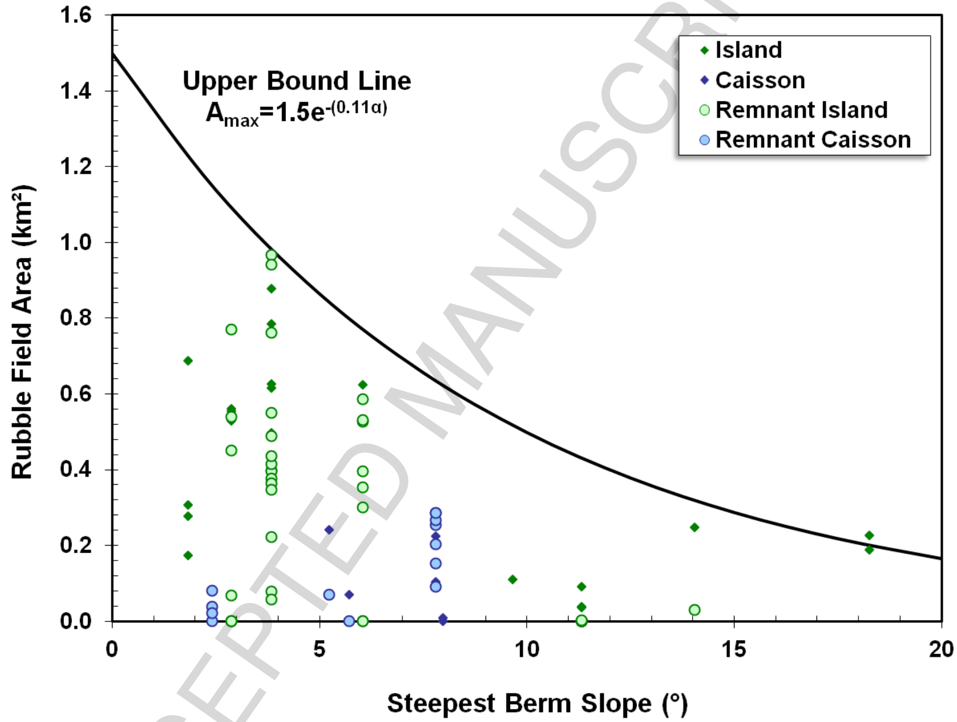


Figure 25: Plot of rubble field area versus berm slope. The value for the slope is taken as the steepest underwater slope, as-built conditions. Due to erosion and migration of the remnant berms, the slope will likely no longer be that steep, which would have the effect of shifting remnant data points to the left of the plot. The plot shows the upper-bound line fitted to the data.

7. RUBBLE FIELD PREDICTIONS

The previous sections have presented a considerable amount of information on the formation, geometry, size and decay of observed, grounded rubble fields. The objectives of this work were to see if it was possible to (1) predict if a rubble field will form based on historical data, and if so provide insight on its (2) formation, (3) duration, and its (4) properties and size, based upon available data sets. The analysis investigated a large number of rubble fields with input on temporal and spatial differences. One thing that was abundantly clear was that the creation of a rubble field is complicated with many factors directly and indirectly affecting its formation and properties. No single parameter proved to be essential for its formation. In addition to the analysis presented in this paper, many other relationships were investigated, such as multiple linear regression to predict rubble field area. This analysis, using combinations of variables including water depth, berm area, number of days of moving ice and steepest slope, showed only marginal correlation, with a best multiple R^2 value of 0.59. Table 2 provides a summary of the results formally discussed in this paper as well as those that were not discussed in detail here.

Table 2: Summary of rubble field relationships

Dependent Variable	Independent Variable	Functional Form	Limits	Figure
D_R - duration of rubble field (days)	d_w - water depth (m)	$D_R = -0.25\ d_w^{\ 2} + 0.92\ d_w + 277$	$10 < d_w < 33$; upper bound	8
D_R - duration of rubble field (days)	effective water depth	no relationship found		
D_R - duration of rubble field (days)	Di - number of days of moving ice	$D_R = -0.0052\ Di^2 - 0.13\ Di + 245$	upper bound equation	
D_R - duration of rubble field (days)	Rubble field area	no relationship found		
RDD- rubble field disappearance date (Julian Day)	BUD - break-up date (Julian Days)	RDD = 0.8 BUD + 70	reasonable upper bound	11
RDD- rubble field disappearance date (Julian Day)	TDD - thawing degree days (C-day)	RDD = 152 + 0.113 TDD		12
H_{sm} - maximum sail height (m)	h_i - ice thickness at formation (m)	H_{sm} of 5 to 14 m independent of h_i from 0.2 to 2 m	$0.2 < h_i < 2$	13
L_{max} - maximum rubble field length (m)	W_{max} - maximum rubble field width (m)	$L_{max} = 1.7\ W_{max} + 65$		17
PE - Probability of Exceedance	L - Rubble field length	$PE = 1.583\ e^{-0.002L}$	Excluding years of no rubble for lengths up to 2000m	18
PE - Probability of Exceedance	L - Rubble field length	$PE = 0.786\ e^{-0.002L}$	Including years of no rubble for lengths up to	18

			2000m	
PE - Probability of Exceedance	A - Rubble field Area	$PE = 0.998\, e^{-3.66A}$	Excluding years with no rubble for areas up to 0.95 km^2	22
PE - Probability of Exceedance	A - Rubble field Area	$PE = 0.65\, e^{-3.67A}$	Including years with no rubble for areas up to 0.95 km^2	22
A_{max} - maximum rubble field area (km^2)	d_w - original water depth (m)	$A_{max} = -0.0034\, dw^2 + 0.12\, dw + 0.068$ $A_{max} = 0.3$	2m < d_w < 20m 20 m < d_w < 32	23
A_{max} - maximum rubble field area (km)	LSI - Julian Date of Landfast Ice	$A_{max} = 0.5\, e^{(-0.08LSI)}$	upper bound equation	
Rubble field area	berm/island footprint area	smaller berms result in smaller rubble fields		24
A_{max} - maximum rubble field area (km^2)	α - steepest berm slope (degrees)	$A_{max} = 1.5\, e^{(-0.11\alpha)}$	upper bound equation	25
Rubble field area	ice flux	no relationship found		

Table 2 shows that although there are many necessary factors to initiate and grow a grounded rubble field, there is no one sufficient condition that will generate a grounded rubble field. For example, this analysis has shown that water depth and an obstacle to initiate the pile-up ice are certainly necessary factors but they alone do not guarantee the generation of a rubble field. To illustrate this, consider the well that Devon drilled in 2005/06 using the caisson structure SDC at the Paktoa C-60 site which is in 13 m of water in the Beaufort Sea. With this water depth and a caisson platform, the predicted ice loads were based on the premise that a grounded rubble field would form. But, as shown in Figure 26, no rubble field did form. This was a surprising event[1]. An analysis showed that the ice was heavily grounded early in the season on the remnant berm at the Minuk site which was approximately 6.5 km to the north of the Paktoa C-60 location. This grounded rubble at Minuk effectively "pinned" the ice in this region so there was relatively little ice movement at the Paktoa C-60 site and no rubble field formed there. The subsequent formation of landfast ice then precluded the formation of rubble at

[1] It should be noted that although it was assumed that a grounded rubble field would form, the ice load predictions by Industry and the review that the NRC did for the National Energy Board included the scenario where no rubble field would form. It was concluded that even without a grounded rubble field to reduce the loads, the SDC would withstand the ice forces at that site.

that site. This shows that although water depth and the presence of an obstacle appear to be necessary conditions, they alone or together are not sufficient conditions to guarantee the generation of a rubble field. It also clearly illustrates the far-reaching effects of a grounded rubble field on the local ice regime.

Figure 26: Photograph showing the lack of a grounded rubble field along the SDC at the Paktoa C-60 site in March 2006 (photo A. Barker, NRC).

8. IMPLICATIONS FOR BEAUFORT ACTIVITIES

This paper has outlined several aspects related to grounded rubble fields in the Beaufort Sea. One of the objectives of the paper was to provide some qualitative information on how these rubble fields can affect marine operations, emergency evacuation systems, rescue operations and aid in reducing ice loads.

Table 3 summarizes the findings in this paper with an analysis of how they would affect these offshore operations. Note that this analysis is cursory to highlight possible impacts. A more detailed, thorough analysis should be performed for a design of a platform at a specific location. This table presents a starting point for this analysis.

Table 3: Implications of rubble field characteristics on offshore operations

Rubble Characteristics	Marine Operations	Emergency Evacuation	Ice Loads
Unable to reliably predict their formation	Must be tailored to be able to deal both the presence and absence of a rubble field	Cannot be reliably used for effective emergency evacuation systems. But in landfast ice, Evacuation Shelters (ES) should be possible. Cannot ignore possibility of extensive formation	Ice load reduction due to grounded rubble cannot be factored in with certainty, without intervening efforts to ensure formation (e.g. spray ice, operational plans to move ice, etc.)
Rubble forms early in season and once grounded, generally remains in place throughout the rest of the winter season	If year-round access to the platform is required, must keep active ice management throughout the early part of the season to remove rubble (see Figure 27)	Once stable in landfast ice, can be used to house an ES (see Barker et al. 2007, 2009b)	Ice loads mainly present during the freeze-up season with low loads throughout the winter months
Rubble fields generally have an elongated shape	Must be accounted for in designs for platform access by ensuring that loading-offloading equipment is on the side which historically has less grounded rubble	Will limit the locations of topsides evacuation systems placement, generally to the long side (but this is often in the predominate wind or storm direction) so this must be considered if sour gas present.	Generally no influence since even small amounts of grounded rubble effectively lower platform loads
Once formed, the duration of the rubble field can be reasonably deduced.	Can reasonably schedule delivery of supplies	Signals the change-over to an new ice regime which likely will change the mode of evacuation from the platform	Once rubble is gone, platform susceptible to impact of isolated floes so detailed floe tracking will become necessary
Sail heights up to 10 to 15 m are possible in the grounded rubble	Large amounts of ice management will be required to remove rubble if year-round marine access is planned	Must prepare groomed egress routes to an ES or to the edge of the rubble field (if personnel to be picked up by an evacuation vessel) – (see Spencer et al. 2007)	No influence on ice loads. Factors into rubble resistance to displacement by moving ice
Rubble fields can have large areas (up to 1 km^2) and long axis up to 1 km long	Large amounts of ice management will be required to remove rubble if year-round marine access is planned for all sides	This provides ample space for ES but longer egress trails must be groomed for edge pick-up of personnel by an evacuation vessel	No influence on ice loads. Factors into rubble resistance to displacement by moving ice

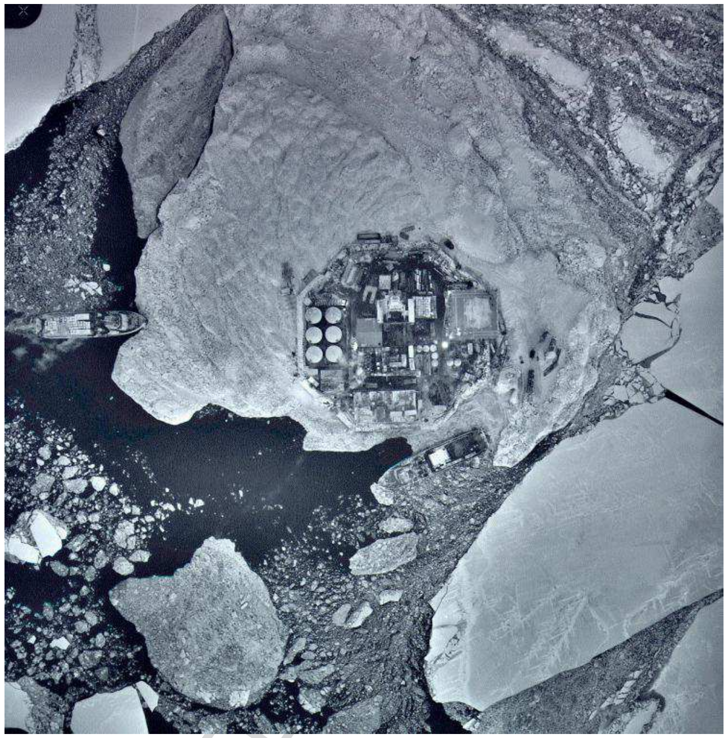


Figure 27: Quasi-stable rubble field surrounding the Tarsiut caissons (Tarsiut N-44 drill site) in late autumn, in the Canadian Beaufort Sea. Note the marine support maintaining a clear passage way to the platform, while leaving rubble to provide a location for supplies, evacuation canisters and, eventually, a relief-well drill pad on the ice surface (photo courtesy Gulf Canada Resources Ltd.).

9. SUMMARY

This paper has examined historical and recent grounded rubble fields in the Canadian and American Beaufort Sea. It used data from previous Beaufort Sea island and caisson sites, as well as data from ice rubble pile-ups on subsea remnant berms, to paint a clear overview of the size, shape and aerial extent of grounded rubble fields. The rubble fields were examined in terms of their likelihood of formation, development, duration, sail heights, size and anisotropy, and aerial extent. There is considerable scatter in the data and due to the many factors involved in the creation of a grounded rubble field, definitive trends could not be developed.

The results of this analysis presented a summary of relevant rubble field relationships, such as:

- There was a likelihood of occurrence of 76% (caisson) and 87% (island) when a structure was present in water depths from 5 to 32 m;

- A polynomial upper bound line for rubble field duration (D_R) versus water depth (d_w) was $D_R = -0.25\ d_w^2 + 0.92\ d_w + 277$ where D_R is duration in days and d_w is water depth in metres;
- An approximate upper bound estimate of the area of a rubble field (A_{max}) based upon water depth (d_w) was $A_{max} = -0.0034\ d_w^2 + 0.12\ d_w + 0.068$ for $2\ m < d_w < 20\ m$ where A_{max} is in square kilometres and d_w is in metres. For water depths between 20 m and 32 m, the maximum area observed was 0.3 km^2.

The potentially significant implications of rubble field formation were also examined, in the contexts of marine operations, emergency evacuation systems and design for platform ice loads. The presence of such fields around a drill site can have both positive and negative ramifications, both of which need to be assessed during planning phases, in order to ensure that the advantages of grounded rubble fields are maximized and the disadvantages are minimized.

This analysis indicated that there are many necessary factors for rubble fields to form in regions such as the Beaufort Sea. However there is no one sufficient condition that will ensure that this rubble formation occurs. In the absence of such a condition, probability of occurrence tables and upper bound values based upon empirical data can provide guidance to designers and regulators involved with nearshore Arctic drilling, to support their planning and design processes, as well as their potential operational requirements. However, the designers and operators must be cognisant of the fact that although the probability analysis may indicate a rubble field will likely form, the data shows that this is not always the case. Further, the data shows wide variability in rubble size and shape, and these extremes should also be factored in to design and operational planning.

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