Geohazard investigations of permafrost and gas hydrates in the outer shelf and upper slope of the Canadian Beaufort Sea

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Building on the early work of J. Ross Mackay, this paper reviews the state of knowledge of offshore permafrost and gas hydrates beneath the Beaufort Shelf. A thick and extensive interval of transgressed terrestrial permafrost is present beneath the central shelf, warming seaward and pinching out at 90-100 m water depth near the shelf-slope break. A complex gas hydrate regime is recognised with possible intrapermafrost and subpermafrost gas hydrate beneath the shelf, a zone with no gas hydrates at the shelf-slope transition, and a marine gas hydrate zone where water depths are greater than ~270 m. We believe that changes induced by transgression (formation and thawing of ground ice and gas hydrate) have created unique porous media conditions in this setting that can influence geohazards and active geologic processes. To this end we have undertaken a variety of multidisciplinary field investigations that have included marine geophysics, high resolution sea bed mapping, sediment coring, sea floor moorings and ROV dives.

RÉSUMÉ
Se basant sur les premiers travaux de J. Ross Mackay, ce manuscrit fait la synthèse de l'état des connaissances sur le pergélisol sous-marin et sur les hydrates de gaz se situant sous le plateau continental de la mer Beaufort. Une vaste zone épaisse de pergélisol terrestre formée lors d'une transgression marine est présente sous la région centrale du plateau. Vers le large, le pergélisol se réchauffe et s'amincit progressivement jusqu'à disparaitre à des profondeurs d'eau de 90-100 m, près de la transition plateau-pente continentale. Un régime complexe d'hydrates de gaz est documenté avec la présence possible d'hydrates de gaz intra et subpergélisol sous le plateau, une zone sans hydrates de gaz à la transition plateau-pente continentale, et enfin une zone d'hydrates de gaz marins là où les profondeurs d'eau sont supérieures à ~270 m. Nous croyons que les changements résultant de la transgression marine (soit la formation et la fonte de glace de sol et des hydrates de gaz) ont créé les conditions d'un milieu poreux unique qui peuvent influencer les risques géologiques et les processus géologiques actifs. Nous avons donc entrepris un programme multidisciplinaire de recherche sur le terrain qui inclut la géophysique marine, la cartographie de fonds marins à haute résolution, le carottage de sédiments, des systèmes d'amarrage aux fonds marins, et des plongées avec un véhicule sous-marin téléguidé.

1 INTRODUCTION

In his 1972 publication in the Canadian Journal of Earth Sciences (Mackay 1972), J. Ross Mackay made a milestone scientific contribution that substantially advanced the understanding of the factors controlling the distribution, origin, and thermal regime of offshore permafrost beneath Arctic shelves. Mackay proposed that two types of permafrost were widespread beneath the Beaufort Shelf; subsea permafrost that was in equilibrium with negative seabottom temperatures, and submerged terrestrial permafrost which is in disequilibrium with seabottom temperatures. He also pointed out that in certain settings, a thin active layer was likely present in the offshore near the sea bed. The concepts proposed by Mackay were quickly accepted by industry, which at the time was actively undertaking hydrocarbon exploration in the area. Mackay's work helped to foster several decades of close collaboration between industry, government, and academic scientists. This collaboration led to the first geothermal measurements and well log interpretations that documented and mapped a thick body of offshore permafrost beneath the Beaufort Shelf. Geophysical indicators of the occurrence of offshore permafrost were also appraised and industry conducted a number of geotechnical coring studies.

The recent sale of offshore leases in the outer shelf and upper slope has stimulated a new phase of exploration and scientific investigations in the Canadian Beaufort Sea. In the past five years, we have had the opportunity to undertake research expeditions to investigate permafrost and gas hydrates in the transitional area from the outer shelf to upper slope. Following the example of Mackay, and fundamental to our science, we have developed testable hypotheses to guide our fieldwork. To this end we have carried out geothermal modeling to provide a conceptual model of the present geothermal setting of the southern Beaufort Sea and consider changes that may have occurred in the permafrost and gas hydrate regime as a consequence of Holocene marine transgression. This paper briefly reviews the regional setting of this area and provides an overview of our approach to studying geohazards.

2 PERMAFROST AND GAS HYDRATE SETTING OF BEAUFORT SHELF AND UPPER SLOPE

Throughout the past two million years, shelf areas of the Arctic Ocean have experienced substantial changes in surface temperatures. During periods of low sea level associated with continental glaciations, many areas were terrestrially exposed and experienced mean annual air temperatures that were often -20ºC, or colder (Brigham and Miller 1983). These cold temperatures caused aggradation of thick ice-bonded permafrost occurrences and established substantial thicknesses of subsurface sediments with pressure and temperature conditions conducive for the formation of permafrost gas hydrate. In contrast, sea level rise during interglacial periods resulted in marine transgression that inundated coastal areas with warm seawater. Mackay (1972) recognised that because heat diffuses slowly it can take thousands of years after transgression to fully melt the subsurface ice-bonded permafrost. Indeed, the processes associated with the Holocene marine transgression continue today with ongoing warming and thawing of thick permafrost and gas hydrate occurrences beneath shelf areas of the Arctic Ocean. Figure 1 illustrates the geothermal, permafrost and gas hydrate regime of a typical transgressed permafrost setting and the contrasting marine geothermal setting of the upper slope.

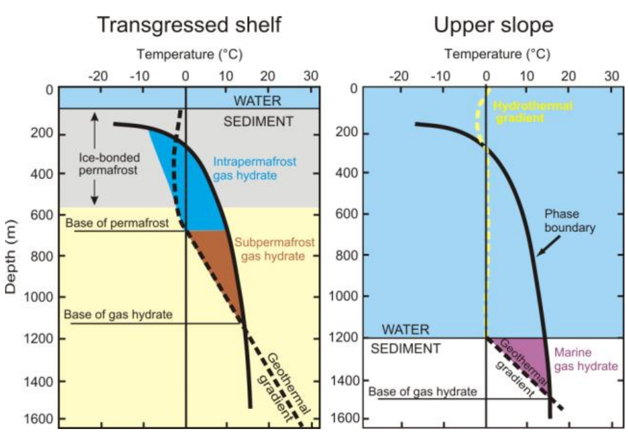

Figure 1. Plots showing examples of contrasting geothermal setting of shelf vs slope. Left panel depicts permafrost and permafrost gas hydrate where transgression has submerged terrestrial permafrost (note near-isothermal section within the permafrost interval). Right panel depicts marine geothermal setting typical for the Beaufort Sea and marine gas hydrate stability as expected in the deep water setting of the upper slope.

The scientific underpinning for our research is based on establishing reasonable geologic hypotheses for the geothermal and porous media setting of the shelf and the contrasting setting associated with the upper continental slope. Field programs were designed to characterize the geology and geologic processes as a basis to evaluate these hypotheses. Geothermal modeling is a particularly effective way to assess the evolution of ground temperatures during marine transgression (Taylor et al. 1996; 2005; 2013). To evaluate the lateral changes in the geothermal setting of the transgressed Beaufort shelf during the last 125,000 years we applied worldwide sea level trends as well as terrestrial and marine ground temperature estimates in a numerical model (Taylor et al. 2013). This scenario is considered a reasonable portrayal of the geologic history of areas of the Beaufort Shelf that were not glaciated. As shown in a simplified view on Figure 2, the model is particularly useful in defining the geothermal basis for permafrost occurrence beneath the shelf and the conditions where permafrost gas hydrate could be stable. A thick and continuous body of permafrost, with near isothermal conditions is predicted from the coast to approximately 60 m water depth (~80 km offshore). The permafrost body then warms and thins seaward (~80-120 km offshore), until it pinches out at about 90-100 m water depth near the shelf-slope break.

The geothermal conditions for gas hydrate stability are complex with a permafrost gas hydrate interval beneath the shelf pinching out at the shelf break coincident with the permafrost boundary. Geothermal conditions for stable marine gas hydrate are predicted further offshore, but a notable gap in gas hydrate stability is inferred from the shelf break to approximately 270 m water depth.

We have chosen not to model a scenario for glacial ice cover on the shelf as ground surface temperatures near freezing may have persisted during glaciation, limiting the formation of a significant ice bonded permafrost interval. While there is no published evidence to suggest the shelf offshore of the Tuktoyaktuk Peninsula was glaciated, recent interpretation of reflection seismic data suggest that two glacial tills may be present in the Mackenzie Trough area (Batchelor et al. 2012).

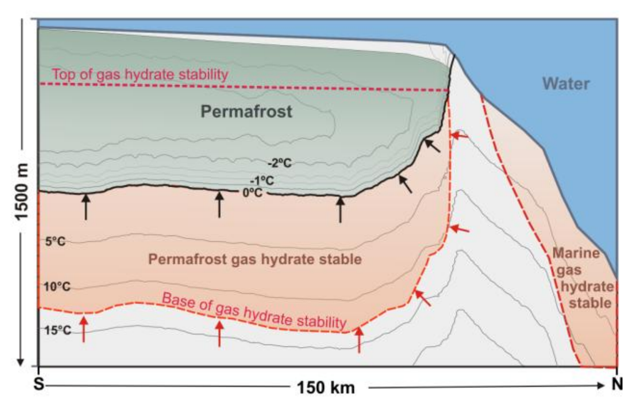

Figure 2. Cross-section portrayal of ground temperature regime and distribution of permafrost and gas hydrate realms in the shelf and upper slope of the Beaufort Sea. The scenario presented is based on geothermal modeling presented in Taylor et al. (2013) along the transect shown on Figure 3. The arrows show the intervals where substantial changes in the base of permafrost and gas hydrate stability were modelled.

3 POROUS MEDIA CONSIDERATIONS

3.1 Ice-bonded Permafrost

While permafrost is formally defined on a geothermal basis as sediments that have mean annual temperature below 0^{o} C, the critical consideration in terms of geologic processes and engineering properties relates to the presence or absence of ice within the sediment matrix (commonly referred to as ice-bonding). In a setting like the Beaufort Shelf, where sediments have experienced a varied ground surface history, both the formation and degradation of ice-bonding must be considered. The geothermal modeling has provided us with a basis to predict some the sediment processes that may have occurred. Because permafrost aggradation occurred as a consequence of very cold terrestrial ground temperatures, pore ice formed in nearly all of the permafrost interval substantially increasing the sediment strength, impeding conventional sediment consolidation and reducing sediment permeability. Under some circumstances, often associated with fine-grained sediments, ice in excess of the pore space was likely formed. The main geotechnical consideration as permafrost warms relates to the thawing of ground ice which substantially weakens the affected sediments as a consequence of loss of particle to particle bonding. Where the ground ice volume is substantive, the release of excess water can also increase sediment pore pressure reducing the effective stress.

While the geothermal model presented in Figure 2 is quite simplified, the inferred porous media response to transgression is intriguing. Two environments with the potential for significant sediment response can be anticipated. As shown by the arrows on Figure 2 an upward shift in the base of permafrost is predicted with consequent thawing of ground ice and liberation of excess pore waters. Less obvious from the model are the effects of warming of the permafrost interval from the coast to the shelf break. Within the range of temperatures inferred (-2.5 to 0°C) sediments with different grain size or pore water salinity can be expected to respond quite differently. Whereas fine-grained saline sediments can thaw completely within this temperature range, fresh water sands may stay ice-bonded. This reveals the very important consideration of geology, with warming of the permafrost creating the possibility for differential permafrost response to warming in sand vs silt vs clay. The complexities of these effects are challenging to model without detailed subsurface information.

3.2 Gas Hydrates

Methane gas hydrate, a solid form of natural gas, has been inferred in many offshore exploration wells primarily on the basis of well log response and indications of subsurface gas (Judge 1982; Majorowicz and Osadetz 2001; Smith and Judge 1993; Weaver and Stewart 1982; Weaver 2013). In order for gas hydrate to occur in sediments, there needs to be cold formation temperatures, moderate pressure, and a suitable geologic setting (presence of pore water and natural gas as well as suitable porous media nucleation sites). In shelf areas the gas hydrate stability field is controlled by the thermal regime established by the transgressed permafrost body (Fig. 2). Intrapermafrost gas hydrate (Dallimore and Collett 1995) may occur from ~250 m depth to the thermally defined base of permafrost. Conditions occur in this setting for the co-existence of gas hydrate and sediment pore ice. A substantial sub-permafrost gas hydrate interval is also well defined. Similar to the permafrost realm, the most significant changes in the gas hydrate regime can be expected at the base of hydrate stability and the base of permafrost. Smaller but potentially significant changes may also occur at the top of permafrost. As discussed in a recent paper by Weaver (2013) changes in the gas hydrate regime can induce significant changes in the porous media conditions of affected sediments. These relate gas hydrate degradation, which dramatically reduces sediment strength, and the potential for the release of both gas and water creating sediment over-pressure. This has the potential consequence of dramatically reducing effective stress conditions or inducing potential for water or gas migration.

In the upper continental slope where water depths are greater than ~270 m, geologic conditions conducive for the formation of conventional marine gas hydrate can be anticipated.

4 REGIONAL PERMAFROST AND GAS HYDRATE OCCURRENCE

The legacy of hydrocarbon exploration data collected by industry in the 1980s and 1990s provided researchers with a basis for the appraisal of regional permafrost occurrence beneath the Beaufort Shelf. The efforts of Bernard Pelletier, a contemporary of J. Ross Mackay, are particularly noteworthy as his 1987 Marine Sciences Atlas of the Beaufort Sea (Pelletier 1987) includes many substantial compilation efforts (i.e., O'Connor and Blasco 1987; Judge et al. 1987; Pullan et al. 1987). Figure 3 provides a summary of some of this work by overlaying basedata from determinations of permafrost extent from seismic refraction studies (Pullan et al. 1987) and well log interpretations (Judge et al. 1987) with subsequent revisions by Smith and Judge (1993) and Hu et al. (2013).

5 DISCUSSION

5.1 Geohazards Related to Exploratory Drilling

As reviewed by Collett and Dallimore (2002), operators undertaking exploratory drilling in the Arctic have encountered numerous problems advancing well bores through the permafrost and permafrost gas hydrate interval. Given our interest in assessing porous media conditions in the outer shelf area, we have reviewed the well history reports and well log data for 16 wells drilled in the Beaufort Sea in the mid-shelf area to the outer shelf (water depths from ~35-65 m). While many of the drilling problems in the upper kilometre were managed adequately with the operational procedures in place at the time, the Immiugak N-05 well experienced a blowout at ~500 m depth which necessitated evacuation of personnel from the drill rig and eventual abandonment of the well site (COGLA 1989).

Our preliminary appraisal of the well history reports suggest that the porous media changes associated with marine transgression of terrestrial permafrost and gas hydrates (section 3 of this paper) can

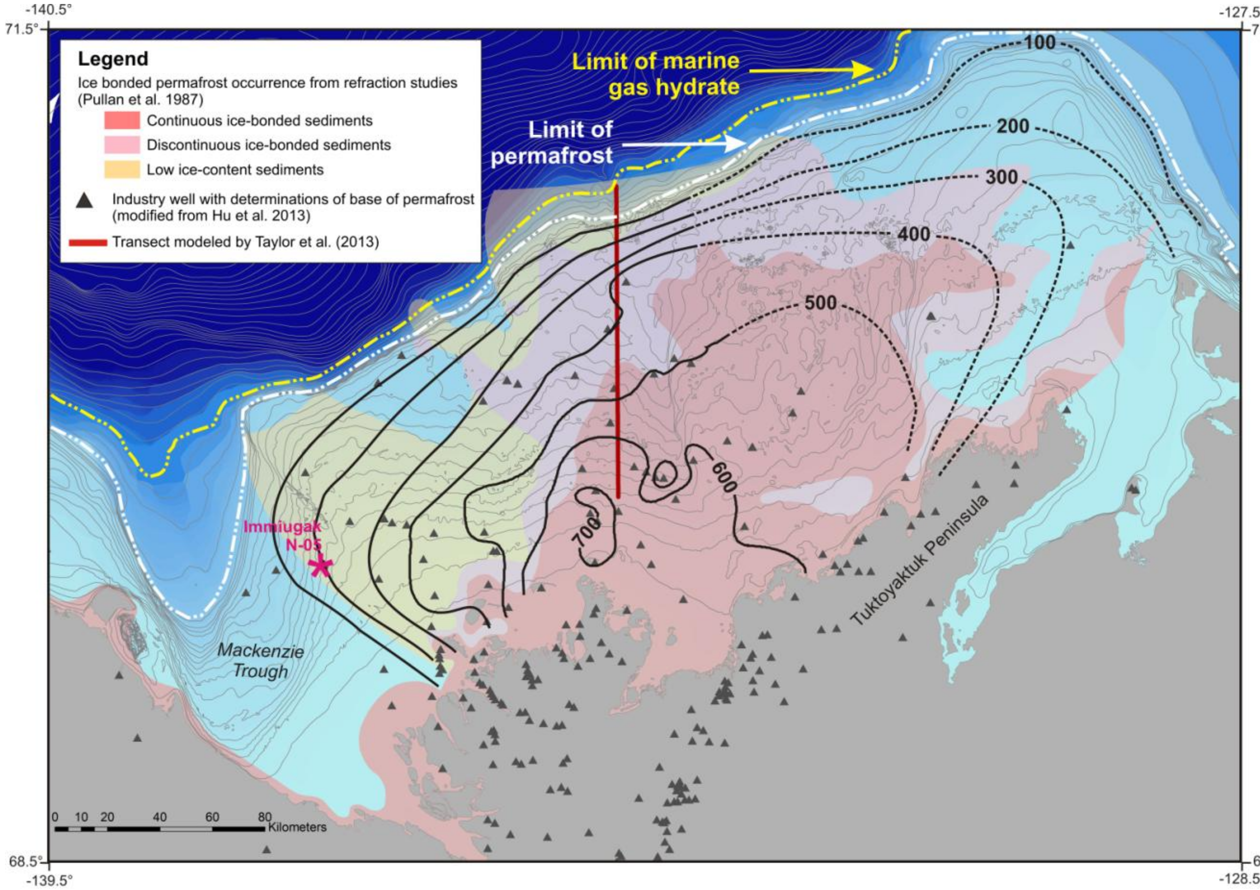

Figure 3. Map depicting permafrost features in the southern Beaufort Sea. Legend shows sources of historical data and contour lines indicate the approximate base of ice-bonded permafrost in metres (solid vs dashed line indicating level of confidence in interpretations). Given that historical data are limited in the vicinity of the shelf edge and upper slope, we have guided our interpretations of limits of offshore permafrost and marine gas hydrate stability based on our geothermal model along the N-S transect shown in red (Taylor et al. 2013).

result in unique drilling challenges. Not surprisingly, formation gas, as observed as high mud gas concentrations or short duration gas kicks, was commonly encountered. Most gas occurrences were observed beneath the base of the ice-bonded permafrost interval or deeper, perhaps associated with the base of the subpermafrost gas hydrate interval. However, three observations of formation gas were observed within the ice-bonded interval suggesting the possibility of intrapermafrost gas hydrates. Drilling problems were often associated with gas occurrences and included tight hole conditions, oversized hole and some incidents of loss of circulation. The incident review of the Immiugak N-05 well (COGLA 1989) revealed that the blowout occurred beneath the ice-bonded permafrost interval. While the report alluded to gas hydrates being a possible cause, it is more likely in our opinion that the event was a free gas release possibly associated with perturbed gas hydrates at the base of the gas hydrate stability field (see Fig. 2).

5.2 Unique Geologic Processes

Our field research has focussed largely on the shelf-slope transition area where there are a rather striking number of sea bed features that may be controlled, in part, by processes generated deeper in the substrate. There is mounting evidence of ground water and free gas migration from depth (e.g. Hughes Clarke et al. 2009; Paull et al. 2011). In the central and outer shelf area, sea bed instability relating to degassing of permafrost gas hydrates has been proposed as a factor affecting the formation of isolated pingo-like features (PLF) (Paull et al. 2007). Evidence for regional gas release associated with possible sea bed deformation has also been identified at the shelf edge (Hughes Clarke 2009) and in the upper slope distinct mud volcano features are actively degassing (Paull et al. 2011). Large submarine landslides, some of which have headwalls near the shelf-slope boundary have also been identified (Saint-Ange et al. 2014). The failure modes of these features may also be influenced by deeper geologic processes generated by thawing of shelf edge permafrost or gas hydrate dissociation.

5.3 Ongoing Geohazard Field Investigations

The portrayals of possible permafrost and gas hydrate distribution and response to transgression shown in Figures 2 and 3 have been particularly important in our design of recent field investigations. In 2013 and 2014 we conducted reflection seismic studies onboard the Korean ice breaker *RV Araon* (Jin et al. 2015; Riedel et al. 2014) focusing on the shelf-slope transitional zones near our modeled permafrost transect. These studies allowed us to verify the determinations of the boundaries of the permafrost zones in the outer shelf mapped by Pullan et al. (1987) based on industry seismic data. We also observed the abrupt pinch-out of shelf permafrost at 90-100 m water depth near the shelf-slope break as portrayed in Figure 2. In three recent cruises onboard the *CCGS Sir Wilfrid Laurier* we have focused on studying geologic processes at the sea floor including shelf edge landslides, evidence of sea floor instability and upper slope mud volcanism. Experiments have been designed to document gas release and core studies have focused on developing a seismostratigraphic model that considers the strength and geothermal setting of near surface sediments.

6 CONCLUSIONS

In response to a new phase of exploration in the outer shelf and upper slope areas of the Canadian Beaufort Sea, we have undertaken an appraisal of the regional permafrost and gas hydrate setting by examining historical data, undertaking new geothermal modeling and advancing multidisciplinary field studies. As recognised by Mackay (1972), a thick and extensive interval of transgressed terrestrial permafrost is present beneath the central shelf, warming seaward and pinching out at 90-100 m water depths near the shelf-slope break. A complex gas hydrate regime is recognised with possible intrapermafrost and subpermafrost gas hydrate beneath the shelf, a zone with no gas hydrates at the shelf-slope transition, and a marine gas hydrate interval where water depths are greater than ~270 m. Review of drilling information and well logs for hydrocarbon exploration wells drilled in the central and outer shelf suggest drilling problems and at least one blowout may be related to the complex porous media environment in this setting. Our field studies have endeavored to establish linkages between active geologic processes such as landslides and sea floor instability and deeper processes related to changes in the permafrost and gas hydrate realm.

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