



Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates

Charles K. Paull,¹ William Ussler III,¹ Scott R. Dallimore,²
 Steve M. Blasco,³ Thomas D. Lorenson,⁴ Humfrey Melling,⁵
 Barbara E. Medioli,⁶ F. Mark Nixon,⁶ and Fiona A. McLaughlin⁵

Received 23 August 2006; revised 15 November 2006; accepted 20 November 2006; published 5 January 2007.

[1] The Arctic shelf is currently undergoing dramatic thermal changes caused by the continued warming associated with Holocene sea level rise. During this transgression, comparatively warm waters have flooded over cold permafrost areas of the Arctic Shelf. A thermal pulse of more than 10°C is still propagating down into the submerged sediment and may be decomposing gas hydrate as well as permafrost. A search for gas venting on the Arctic seafloor focused on pingo-like-features (PLFs) on the Beaufort Sea Shelf because they may be a direct consequence of gas hydrate decomposition at depth. Vibracores collected from eight PLFs had systematically elevated methane concentrations. ROV observations revealed streams of methane-rich gas bubbles coming from the crests of PLFs. We offer a scenario of how PLFs may be growing offshore as a result of gas pressure associated with gas hydrate decomposition. **Citation:** Paull, C. K., W. Ussler III, S. R. Dallimore, S. M. Blasco, T. D. Lorenson, H. Melling, B. E. Medioli, F. M. Nixon, and F. A. McLaughlin (2007), Origin of pingo-like features on the Beaufort Sea shelf and their possible relationship to decomposing methane gas hydrates, *Geophys. Res. Lett.*, 34, L01603, doi:10.1029/2006GL027977.

1. Introduction

[2] Gas hydrate is a solid phase comprised of water and low-molecular-weight gases, usually methane, that forms within sediments under conditions of low temperature, high pressure and adequate gas concentration. On a worldwide basis, gas hydrates have been identified in deep water marine settings and in the Arctic associated with areas with thick permafrost [Kvenvolden and Lorenson, 2001]. Because in nature these deposits exist close to their pressure-temperature equilibrium, a modest increase in formation temperature, or decrease in pressure may induce decomposition. In this case formerly gas-hydrate-bound methane will be released with the potential for gas migration to the surface, and ultimately the atmosphere. Because methane is a potent greenhouse gas, the fate of decomposing gas hydrate is of considerable interest in global warming scenarios.

[3] This paper focuses on evidence of degassing from decomposing Arctic gas hydrate deposits beneath the southern Beaufort Shelf. This area is arguably one of the most gas-hydrate-rich regions in the Arctic [Bily and Dick, 1974; Judge, 1982; Weaver and Stewart, 1982]. During the Pleistocene much of the Beaufort Shelf was an emergent, unglaciated coastal plain exposed to very cold mean annual surface temperatures [Brigham and Miller, 1983], which aggraded thick permafrost. The geothermal regime is conditioned by this permafrost interval and as a result methane hydrate may be theoretically stable to depths as great as 1500 m [Pelletier, 1988]. Marine transgression during the Holocene has caused much of the Beaufort Shelf to be inundated by relatively warm marine and estuarine waters. This has imposed a step change from mean annual land surface temperatures perhaps as low as -20°C during glacial times [Brigham and Miller, 1983] to present bottom water temperatures which are no colder than -1.8°C. The consequence of this warming is to reduce the vertical extent of both permafrost and the stability zone in which gas-hydrate-bearing sediments may occur. Because of the slow process of heat conduction, the transient effects of the transgression are still occurring [Lachenbruch et al., 1982; Taylor, 1991; Taylor et al., 2005]. Thus, methane gas release, if it is occurring, should be continuing today.

[4] Little is known about the fate of methane released from decomposing gas hydrate under the Arctic Shelf [e.g., Lorenson and Kvenvolden, 1997]. Our research was carried out in the offshore areas adjacent to the Tuktoyaktuk Peninsula [Blasco et al., 1990], an area where many distinct ovoid and concentric-shaped positive relief features, referred to as pingo-like-features or PLFs have been identified on the sea floor. Our supposition was that the PLFs might be formed from methane released from decomposing gas hydrates at depth.

[5] Early researchers studying the submarine geology of the Beaufort Shelf used the name PLF to describe bathymetric features similar to terrestrial pingos observed along the coastal plain in this area [Shearer et al., 1971]. Terrestrial pingos are conical, ice-cored hills or mounds [Mackay, 1998, and references therein] commonly 10–40 m in height and 100 m or more in diameter. The coastal plain adjacent to the Beaufort Sea contains over 1350 pingos, most of which are thought to have formed within a closed system as permafrost aggraded into previously thawed lake basins. The positive relief of most terrestrial pingos is almost entirely attributed to expansion associated with ground ice formation [Mackay, 1998, and references therein]. Submarine PLFs are similar in size to the largest terrestrial pingos, rising as shallow as 18 m below the sea surface. Some, but

¹Monterey Bay Aquarium Research Institute, Moss Landing, California, USA.

²Natural Resources Canada, Sidney, British Columbia, Canada.

³Natural Resources Canada, Dartmouth, Nova Scotia, Canada.

⁴U.S. Geological Survey, Menlo Park, California, USA.

⁵Fisheries and Oceans Canada, Sidney, British Columbia, Canada.

⁶Natural Resources Canada, Ottawa, Ontario, Canada.

not all, PLFs emanate from within roughly circular, 1–2 km diameter, 10- to 20-m deep bathymetric depressions, referred to here as moats.

[6] Previous geologic investigations of PLFs on the Beaufort Shelf have focused mainly on mapping their occurrence and characterizing their geomorphic expressions using marine imaging techniques [e.g., Shearer *et al.*, 1971; Pelletier, 1988]. While little geochemical data is available, sediment coring at several PLFs shows that shallow sediments within the PLFs features are frozen at shallow depth with visible freshwater ice [Yorath *et al.*, 1971; Poley, 1982]. Debate has ensued as to the origin of PLFs with suggestions that they may be transgressed terrestrial pingos or that they may have formed in a marine environment since transgression in a similar manner to mud volcanoes [Kopf, 2002].

2. Methods

[7] Multidisciplinary field investigations were undertaken during the fall of 2003 using Canadian Coast Guard (CCG) vessels. The CCG *Nahidik* was used primarily for multi-beam bathymetric and seismic surveys while the CCG *Sir Wilfrid Laurier* was used to collect sediment cores using a Rossfelder vibracorer. In total 81 cores, up to 5.63 m long, were collected from around 8 PLFs (14 cores at the Kaglulik feature, 19 cores at Admirals Finger Pingos A, B, and C, 13 cores at Kopanoar, and 3 cores from two PLFs named the Pingo Z complex; Figure 1, see auxiliary material¹). Background cores were taken along a transect across the shelf and other locations as sea ice and weather allowed. Cores were quickly assessed after recovery for the presence of ground ice and pore waters were extracted from subsamples at 50 cm or 1 m intervals. Sediment samples were canned for headspace gas composition measurements. Chloride and sulfate concentrations were analyzed shipboard using a Dionex DX-100 ion chromatograph and subsamples were preserved for shore-based analyses. Methane concentrations were measured shipboard using a Shimadzu mini-2 gas chromatograph equipped with a flame-ionization detector. Short dives with a Phantom ROV were conducted on the crests of Kaglulik, Kopanoar, Admirals Finger B and the westernmost of the Pingo Z complex. An overturned funnel connected by tubing that ran along the ROV's umbilical was used to collect gas samples at one site.

[8] A post-cruise laboratory program included detailed sedimentologic and ground ice descriptions and geochemical studies. Dating of disseminated organic matter in sediment samples were performed at the Center for Accelerator Mass Spectrometry (AMS) facility at Lawrence Livermore National Laboratories, Livermore, CA. AMS dating of shell samples was undertaken at the University of California, Irvine. Headspace gas samples were analyzed for methane to heptane concentration using a Shimadzu GC14-A gas chromatograph at the USGS, Menlo Park, CA. Carbon isotopic composition of hydrocarbon gases was determined by GC-IR-MS at the University of Victoria, British Columbia. Measurements of the ¹⁴C content of methane

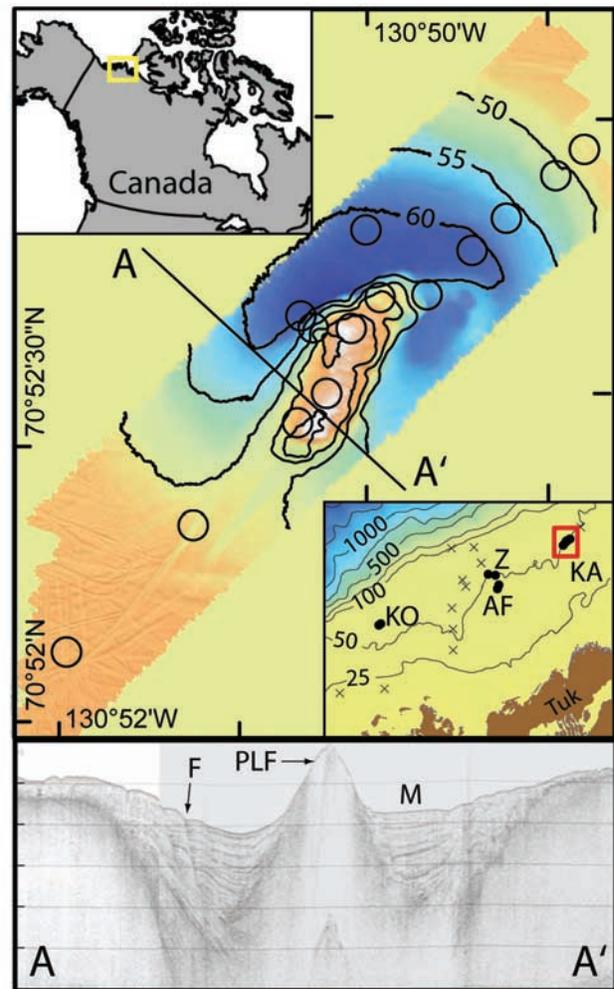


Figure 1. (top) A strip of multibeam data, core locations (open circles), and (bottom) a seismic profile (A-A') associated with the Kaglulik PLF. Note the PLF is surrounded by a collapse moat (M) filled with layered sediments containing normal faults (F) in Figure 1 (bottom). General location of the study area is indicated with the yellow box within the regional area in Figure 1 (top, left inset). A map of the Beaufort Sea Shelf shows locations of vibracoring sites in Figure 1 (top, right inset). Dots indicate PLFs at which multiple cores were taken, crosses indicate background shelf cores, and the red box outlines the area covered with more detailed map of Kaglulik PLF.

emanating from the top of Pingo Z were made by Zymax Forensics, San Luis Obispo, CA.

3. Results

[9] Multibeam bathymetric data and seismic reflection profiles have allowed for detailed assessment of the morphology and shallow stratigraphy of PLFs. In seismic profiles PLFs lack internal structure and are surrounded by negative relief moats. The moats are underlain by layered sediments which fan downward toward the PLF and outline a basin that is more than three times as deep as the present moat. The sediments that fill the basin are cut by small

¹Auxiliary materials are available at <ftp://ftp.agu.org/apend/g/2006g1027977>.

normal faults (Figure 1), suggesting increased subsidence towards the basin interior.

[10] ROV dives with comprehensive spatial coverage over the PLFs were carried out at Pingo Z and Admirals Finger Pingo B. Gas release was seen from the crest of these PLFs with discrete bubbles emanating from ~ 5 cm diameter holes. Multiple sites were visible in the ~ 10 m² ROV field of view. No shimmering water or other evidence of flowing water, indications of exotic fauna, bacterial mats, or authigenic carbonates were seen. The ROV dives and multibeam images show that PLF crests are crossed by linear grooves apparently associated with ice scour [Blasco *et al.*, 1998]. A gas sample was collected by ROV from a bubble stream on the crest of Pingo Z in 18 m of water. By timing the filling rate of an inverted funnel a flux rate of ~ 5 L hr⁻¹ was estimated. The gas is predominantly methane ($\delta^{13}\text{C} = -76.6\text{‰}$ and $\delta\text{D} = -179\text{‰}$), which is similar to the other gas samples from PLF, and contains only 0.93 percent modern carbon (pMC).

[11] Background shelf cores were typically very stiff, interbedded silts and fine- to medium-grained sands. In contrast, sediments recovered from moat cores are primarily soft, organic-rich clayey silts, which are finely laminated to massive with heavily bioturbated, shell-rich horizons. A few specimens of bivalves of marine origin were encountered within the moat sediments and provided ¹⁴C ages that range from 1,000 to 4,475 yrs BP ($n = 13$). The ¹⁴C content of disseminated organic matter in moat cores ranges from 34.5 to 7.7 pMC (8,545 to 20,620 yrs BP, $n = 7$).

[12] Sediments from PLFs are predominantly stiff silt-rich clays with little evidence of primary sedimentary structures or grain size variation and are remarkably distinct from either those on the surrounding shelf or within the moat. The physical texture was dominated by the occurrence of ground ice, which was observed at shallow depth in every PLF core. Ice occurred as small isolated nodules that were very apparent in freshly cut cores. Some nodules were up to 8 cm, although most were 1 to 5 mm across. When extracted from the sediment, these ice crystals were observed to be transparent. Sediment thawing created an unusual distorted sediment structure with irregular open voids similar to the sediment degassing texture observed in deep-sea cores [Paull and Ussler, 2001]. Visual estimates suggest the volumetric ice content in PLF crest cores was between 10 and 30%, and perhaps more in some samples. The ¹⁴C content of disseminated organic matter from the PLF crests ranges from 1.9 to 0.16 pMC (32,030 to 51,700 yrs BP, $n = 4$), suggesting a distinctly older age compared with the moat sediments. Because no pristine macrofossils were observed in PLF crest sediments, it is difficult to accurately constrain the age of deposition or the environment of deposition. However, it is reasonable to conclude that the crest sediments are significantly older than the moat sediments and they almost certainly pre-date the marine transgression [Hill *et al.*, 1993].

[13] Pore water chloride concentrations from PLF crests and flanks are variable (range 66 to 557 mM, mean $\pm 1\sigma = 358 \pm 129$ mM, $n = 87$), but distinctly fresher than those from PLF moats (487 to 607 mM, 518 ± 23 mM, $n = 67$) and surrounding shelf cores (405 to 521 mM; 502 ± 24 , $n = 33$). Meltwater captured from nine transparent ice crystals extracted from cores (some with adhering sediment)

contained from 1.0 to 76 mM chloride and from 0 to 0.4 mM sulfate, indicating the ice was composed of freshwater.

[14] Pore water sulfate was essentially depleted in the shallowest samples (1 or 0.5 mbsf) from the PLFs. In contrast, sulfate is present to 4 mbsf or more in moat and background cores. Methane concentrations were elevated in cores from the PLFs (up to 6 mM, median 380 μM ; $n = 76$), but modest in both the moat (median 0.1 μM ; $n = 50$) and background cores (median 0.8 μM ; $n = 43$). Shore-based determinations of methane to ethane ratios (C_1/C_2) ranged from 1,366 to 454,167 [mean $\pm 1\sigma = 83,000 \pm 137,000$ ($n = 23$)] and methane $\delta^{13}\text{C}$ values ranged from -99.4‰ to -72.1‰ (PDB, $n = 30$). Based on $\delta^{13}\text{C}$ and C_1/C_2 criteria, the pore waters contain primarily microbially produced methane [Bernard *et al.*, 1977].

4. Discussion

4.1. Marine Origin for PLFs

[15] Eight PLF sites were studied on the Beaufort Shelf, some more than a hundred kilometers distance from each other. The similarity of field observations, geological and geochemical data is striking and indicates that these features are forming in a similar manner.

[16] Because disseminated organic matter in the PLF sediments is distinctly older than that in the surrounding moat sediments, we conclude that the PLF sediments pre-date the latest marine transgression [Hill *et al.*, 1993]. The presence of pristine marine bivalve shells in growth position and sediment ages that post-date the local transgression indicate that the moat sediments formed in a marine environment since transgression. The sediment age and PLF morphology are consistent with the PLFs being constructional features formed from material extruded from depth. The moats indicate local subsidence of the sea floor has formed small basins surrounding the PLFs that collect recent marine deposition (Figure 1).

4.2. Model for the Formation of PLFs

[17] A broader question is whether the formation of PLFs is related to thermal equilibration of the modern seafloor with warmer, transgressing Arctic Ocean water. The temperature and pressures within the terrestrial permafrost environment that existed on the Arctic Shelf prior to transgression indicate that gas hydrate was stable at burial depths as shallow as 150 m. Intra-permafrost gas hydrate (gas hydrate within ice-bonded permafrost) has been observed in Mackenzie Delta core samples at 451 m depth and inferred, on the basis of *in situ* gas concentrations, at depths as shallow as 119 m [Dallimore and Collett, 1995]. Sub-permafrost gas hydrate has also been observed in many offshore exploration wells [Weaver and Stewart, 1982].

[18] We propose that gas release and bubble formation associated with decomposing gas hydrates at depth causes expansion of the sediment matrix that drives the upward extrusion of sediment to form the PLFs. Decomposition of intra-permafrost methane hydrate can supply substantial quantities of methane gas that generate large localized over-pressures. At the pressure and temperature conditions at the top of the gas hydrate stability field, gas hydrate will decompose into water ice and gas. Because ice has essentially the same density as gas hydrate, any gas released during decomposition will create gas expansion voids and

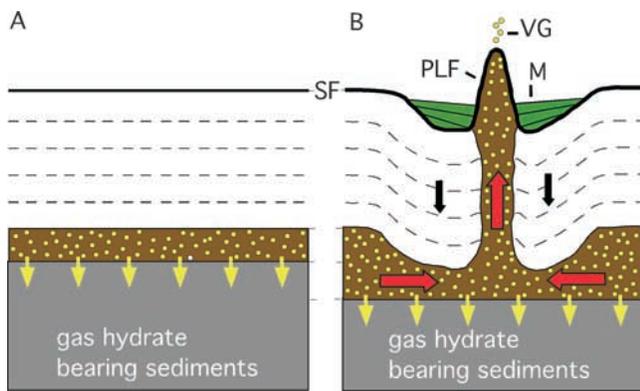


Figure 2. Schematic drawing outlining PLF and moat formation (M) associated with gas hydrate decomposition. (a) Cross-section of the permafrost-bearing Arctic seafloor (SF) (previously $<-10^{\circ}\text{C}$) after being transgressed by Arctic Ocean water ($<-1^{\circ}\text{C}$). As the subsurface warms, the top of the gas hydrate stability zone will move downward. Warming results in gas hydrate decomposition in a gradually thickening zone (brown), releasing gaseous methane into the sediments (yellow). Bubble formation associated with this phase change will create overpressured conditions. (b) Shows how material may flow (red arrows) both laterally and vertically in response to overpressure. Displaced sediments rise upward to form the PLF and allow the gas to vent (VG). As the pressure is dissipated through both the transfer of solids and degassing, subsidence in the area immediately surrounding the PLF (black arrows) creates the moat.

create local over pressures. Substantial overpressures will not be maintained because they will exceed the mechanical strength of shallow sediments. As pressures build within subsurface horizons, gas is forced through weaknesses in the overlying permafrost layers (Figure 2). Extruded material builds up on the seafloor to form the PLF. The observed amount of vertical displacement of the PLFs implies that material moves laterally within the over-pressured horizons to these zones of weakness, then upward to the seafloor. The source of the displaced material and pressure to drive the vertical expansion may extend over a much larger area than the PLF itself. As sediment migration and gas venting proceeds, subsurface volume losses ultimately result in the collapse and formation of moat basins around the sites of sediment expulsion (Figure 2).

[19] Several lines of evidence suggest that these processes may be operative in the formation of Beaufort Sea PLFs. Elevated formation pressures, up to 1.6 times hydrostatic conditions, have been measured in several offshore exploration wells, including the Kopanoar PLF site where sub-permafrost gas hydrate has been documented [Weaver and Stewart, 1982]. Venting of gas at PLF summits has been observed in video footage from ROV dives. High methane concentration and a rapid decrease in sulfate concentration in cores from PLF crests, contrasting with the absence of these features in moat and background sites, suggest a focused methane flux occurs through the PLF from a gas source at depth. The molecular composition and carbon isotope signature indicate that the venting gas is microbial and derived from pre-Holocene carbon sources. Gas with

similar chemistry occurs within the permafrost interval above deeper gas hydrate deposits in the Mackenzie Delta [Dallimore et al., 1999; Lorenson et al., 1999].

[20] The settling of the moats surrounding PLFs is also consistent with the dissociation of a laterally extensive gas hydrate deposit at depth. The zone of dissociating gas hydrate would initially experience an increase in pressure. With time, local stresses may exceed the overburden strength, causing sediment failure and vertical migration of gas and sediment within a conduit beneath the nascent PLF. As gas and sediment move upward, venting and heaving of the sea floor is expected. At the same time, the relief of stress within and export of material from the area surrounding the conduit would promote consolidation and in turn subsidence of the sea floor to form a moat basin (Figure 2).

[21] The occurrence of vesicular-textured freshwater ice comprising up to 30% of the volume of the PLF sediments is consistent with this model. The void shape and spacing is similar to gas exsolution voids observed in deep-sea cores [Paull and Ussler, 2001]. We suggest this ice texture, which has not been described in the literature, is consistent with an initial gasified sediment texture and subsequent infilling of the gas voids by freshwater ice.

[22] Upon warming caused by transgression, dissociation of intra-permafrost gas hydrate would first occur at the top of the methane hydrate stability field at temperatures substantially less than zero degrees Celsius. In the environment where the gas hydrate is dissociating, decomposing gas hydrate, free gas, and freshwater ice co-exist. For liquid water to occur immediately above the gas hydrate stability zone, substantial quantities of salt or other physical-chemical inhibitors are required. The occurrence of freshwater ice in the PLFs argues against the existence of brines in these sediments.

[23] Industry coring has confirmed that at Admirals Finger PLF, high ground ice contents extend to at least 40 m below the surface. With 30% volumetric ice fraction, the freezing of ground water within a gasified sediment fabric can account for approximately 12 m of heave at the sea floor. Because the relief of many PLFs is more than 12 m, additional material movement is needed to satisfy mass balance and the age of the material.

[24] The occurrence of freshwater ice within the shallow sediments sampled within the Beaufort Shelf is unique to the PLFs and not the surrounding sediments. This implies a subsurface source for the freshwater. Decomposition of gas hydrate within the permafrost would leave behind freshwater ice, because bottom water temperature data and thermal models indicate ground temperatures remain below the freezing point for freshwater for hundreds of meters below the seafloor. Thus, freshwater ice may be carried upwards in the extruded sediments. How water migrates into the gas voids and optically clear ice forms in the subsurface remains unclear.

[25] We propose that methane gas hydrate decomposition is a key factor in PLF formation (Figure 2). This process provides an explanation for the source of the observed venting methane, the uplifted, older freshwater-ice-bearing sediments on the PLF, and the existence of collapse depressions surrounding PLFs.

5. Conclusions

[26] A new model is proposed for PLF formation that involves gas-driven sediment expansion and movement. Pressure generated by methane gas hydrate decomposition within layers in subsurface permafrost extrude relatively cold, Pleistocene-aged ice-bound sediments upwards onto the seafloor and elevate them above the surrounding seafloor, forming PLFs. After the subsurface sediment loss and degassing, the seafloor will subside around the PLF to form moat-like depressions. The existence of venting methane, freshwater ice, uplifted older sediments on the PLF, and the depressions surrounding some PLFs containing younger sediments can be generated as a consequence of thermal warming of subsurface gas hydrate permafrost associated with the Holocene transgression of the Arctic Shelf.

[27] **Acknowledgments.** The US NSF (OCE-0117661) and the David and Lucile Packard Foundation provided support.

References

- Bernard, B. B., J. M. Brooks, and W. M. Sackett (1977), A geochemical model for characterization of hydrocarbon gas sources in marine sediments, paper presented at Ninth Annual Conference, Offshore Technol. Conf., Houston, Tex., 2–5 May.
- Bily, C., and J. W. L. Dick (1974), Naturally occurring gas hydrates in the Mackenzie Delta, N. W. T., *Bull. Can. Pet. Geol.*, *32*, 340–352.
- Blasco, S. M., G. Fortin, P. R. Hill, M. J. O'Connor, and J. Brigham-Grette (1990), The late Neogene and Quaternary stratigraphy of the Canadian Beaufort continental shelf, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 491–502, Geol. Soc. of Am., Boulder, Colo.
- Blasco, S. M., J. M. Shearer, and R. Myers (1998), Seabed scouring by sea-ice; scouring process and impact rates; Canadian Beaufort shelf, paper presented at 13th International Symposium on Okhotsk Sea and Sea Ice, Cent. for Cold Ocean Resour. and Eng., Mombetsu, Japan, 1–4 Feb.
- Brigham, J. K., and G. H. Miller (1983), Paleotemperature estimates of the Alaskan Arctic coastal plain during the last 125,000 years, paper presented at 4th International Conference on Permafrost, Int. Permafrost Assoc., Fairbanks, Alaska, 18–22 Jul.
- Dallimore, S. R., and T. S. Collett (1995), Intrapermafrost gas hydrates from a deep core in the Mackenzie Delta, Northwest Territories, Canada, *Geology*, *23*, 527–530.
- Dallimore, S. R., T. Uchida, and T. S. Collett (Eds.) (1999), Scientific results from JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, Mackenzie Delta, Northwest Territories, Canada, *Bull. Geol. Surv. Can.*, *544*, 403 pp.
- Hill, P. R., A. Hequette, and M.-H. Ruz (1993), Holocene sea-level history of the Canadian Beaufort shelf, *Can. J. Earth Sci.*, *30*, 103–108.
- Judge, A. S. (1982), Natural gas hydrates in Canada, in *Proceedings, Fourth Canadian Permafrost Conference*, edited by H. M. French, pp. 320–328, Natl. Res. Council of Can., Ottawa, Ont.
- Kopf, A. J. (2002), Significance of mud volcanism, *Rev. Geophys.*, *40*(2), 1005, doi:10.1029/2000RG000093.
- Kvenvolden, K. A., and T. D. Lorenson (2001), Global occurrence of natural gas hydrates, in *Natural Gas Hydrates: Occurrence, Distribution, and Detection*, *Geophys. Monogr. Ser.*, vol. 124, edited by C. K. Paull and W. P. Dillon, pp. 3–18, AGU, Washington D. C.
- Lachenbruch, A. H., J. H. Sass, B. V. Marshall, and T. H. Moses Jr. (1982), Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska, *J. Geophys. Res.*, *87*, 9301–9316.
- Lorenson, T. D., and K. A. Kvenvolden (1997), Methane in coastal sea water, sea ice, and bottom sediments, Beaufort Sea, Alaska; results from 1995, *U. S. Geol. Surv. Open File Rep.*, *97–54*, 77 pp.
- Lorenson, T. D., M. J. Whiticar, A. Waseda, S. R. Dallimore, and T. S. Collett (1999), Gas composition and isotopic geochemistry of cuttings, core, and gas hydrate from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, in *Scientific Results From JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada*, edited by S. R. Dallimore, T. Uchida, and T. S. Collett, *Bull. Geol. Surv. Can.*, *544*, 143–163.
- Mackay, J. R. (1998), Pingo growth and collapse, Tuktoyaktuk Peninsula area, western Arctic coast, Canada: A long-term field study, *Geogr. Phys. Quat.*, *52*, 271–323.
- Paull, C. K., and W. Ussler III (2001), History and significance of gas sampling during the DSDP and ODP, in *Natural Gas Hydrates: Occurrence, Distribution, and Detection*, *Geophys. Monogr. Ser.*, vol. 124, edited by C. K. Paull and W. P. Dillon, pp. 53–66, AGU, Washington D. C.
- Pelletier, B. R. (1988), Marine science atlas of the Beaufort Sea: Geology and geophysics, *Misc. Rep. 40*, 41 pp., Geol. Surv. of Can., Ottawa, Ont.
- Poley, D. F. (1982), A detailed study of a submerged pingo-like-feature in the Canadian Beaufort Sea, Arctic, Canada, M. S. thesis, 96 pp., Dalhousie Univ., Halifax, N. S., Canada.
- Shearer, J. M., R. F. Macnab, B. R. Pelletier, and T. B. Smith (1971), Submarine pingos in the Beaufort Sea, *Science*, *174*, 816–818.
- Taylor, A. E. (1991), Marine transgression, shoreline emergence: Evidence in seabed and terrestrial ground temperatures of changing relative sea levels, Arctic Canada, *J. Geophys. Res.*, *96*, 6893–6909.
- Taylor, A. E., S. R. Dallimore, R. D. Hyndman, and F. Wright (2005), Comparing the sensitivity of terrestrial and marine gas hydrates to climate warming at the end of the last ice age, in *Scientific Results From the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories*, edited by S. R. Dallimore and T. S. Collett, *Bull. Geol. Surv. Can.*, *585*, 11 pp.
- Weaver, J. S., and J. M. Stewart (1982), In situ hydrates under the Beaufort Sea shelf, in *Proceedings, Fourth Canadian Permafrost Conference*, edited by H. M. French, pp. 312–319, Natl. Res. Council of Can., Ottawa, Ont.
- Yorath, C. J., J. Shearer, and C. J. Havard (1971), Seismic and sediment studies in the Beaufort Sea, *Pap. Geol. Surv. Can.*, *71-1A*, 243–244.

S. M. Blasco, Natural Resources Canada, 1 Challenger Drive, Room M-419, Dartmouth, NS, Canada B2Y 4A2.

S. R. Dallimore, Natural Resources Canada, 9860 West Saanich Road, Room 4717, Sidney, BC, Canada V8L 4B2.

T. D. Lorenson, U.S. Geological Survey, Mail Stop 999, Menlo Park, CA 94025, USA.

F. A. McLaughlin and H. Melling, Fisheries and Oceans Canada, 9860 West Saanich Road, Sidney, BC, Canada V8L 4B2.

B. E. Medioli and F. M. Nixon, Natural Resources Canada, 601 Booth Street, Ottawa, ON, Canada K1A 0E8.

C. K. Paull and W. Ussler III, Monterey Bay Aquarium Research Institute, 7700 Sanholdt Road, Moss Landing, CA 95039-9644, USA. (paull@mbari.org)