Modelling the thermal regime of permafrost and gas hydrate deposits to determine the impact of climate warming, Mallik field area

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Abstract: We apply a two-dimensional geothermal model to predict the permafrost and natural gas hydrate structure in the Mallik field area, based on two paleoenvironmental scenarios deduced at other wells in the Mackenzie Delta area. Scenario A indicated a subaerial history throughout the Holocene, and scenario B documented a several thousand year, subaqueous episode during the Holocene followed by recent subaerial exposure. The effects of these histories is limited largely to the 600 m thick permafrost zone, with scenario B predicting a substantial talik. The most defensible scenario can be resolved with ground temperatures or independent paleoenvironmental indicators. The effect of climate warming will be apparent in a warming of the permafrost and, with marine transgression, creation of an underlying talik. Terrestrial methane hydrate deposits remain stable with increasing surface temperatures over several centuries, but the base of gas hydrate stability rises about 2 m after 300 years.

Résumé : On a appliqué un modèle géothermique bidimensionnel afin de prévoir la structure du pergélisol et des hydrates de gaz naturels dans la région du champ de Mallik, en se basant sur deux scénarios paléoenvironnementaux déduits de données d'autres forages exécutés dans le delta du Mackenzie. Le scénario A préconise des conditions subaériennes tout au long de l'Holocène, alors que le scénario B fait état d'une période subaquatique d'une durée de plusieurs milliers d'années à l'Holocène, à laquelle a succédé, dans un passé récent, une période d'exposition subaérienne. les effets de ces périodes se limitent pour l'essentiel à la zone de pergélisol de 600 m d'épaisseur, mais, selon le scénario B, il y aurait formation d'un important talik. Le scénario le plus plausible pourra être déterminé à l'aide des températures du sol ou de traceurs environnementaux indépendants. Un réchauffement climatique se manifesterait par un réchauffement du pergélisol et, à la suite d'une transgression marine, par la formation d'un talik à la base de celui-ci. Les dépôts terrestres d'hydrates de méthane demeuraient stables à des températures de surface augmentant sur plusieurs siècles, mais la base de la zone de stabilité des hydrates de gaz s'élèverait de 2 m en 300 ans.

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INTRODUCTION

The Japan National Oil Company (JNOC) has launched a five-year study to assess the resource potential of natural gas hydrate deposits (e.g. DeKoker, 1995). Prior to undertaking an offshore gas hydrate drilling program off the eastern coast of Japan, a test hole, sited in the Canadian Mackenzie Delta, was drilled in February 1998 to assess drilling technology and, in a joint program with the Geological Survey of Canada (GSC) and United States Geological Survey (USGS), to investigate outstanding scientific problems in a gas hydrate environment. The gas hydrate research well, designated Mallik 2L-38, is adjacent to the Imperial Mallik L-38 hydrocarbon exploration well (Dallimore et al., 1999b; Fig. 1). Bily and Dick (1974) reported the occurrence of gas hydrate between 880 m and 1100 m depth at Mallik L-38, which provided stratigraphic constraint for the Mallik 2L-38 hole. Two major scientific drilling projects in the Mackenzie Delta–Beaufort Sea area preceded the drilling of Mallik 2L-38, the Beaufort Sea Transect (Dallimore, 1992) and the Cross-delta Transect (Dallimore and Matthews, 1997). The results of these projects provide a regional geological and geotechnical background for the present endeavour.

Ground temperatures and permafrost thickness are a direct physical consequence of subsurface physical properties and past surface temperatures. Glaciation, sea-level

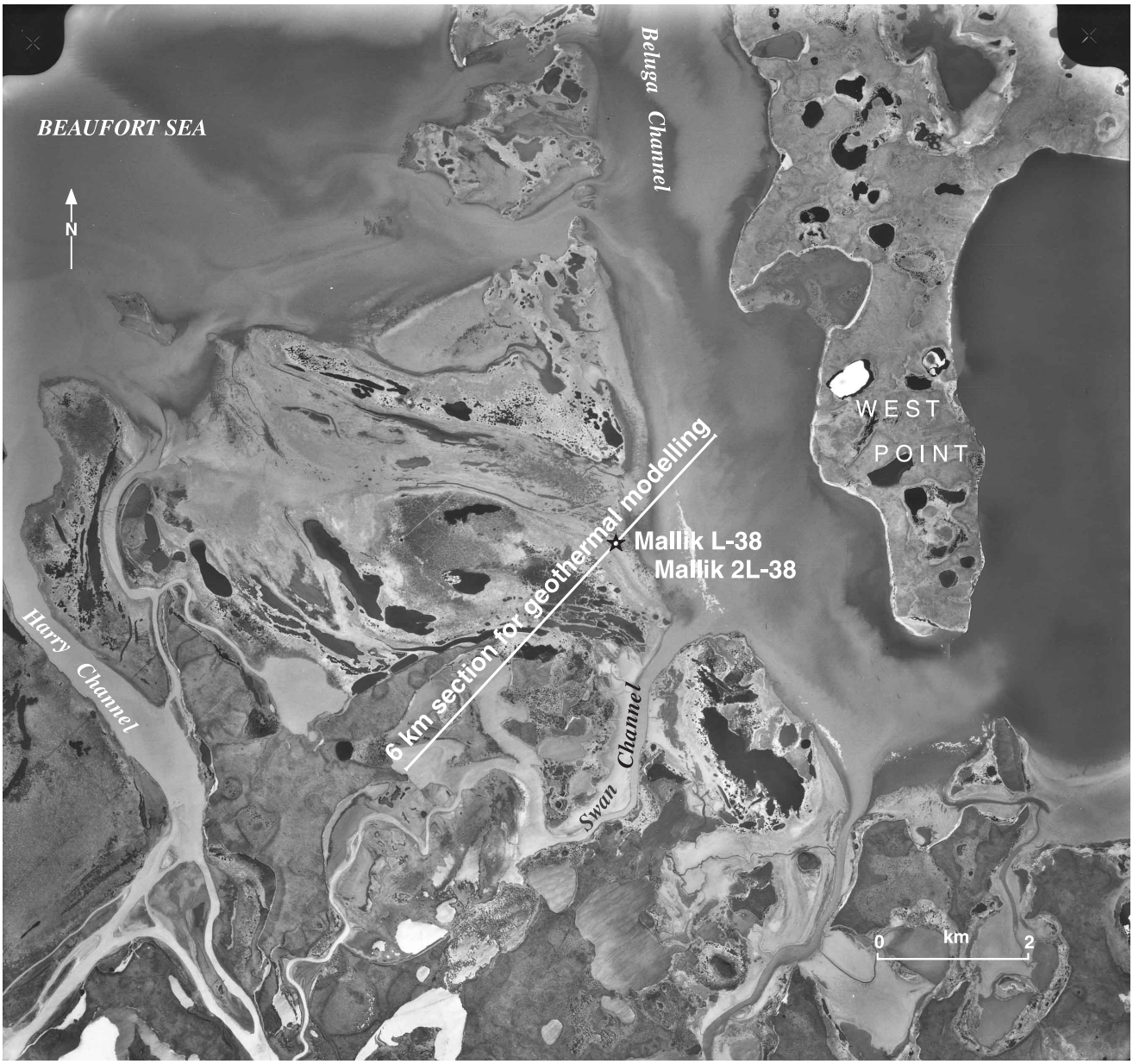

Figure 1. *Location of the Mallik L-38 and Mallik 2L-38 wells, Mackenzie Delta, northwestern Canada, showing the location of the geothermal modelling transect. NAPL A23757-41.*

variation, distribution of lakes, and changing climate have an impact on surface temperatures and, through thermal diffusion, on the subsurface thermal regime observed today. While geothermal modelling may extract this history from a measured temperature-depth profile (e.g. Birch, 1948), carefully constrained modelling also may be used to predict subsurface conditions, permafrost thickness, and the zone of gas hydrate stability.

Several earlier geothermal modelling studies have investigated the structure and temporal development of permafrost and gas hydrate zones in the Mackenzie Delta–Beaufort Sea region (e.g. Allen et al., 1988) and Alaska (Lachenbruch et al., 1987). For both the Beaufort Sea Transect and Cross-delta Transect, Taylor et al. (1996a, b) used a simple one-dimensional numerical model to derive paleoconditions consistent with ground temperatures measured today. The present study proposes to use a similar numerical model and the paleoenvironmental history developed through these earlier studies to predict the present subsurface temperatures at Mallik L-38 and 2L-38 wells.

SETTING UP THE PROBLEM SPACE FOR FINITE ELEMENT MODELLING

In this study, the author used the geothermal modelling program TEMP/W (Geo-Slope International, Ltd., 1995). This two-dimensional finite-element software combines current knowledge of the physics of heat transfer with geological parameters to model the response of the subsurface strata to past changes at the ground surface. Reliability of model predictions depends on ground thermal properties and realistic boundary conditions. This section briefly describes the assignment of these parameters and the set-up of the numerical model to simulate the well environs.

Problem space

A southwest-trending 6 km transect was chosen, with the Mallik L-38 and 2L-38 wells at its centre, and aligned with seismic line 22-71 (Fig. 1; *see also* location map in report by National Energy Board, 1972). Two lakes lie to the southwest of the wells, with shoals and a deeper reach (Beluga Channel) of the Beaufort Sea to the northeast. The subsurface is modelled to a depth of 2000 m, comprising the Iperk, Mackenzie Bay, and Kugmallit sequences (Iperk Group, Mackenzie Bay Formation, and Kugmallit Formation; Fig. 50 *in* Dixon, 1992; Dixon, 1995).

A finite element mesh was designed to model the above problem space. Elements are approximately 125 m (horizontal) by 50 m (depth) near the surface in the area of the lakes and wells, and increase in size towards the ends of the transect and at depth, except in the zone of observed gas hydrate, where the 50 m depth increment is preserved.

Sample descriptions from the Mallik L-38 well (p. 4–8, National Energy Board, 1972) and the refined definition of the gas hydrate intervals (Table 1 *in* Collett et al., 1999) guided the assignment of a simplified lithology to these elements in the model. The 2000 m depth of interest was represented by 15 lithological layers, and each layer was assigned physical properties, as described below.

Assignment of physical properties

Unfrozen water content

This is the primary physical property for problems that involve change of phase (as in permafrost or gas hydrate beds). The model requires specification of both the total saturated volumetric porosity and the variation of unfrozen water content with subzero temperature. The GSC has measured unfrozen water content, salinity, and grain-size distribution for a suite of some 30 subsurface soils from the Mackenzie Delta–Beaufort Sea area (D.E. Patterson, unpub. report, 1994; the data are given in Dallimore and Matthews (1997)). Guided by the Mallik L-38 sample descriptions (National Energy Board, 1972) and Mallik 2L-38 core properties (Dallimore et al., 1998a), the most appropriate smoothed curve for unfrozen water content was selected for each of the 15 lithological materials (A.E. Taylor, unpub. report, 1999).

Porosity

The oversized hole resulting from thermal drilling disturbance within the permafrost degraded most downhole log responses at both the Mallik L-38 and Mallik 2L-38 wells. Thus, sediment porosity was estimated based on the described lithology and data from other projects. Below the permafrost, analysis of the neutron log response (Fig. 2 *in* Collett et al., 1999) was used to assign porosity.

Gas hydrate saturation

This is the portion of the pore space occupied by gas hydrate, and was calculated from an analysis of the Mallik 2L-38 downhole geophysical logs (Fig. 3 *in* Collett et al., 1999).

Thermal conductivity

Because of poor log quality within the permafrost section, an 'effective' thermal conductivity was calculated for each model interval based on the simplified lithological description and conductivity values taken from earlier projects in the region (Beaufort Sea Transect and Cross-delta Transect). Thermal data from Majorowicz (1999) were used for depths below the permafrost.

The thermal conductivity of high-porosity soils varies with subzero temperature according to the unfrozen water content of the pore water. Thermal conductivity as a function of temperature was calculated using the conductivity values described above as well as the porosity, gas hydrate saturation, and unfrozen water content. The frozen and unfrozen volumetric heat capacity values were calculated similarly. In these calculations, the thermal conductivity of methane hydrate was taken as 0.45 W/m·K (Sloan, 1990, p. 389), and the heat capacity of gas hydrate was assumed to be similar to

that of ice, 2.09×10^6 J/m^3 (Kuustraa and Hammershaimb, 1983, p. 103). Figure 2 provides examples of thermal conductivity calculated in this manner; in layer #10, the presence of gas hydrate depresses the water content and thermal conductivity at temperatures below the methane hydrate stability curve.

Latent heat of phase change and heat of dissociation

The latent heat for water-ice is 3.38×10^8 J/m^3; the heat of methane hydrate dissociating to gas and water was taken as 4.5×10^8 J/m^3 (Sloan, 1990, p. 387).

Assignment of boundary conditions

Initial boundary conditions are specified to provide a realistic starting point for the forward modelling, and transient boundary conditions at the surface guide the temporal progression of the analysis. The intent of this study was to invoke results of the paleoenvironmental reconstruction developed for the Cross-delta Transect a few tens of kilometres to the west of the Mallik wells. In that analysis, paleoenvironmental models were constrained by deep temperature profiles and a large database of subsurface physical properties determined by laboratory and field studies. The two major paleoenvironments deduced in the Cross-delta Transect analysis were used here as surface boundary conditions to predict subsurface temperatures at the Mallik wells. For a fuller discussion *see* Taylor et al. (1996a).

Initial boundary conditions

Initial boundary conditions provide the geothermal structure hypothesized for 13 ka BP. Details of the earlier Wisconsinan surface temperature history are not considered, because events of less than a few tens of thousands of years in the Early to Mid-Wisconsinan cannot be resolved by a geothermal analysis. For 13 ka BP, a quasi-equilibrium temperature of -15°C was used as the ground surface boundary condition (e.g. Brigham and Miller, 1983; Smith, 1986). A temperature of 47.1°C was assigned to the bottom of the problem space at 2000 m depth. This was interpolated from calculations of deep temperatures at the Mallik L-38 well based on bottom-hole and drill-stem test temperatures (Majorowicz, 1999). A temperature of -1°C, representing the base of ice-bearing permafrost, was assigned to a depth of 760 m. This depth was chosen through trial and error forward modelling such that an ice-bearing permafrost thickness similar to that reported today (~640 m) was replicated, and that the subpermafrost temperature profile deduced by Majorowicz (1999) was achieved.

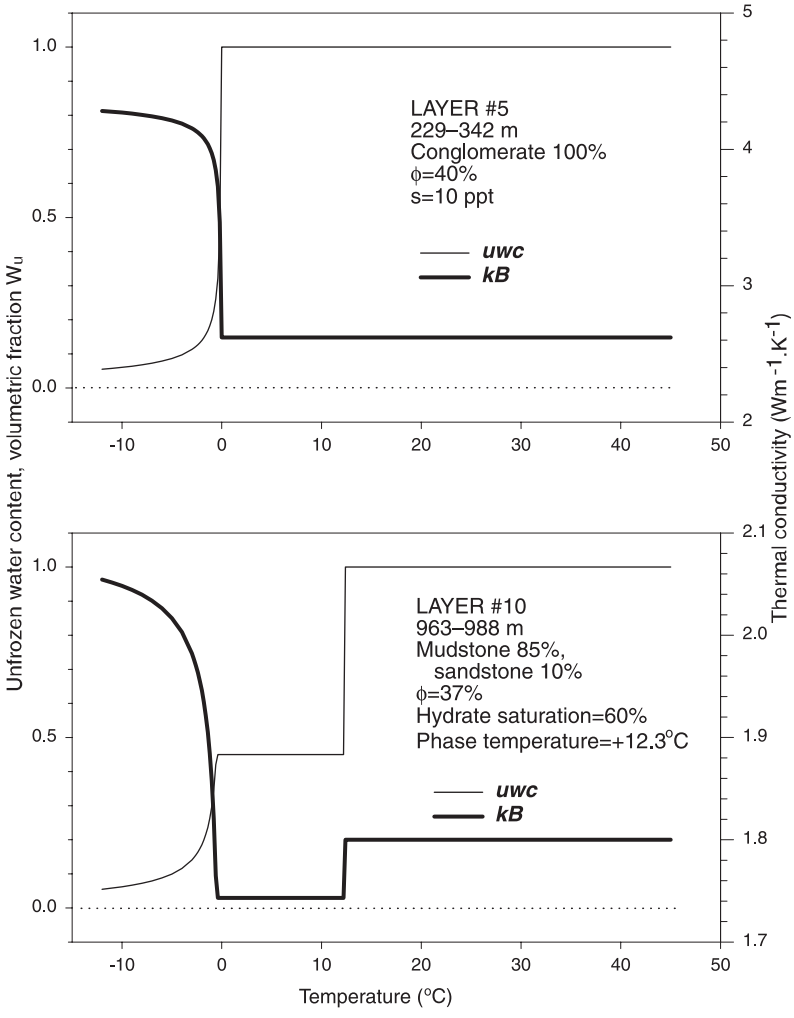

Figure 2.

Unfrozen water content (uwc) and calculated thermal conductivity (kB) assigned to layer #5 (in permafrost) and #10 (in gas-hydrate-bearing interval); ϕ = porosity, s = salinity.

Transient boundary conditions

These specify the variation of ground surface temperatures through time after 13 ka BP at different points along the 6 km transect. In the finite element model, boundary conditions may be specified at each node point independently, giving great flexibility in specifying the variation in surface temperatures along such a topographically diverse transect. The surface temperature boundary conditions are shown graphically in Figure 3, subsequent to the initial surface condition of -15ºC at 13 ka BP (not shown), and are described briefly below.

Land, always subaerial

Surface temperatures vary through the Holocene and were estimated from the literature (e.g. Mackay, 1992; *see* discussion and further references *in* Taylor et al. (1996a)). This boundary condition is applied to areas considered subaerial throughout the Holocene (southwest end of transect, and well site for scenario A).

Lakes

This designation refers to surface (lake bed) temperatures on landscape covered by lakes which formed after 6 ka in the mid-Holocene (e.g. Mackay, 1992); this boundary condition is applied to the two lakes in the transect.

Marine shoals

This boundary condition describes seabed temperatures underlying shoals bordering Beluga Channel following marine transgression of the channel in the mid-Holocene (Hill et al., 1985, 1993). This model assumes that shallow water freezes to the seabed in winter, lowering the mean annual seabed temperature to -2.3ºC (Dyke, 1991; compare site 268, Taylor et al. (1996a)).

Beluga Channel

This boundary condition reflects seabed temperatures beneath Beluga Channel; it assumes that the channel (and shoal area, above) was subaerial until marine transgression around 4.5 ka BP. Submarine temperature is assumed to be +2ºC (compare analogous situation at 90 GSC BH2, Taylor et al. (1996b)).

Well site (scenario A)

This hypothesized surface temperature boundary condition is based on a specific paleoenvironmental model developed at Cross-delta Transect for a site that remains subaerial throughout the Holocene (Taylor et al., 1996a).

Well site (scenario B, Taglu analog)

This hypothesized surface temperature boundary condition is based on the specific paleoenvironmental model developed at Taglu, Cross-delta Transect. The well site was occupied by a lake for a portion of the Holocene, but became subaerial at 0.6 ka BP due to drainage or contraction of the lake (analogous to site #287, Taylor et al. (1996a)). The boundary condition is applied to section of transect between Beluga Channel shoals and lake (Fig. 1).

Climate change model

A simple climate warming scenario was hypothesized for the future for scenario A (Fig. 3), principally to demonstrate the impact of climate change on the permafrost and gas hydrate horizons. A review of recent Global Climate Models in the IPCC (Intergovernmental Panel on Climate Change) assessments (Watson et al., 1995) indicates a global surface

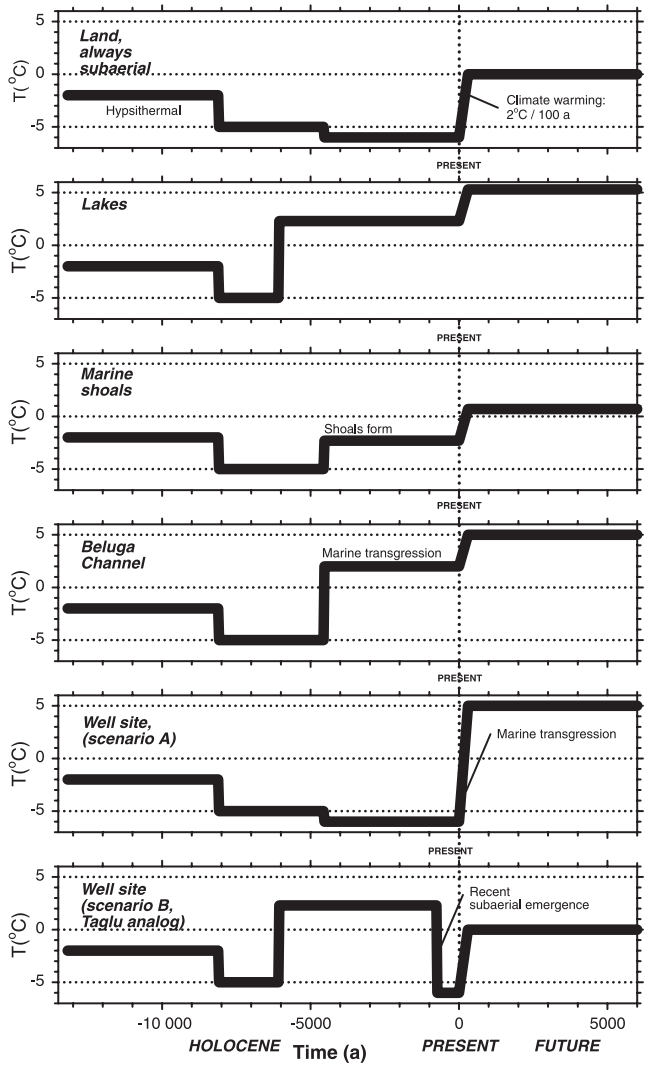

Figure 3. *Transient boundary conditions used for ground surface temperatures in the geothermal model, following initial conditions 13 300 a BP. Hypothesized climate change scenario (to 13 300 a after present) is shown only to 6 ka AP. The lower two panels give the temperatures applied to the land surface surrounding the L-38 and Mallik 2L-38 well sites, according to the two paleoenvironmental scenarios.*

temperature increase of 1ºC to 3.5ºC over the next 100 a; in the Arctic, the magnitude of climate warming is predicted to be greatest. Marine transgression along the Beaufort Sea coast is ongoing (e.g. Hill et al., 1985, 1993) and nearshore sites, like the Mallik field area (Fig. 1) are expected to be eroded and inundated at any time.

For the climate change model, we hypothesize a scenario that embodies these predictions but which, speculatively, extends the changes to 300 a after the present (AP). We assume terrestrial surface temperatures increase at the rate 2ºC per 100 a for 300 a, that water temperatures (lake and sea) increase by half the rate of the land, and that the Beaufort Sea (Beluga Channel) transgresses across the well site as far as the present location of the adjacent lake to the west. To speculate on the long-term stability of permafrost and gas hydrate deposits, surface conditions attained by 300 a were held constant until 13 300 a AP.

CALIBRATION OF THE MODEL

Since there are no temperature observations in the upper portions of these wells, the model calibration is limited by the agreement with the present measure of permafrost thickness and with temperatures at depth derived from bottom-hole and drill-stem test temperatures taken during drilling the well (Majorowicz, 1999).

There is a fundamental difference between the present study and those conducted earlier for the Beaufort Sea Transect and the Cross-delta Transect (Taylor et al., 1996a, b). In the Beaufort Sea Transect and Cross-delta Transect work, we required the paleosurface temperature history and paleoenvironment that, when applied in the models, would give the subsurface temperatures measured today; the free variable was the surface temperature history, which was varied within reasonable limits to achieve the fit. Thus, we used a geothermal model and current deep ground temperatures to deduce the local and regional paleoclimate and paleoenvironment. In this study, we use similar numerical models and the paleoclimate and paleoenvironments derived for the region in the Beaufort Sea Transect and Cross-delta Transect work, to predict the present deep temperatures at the Mallik wells.

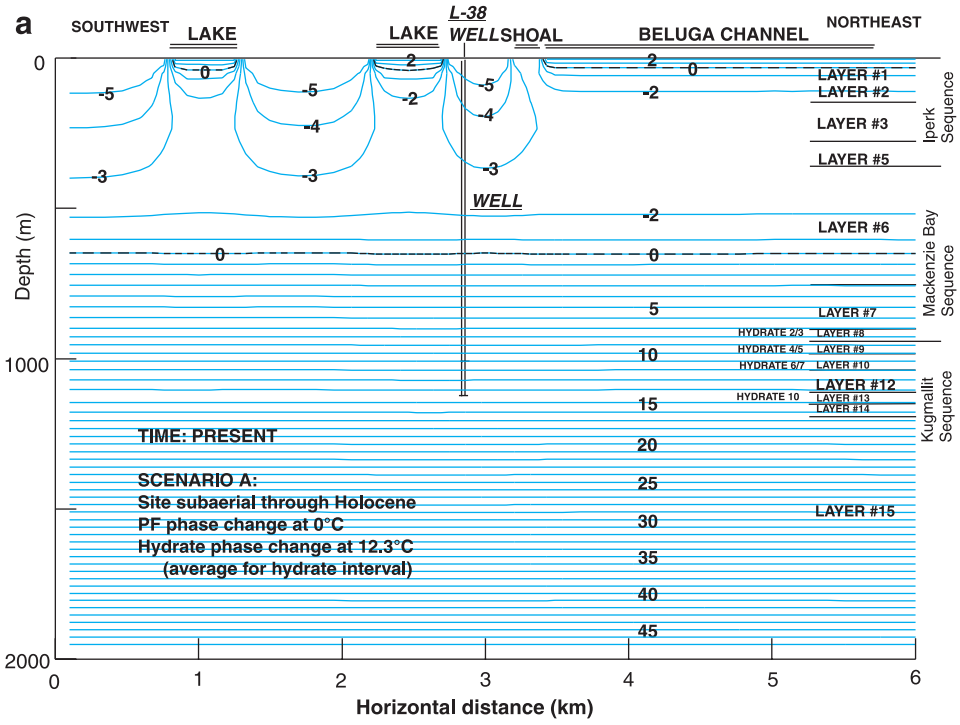

Figure 4. *Results of the geothermal modelling for the 6 km transect through the Mallik wells (Fig. 1). Temperature contours are in ºC (interval, 1ºC). Geological layers are shown along the right side, with formation units. Major intervals of observed gas hydrate are identified as, e.g. "Hydrate 2/3" after the nomenclature of Collett et al. (1999). See Figure 3 and text for boundary conditions along the transect.* ***a)*** *Scenario A and* ***b)*** *scenario B, subsurface geothermal conditions predicted for the present;* ***c)*** *scenario A, 300 a after present.*

RESULTS OF THE FINITE ELEMENT MODEL

Present subsurface thermal regime

The model results are presented as contour plots for a temperature-depth section along the 6 km transect (Fig. 1). The subsurface geothermal regime for the present is depicted in Figure 4a (scenario A) and Figure 4b (scenario B). These figures show the complex two-dimensional thermal structure that develops beneath this diverse landscape. Taliks of some tens of metres thickness develop beneath the mid-Holocene lakes and Beluga Channel. The permafrost beneath these bodies is nearly isothermal at -2ºC, whereas a more uniform temperature-depth gradient underlies land. In particular, the

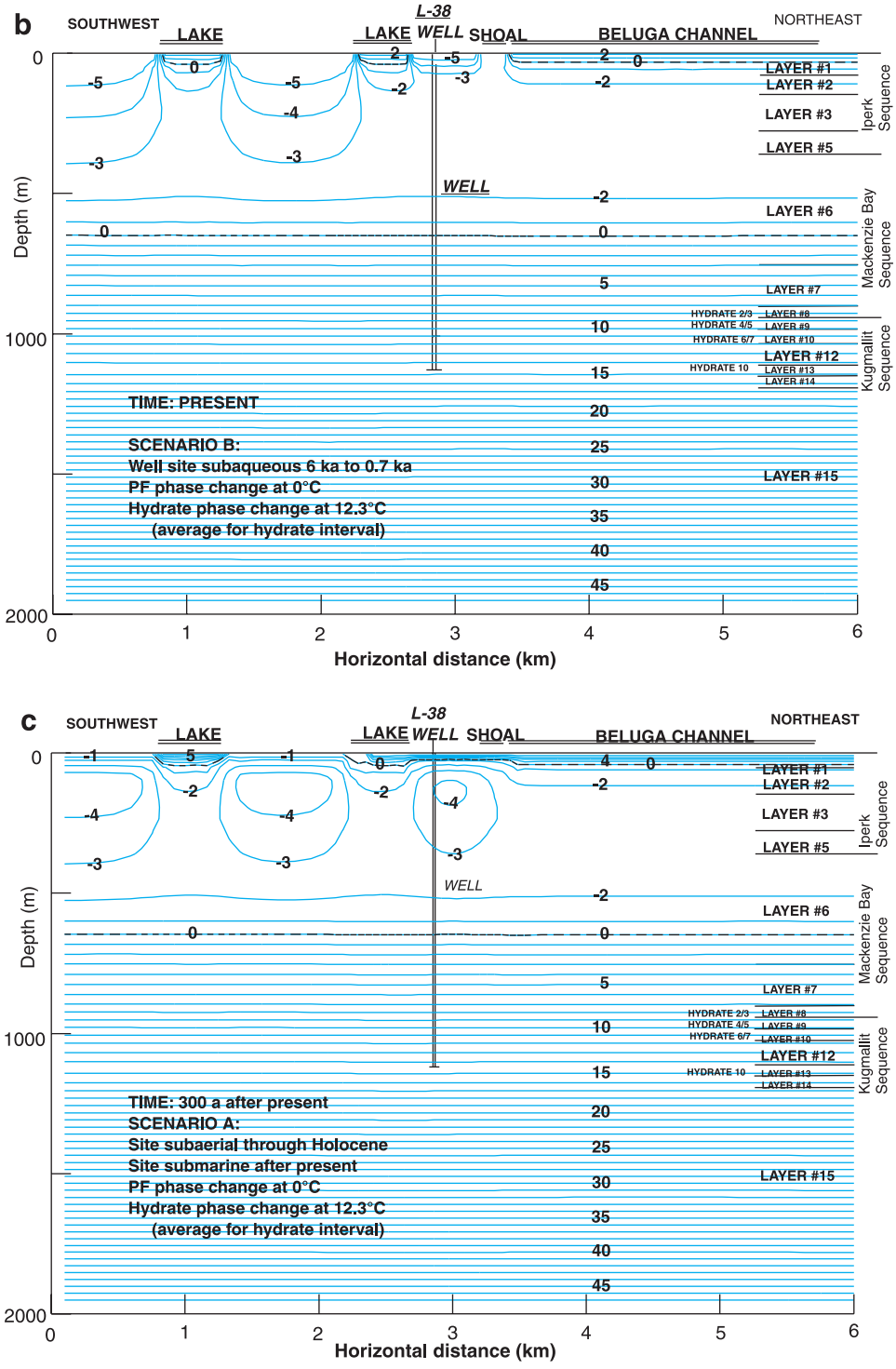

Figure 4 *(cont.)*

effect of a mid-Holocene subaqueous episode, rather than subaerial conditions at the well site, may be seen by comparing Figure 4b to Figure 4a.

Scenario A

Predicted temperature-depth profiles are shown for the well, beneath the middle of Beluga Channel and under the centre of the lake to the east of the well (Fig. 4a). The curvature in well temperatures between about 300 m and the base of permafrost (Fig. 5a, b) is a reflection of the increase in surface temperatures from -15°C assumed at 13 ka BP, while the opposite curvature above 300 m reflects the gradual lowering of surface temperatures since 8 ka BP (Fig. 3). Temperature profiles predicted beneath the two bodies of water are very similar (Fig. 5b), reflecting similar surface temperatures assumed for these areas after the mid-Holocene (Fig. 3) and similar freezing properties of the lithology.

Scenario B

The well temperatures exhibit two distinctive features (Fig. 5). First, an isothermal section through the midpermafrost interval, with temperatures similar to those beneath present lakes and Beluga Channel, is interpreted as evidence of a mid-Holocene subaqueous period (analogous to #287, Taylor et al. (1996a)). Second, the temperature-depth gradient in the upper 100 m (Fig. 4b, 5b) is large compared to the geothermal gradient, and is characteristic of more recently

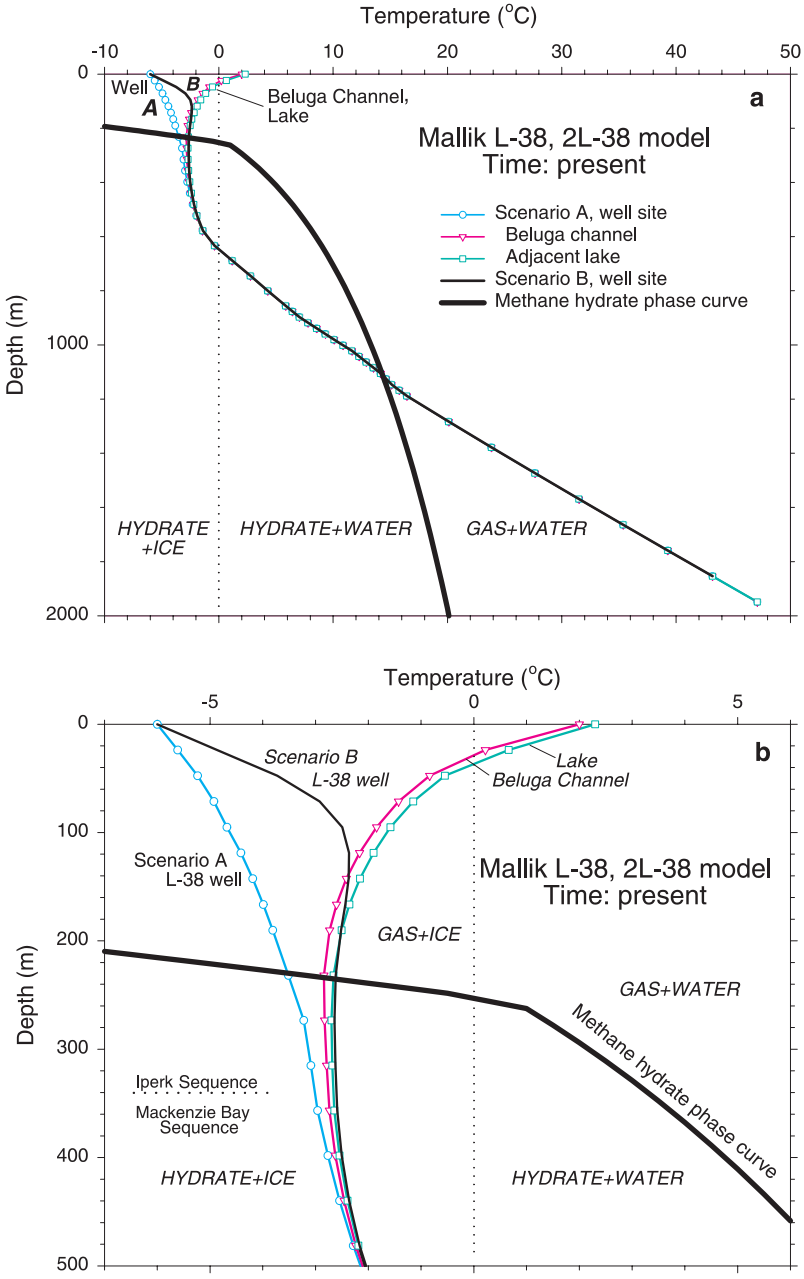

Figure 5.

Modelled temperature-depth profiles for the present at the Mallik L-38 and Mallik 2L-38 wells (both scenarios A and B), and beneath Beluga Channel and the lake southwest of the wells (Fig. 4a, b). Methane hydrate phase curve after Holder and Hand (1982) as presented in Collett (1993).

emergent land (Taylor, 1991). Towards the base of permafrost and beneath, there is no appreciable difference between scenarios A and B.

At Mallik field, a subaqueous episode might be explained by lakes that were larger in the mid-Holocene than today, with recent partial drainage and contraction (Mackay, 1992). Alternatively, the episode could reflect a mid-Holocene marine event, with the surficial Holocene sands being deposited subsequently to create subaerial conditions. *See* discussion *in* Taylor et al. (1996a) for the nearby Taglu wells.

Temperature profiles of both scenarios predict that the base of methane hydrate stability is 1100 m (Fig. 5a). Scenario A predicts a slightly shallower depth to the top of the zone of methane hydrate stability, around 230 m (Fig. 5b).

Permafrost and gas hydrate conditions with climate warming

Figures 4c and 6 illustrate the predicted subsurface temperatures at the well locations for the speculative climate warming hypothesis under scenario A. Positive surface temperatures reflect the transgression of the Beaufort Sea, with temperatures increasing to a depth of 100 m over the next century and to about 200 m in the next 300 a. The large near-surface temperature gradient in this zone indicates a large downwards flow of heat following transgression. However, the latent heat required to melt the permafrost (and creating a talik at the well site) would slow the impact on the deeper thermal regime. The permafrost base would rise about 1 m after 100 a and less than 3 m after 300 a, but is predicted to lie almost 200 m

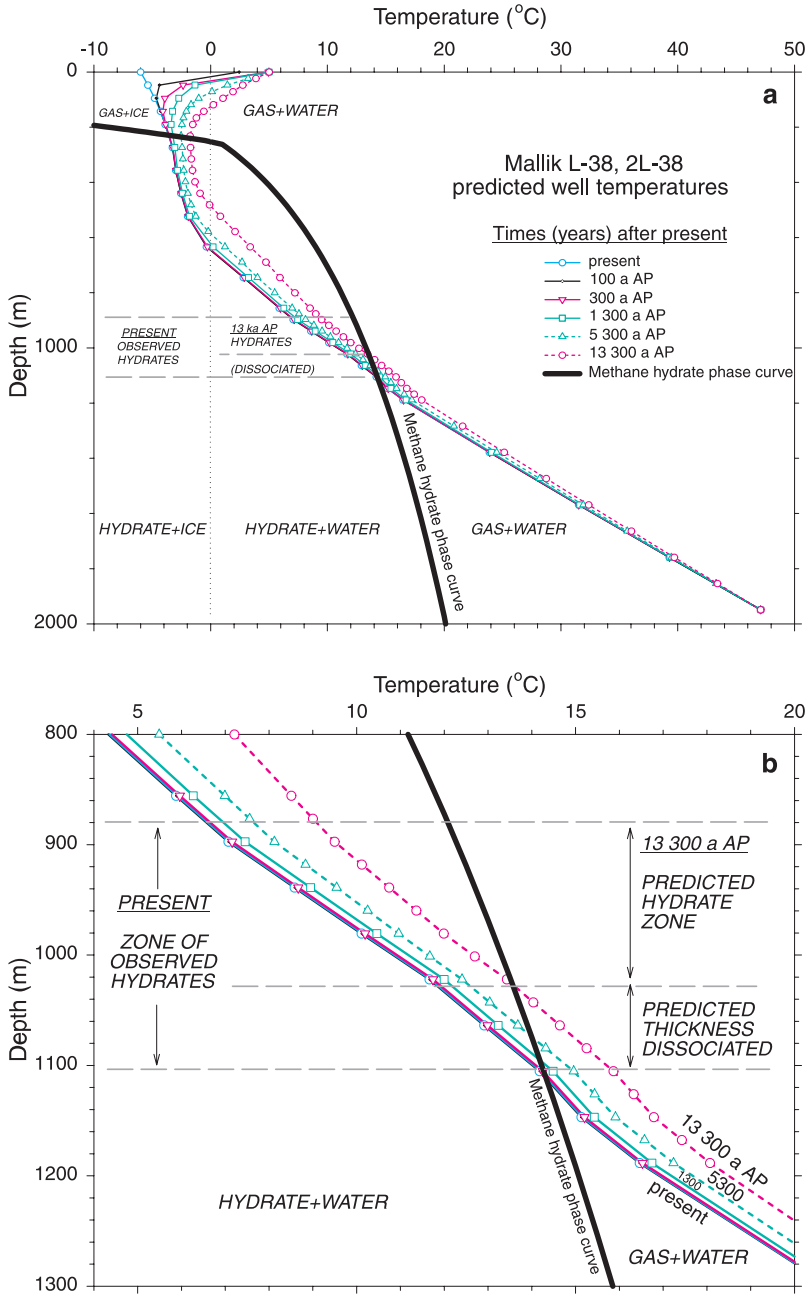

Figure 6.

Modelled temperature-depth profiles at Mallik wells for several times after the present (AP), for the hypothesized climate warming scenario (Fig. 3). The hypothetical impact on the zone of observed gas hydrate is shown for 13 300 a AP.

higher after 13 300 a (Fig. 6a). Temperature increases below permafrost would be smaller, amounting at 1000 m depth to a few tenths of a degree after 1300 a, 1ºC after 5000 a, and 2ºC after 13 300 a (Fig. 6b).

Because of the nearly constant depth of methane hydrate stability for subzero temperatures (Fig. 5b) the upper surface of the stability zone is less sensitive to climate warming. The top of the methane hydrate stability zone may deepen by about 10 m over the course of the climate warming scenario tested here (Fig. 6a). If intrapermafrost gas hydrate exists at this depth, climate warming will cause the zone to become slightly deeper and gas hydrate dissociation would commence.

The steep intersection of the gas hydrate phase curve with the geothermal profile through the zone of observed gas hydrate (Fig. 5a) suggests that the impact of climate warming (or marine transgression) will be greatest at the base of the gas hydrate stability zone (Fig. 6). We assume that the marine transgression of the well site, during which a land surface is eroded and overrun with sea water, has not appreciably changed the pressure conditions at depth. The hypothesized climate warming and marine transgression model results in the base of methane hydrate stability rising about 2 m after 300 a and about 70 m after 13 300 a (Fig. 6b). As the presence of gas hydrate deposits is confirmed between 880–1100 m below surface at this location (Collett et al., 1999), a potential 70 m of gas hydrate would dissociate from the base upwards, by 13 300 a after the present. However, if climate warming is accompanied by a rise in sea level, increased subsurface pressure would tend to stabilize these gas hydrate deposits.

CONCLUSIONS

A two-dimensional finite element geothermal model has been developed for the Mallik L-38 and Mallik 2L-38 well sites. The model is based on two scenarios of paleoenvironmental styles ('A' and 'B') deduced for the 1992 Cross-Mackenzie Delta Project some tens of kilometres to the west. Constraints to the geothermal model at the Mallik sites comprise the present permafrost thickness and temperatures below the permafrost derived from an analysis of bottom-hole and drill-stem test temperatures at the Mallik L-38 well (Majorowicz and Smith, 1999).

The numerical model extrapolates the subpermafrost temperature estimates to the ground surface, according to whether the Mallik field site was subaerial throughout the Holocene (scenario A) or experienced a substantial period of subaqueous conditions in the mid-Holocene (scenario B). Which scenario is appropriate for Mallik L-38 and Mallik 2L-38 can be resolved only with additional paleoenvironmental information. However, the depth interval of methane hydrate stability, 230–1100 m based on hydrostatic conditions at depth, is essentially the same for both scenarios, considering our uncertainty of the nature of the phase curve.

A climate warming scenario is modelled for the following 13 300 a, based on an increase of surface temperatures of 2ºC/100 a (water temperatures 1ºC/100 a) for the next 300 a, after which temperatures remain constant. The climate warming model starts with the inundation of the well sites due to marine transgression. With this model, the permafrost base rises about 1 m after 100 a, less than 3 m after 300 a, and less than 200 m after 13 300 a. Assuming no appreciable changes in pressure conditions at depth following marine transgression, the base of methane hydrate stability rises about 2 m after 300 a and about 70 m after 13 300 a. As gas hydrate deposits were observed between 880–1100 m at this location, a potential 70 m of gas hydrate would dissociate from the base upwards, by 13 300 a after the present.

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