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Abstract: A synthetic magnetotelluric (MT) study was performed based on the electrical logs from the Mallik gas hydrate research wells. The study looks at the MT apparent resistivity and phases to determine the influence on the response due to the presence of a resistor at depth that corresponds to the presence of a gas hydrate layer. The purpose of this work is to determine if MT methods would be able to both detect and characterize gas hydrate deposits in the Beaufort-Mackenzie delta. Based on the modelling, MT methods can detect a resistive feature corresponding to the gas hydrate layer; however, the ability to distinguish the amount of gas hydrate within a layer is reduced by the inability of electromagnetic geophysical techniques to better resolve resistive features.

Résumé : Une étude magnétotellurique (MT) par simulation a été effectuée à l'aide des diagraphies électriques effectuées aux puits de recherche Mallik. La simulation examine la résistivité apparente et la phase MT de la réponse engendrée dans une situation où s'exerce l'influence d'une résistance en profondeur correspondant à la présence d'une couche d'hydrates de gaz. Ces travaux ont pour objet de déterminer l'aptitude de la méthode MT à détecter et à caractériser les gisements d'hydrates de gaz dans le delta du Mackenzie et la mer de Beaufort. Selon les résultats de la modélisation, la méthode MT est en mesure de détecter une entité résistive correspondant à une couche d'hydrates de gaz; cependant, la capacité de la méthode à distinguer la quantité d'hydrates de gaz présente dans une couche est limitée par la difficulté des techniques géophysiques électromagnétiques à bien définir les entités résistives.

INTRODUCTION

Because gas hydrate deposits in the Arctic are difficult to detect from the surface, different geophysical techniques need to be investigated for their reliability and efficacy to assess gas hydrate concentrations. Perhaps the most vexing problem in imaging the gas hydrate layer is their depth. Permafrost-related gas hydrate deposits are stable only within a relatively narrow depth range and are found in the Mallik area at depths of approximately 800–1100 m. Only a few geophysical techniques have the ability to 'see' this deep. One method that may be of use and should be tested is the magnetotelluric (MT) technique. The MT method detects conductivity variations to considerable depth by virtue of its significant 'source' or 'transmitter', namely naturally occurring oscillations in the Earth's magnetic field. The MT method is therefore a low-cost electromagnetic surveying technique. While developed in the 1950s (Tikhonov, 1950; Cagniard, 1953), only relatively recently have there been improvements in MT field acquisition equipment and data modelling capabilities (e.g. Rodi and Mackie, 2001) necessary to make the magnetotelluric method a viable exploration technique. Several case studies have shown the utility of the magnetotelluric method for oil and gas exploration (Watts and Pince, 1998; Xiao and Unsworth, 2006); however, the MT method has not been used for gas hydrate research. In the gas hydrate exploration context it must be borne in mind that, as with all inductive electromagnetic techniques, while excellent at finding conductive units, the MT method is generally not as sensitive to resistive targets such as ice.

In this paper, available downhole electrical logs have been used to generate synthetic MT responses to ascertain if an appreciable response from the resistive gas hydrate can be detected at the surface.

REGIONAL GEOLOGY

The Mallik research wells are located within the Beaufort-Mackenzie Basin (Fig. 1), a rifted continental margin sequence. Approximately two-thirds of the basin underlies the Beaufort Sea, however, the remainder is onshore, prograded by the Mackenzie River delta. At sea, the basin can be more than 12 km thick. The regional geology has been described in numerous publications (e.g. Dixon et al., 1994; Dixon, 1995) and basin stratigraphy has been separated into

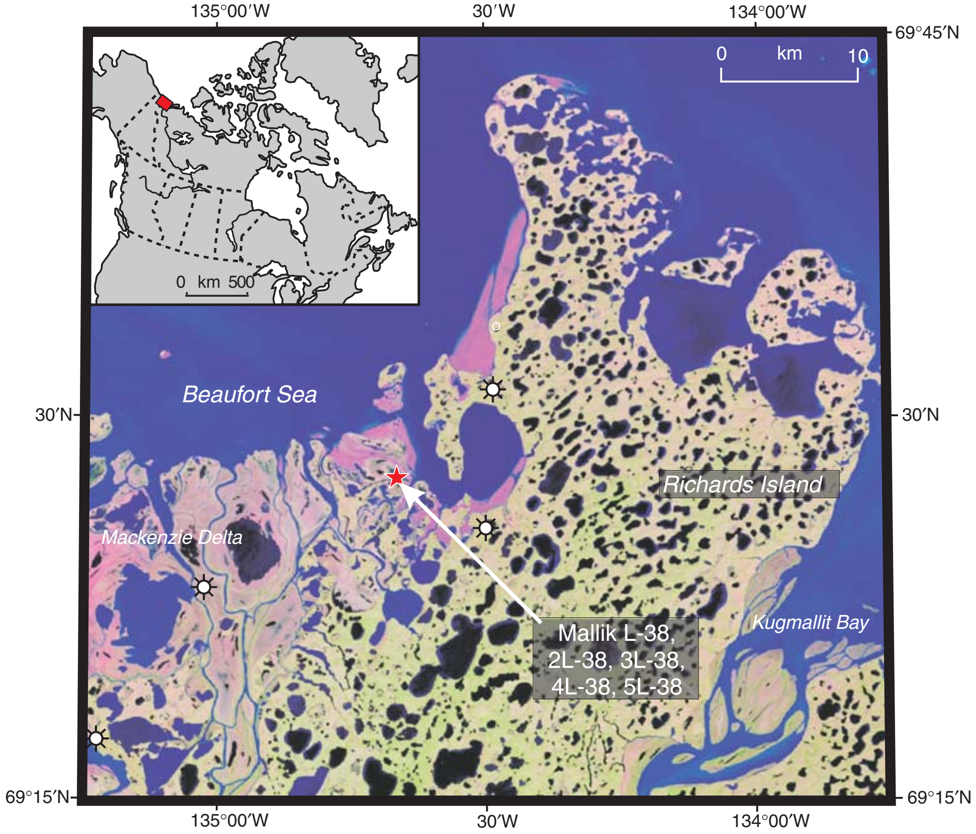

Figure 1. Location of Mallik well site (*modified from* Dallimore and Collett, 2005). Base map is a false-colour mosaic constructed from a Landsat V image taken July 8, 2002. Circles with ticks indicate wells containing gas hydrate.

four tectonostratigraphic sequences composed mostly of deltaic sandstone and shale. Each sequence is separated by major unconformities.

Composed of water in a solid lattice and methane (primarily) gas caged within, gas hydrate deposits have special geochemical and stability characteristics. They are only stable in geological environments characterized by low formation temperatures and moderate formation pressures. Concentrated deposits can occur in the Arctic due to the low surface temperatures and presence of permafrost (Collett and Dallimore, 2000). The first Mallik well, Imperial Oil L-38 (Fig. 1), drilled in 1972, first identified the presence of gas hydrate in the Beaufort-Mackenzie Basin area (Bily and Dick, 1974) and four Mallik research wells (2L-38, 3L-38, 4L-38, and 5L-38) have subsequently been drilled in 1998 (Dallimore et al., 1999) and 2002 (Dallimore and Collett, 2005). These wells have encountered variable amounts of gas-hydrate-bearing stratigraphic units in the depth interval of 810 m to 1110 m, with gas hydrate saturations occasionally exceeding 90%. The gas hydrate tends to occur in the more sandy units, presumably due to the higher porosities. Osadetz et al. (2005) summarized other gas hydrate cuttings and coring in the region; however, the spatial and vertical extents of gas-hydrate-rich intervals are poorly understood (*see* e.g. Osadetz et al., 2005, Fig. 6).

DOWNHOLE LOGGING

A rich variety of state-of-the-art downhole logging equipment such as the Schlumberger Platform Express^{TM} including a High-Resolution Laterolog were deployed in the Mallik wells (Dallimore et al., 2005) and the results are documented in a number of papers (e.g. Takayama et al., 2005; Collett and Lee, 2005). As with all logs, the downhole electrical resistivity information is only obtained beneath the permafrost layer, which can be as thick as 675 m or so in the Mallik area (Collett and Lee, 2005). The electrical resistivity logs from Mallik 5L-38 were calibrated against visible gas hydrate in core obtained from the well (Medioli et al., 2005) by Collett and Lee (2005). Collett and Lee (2005) concluded that the resistivity log can “infer the occurrence of in situ gas hydrate at the Mallik drill site”. Therefore, the present author considers the electrical logs as a useful starting point for synthetic modelling of the MT response.

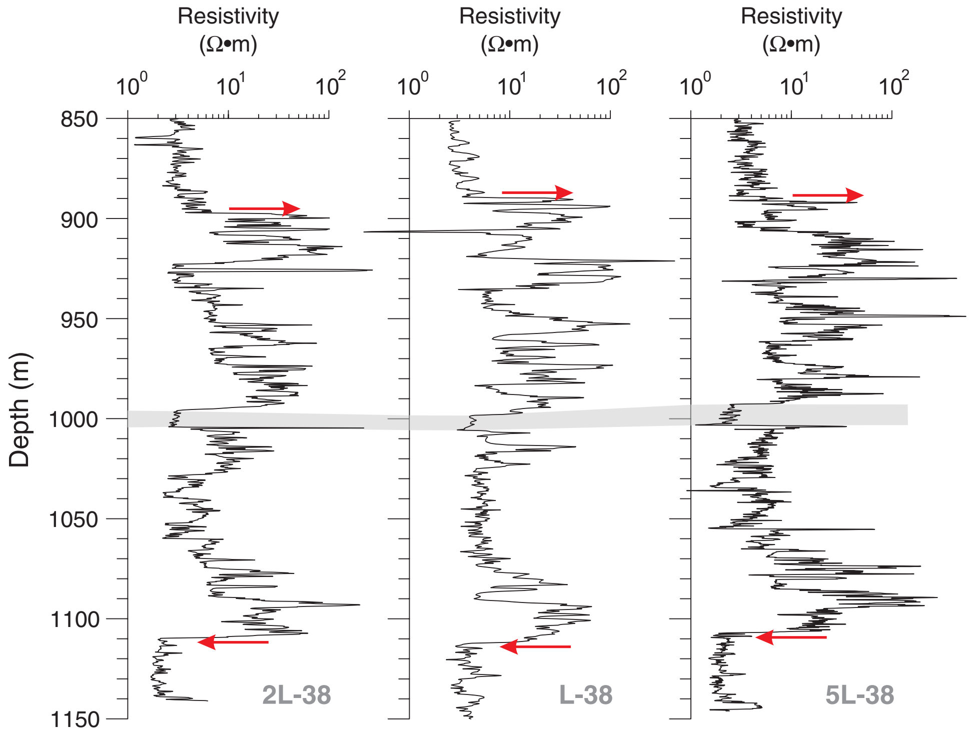

Figure 2. Electrical resistivity logs from three holes. The red arrows demonstrate key changes in resistivity likely to be displayed with the use of MT techniques. The shallower change is less likely to be better resolved due to the general inability of electromagnetic geophysical techniques to image resistive features. The background resistivity is approximately 3 Ω·m. The shaded layer demonstrates that certain correlations can be made with the logs from well to well (J. Mwenifumbo, pers. comm., 2007).

The resistivity logs from three wells are shown below (Fig. 2; J. Mwenifumbo, pers. comm., 2007). The plot demonstrates the utility of resistivity logs to identify the top and bottom of a diffuse gas hydrate layer and can be used to map significant layers within the gas hydrate zone.

SYNTHETIC MT RESPONSES

As mentioned earlier, the MT method is based on measuring amplitudes of the natural variations in the Earth's electric (E) and magnetic (H) fields. Ratios of these amplitudes provide an estimate of the impedance structure of the subsurface, which is sometimes expressed as an apparent resistivity (ρ_a) as a function of frequency (f):

$$\rho_a(\omega)=(\mu\omega)^{-1}\cdot(E(\omega)/H(\omega))^2$$

where $\omega = 2\pi f$ and μ is the magnetic permeability. For a given subsurface structure comprised of layers of fixed resistivity, it is possible to calculate the apparent resistivity as a function of frequency that would be observed by a site located at the surface. The phase lag between the measured E and H fields is also an important response function that can be calculated and measured at the surface. Figure 3a is a plot of various layered

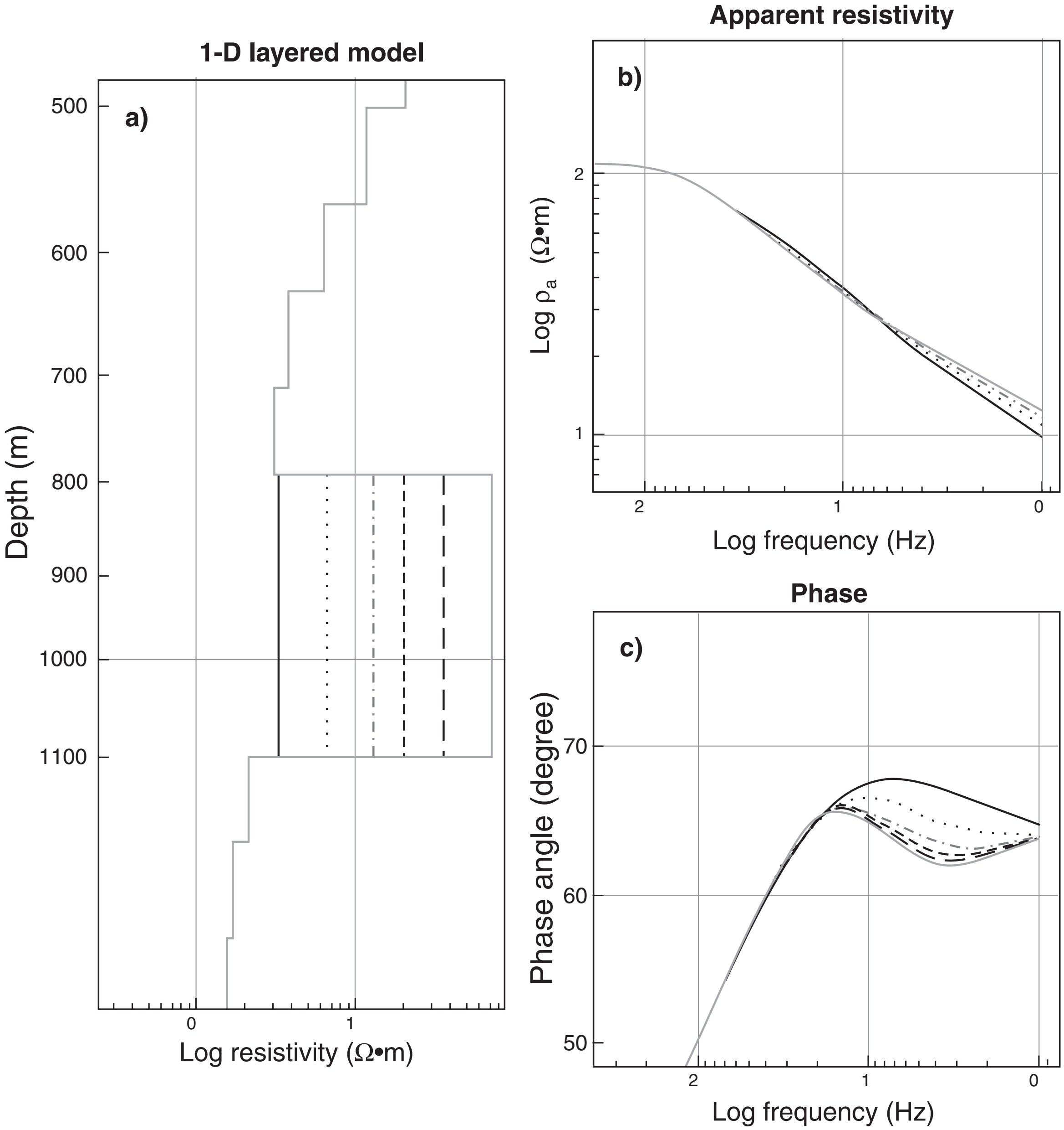

Figure 3. a) Plot of models and **b)** corresponding apparent resistivity and **c)** phase lags. Increasingly resistive values for the layer at 800–1100 m depth, corresponding to increasing gas hydrate content, are portrayed with different line types in Figure 3a. Matching line types are used in Figures 3b and 3c to demonstrate the sensitivity of the apparent resistivity and phase to the increasing resistivity of the layer.

earth models in the logarithmic domain. The synthetic apparent resistivities and phases are shown in Figures 3b and 3c, respectively. The response curve line styles are matched with the corresponding line style in Figure 3a. The layered earth models are based on the electrical borehole logs and represent various gas hydrate saturations for a layer between 800 m and 1100 m. The thicker model is the background based on zero gas hydrate concentrations at 3 Ω·m. As the concentration increases and the resistivity of the layer increases then one can see certain changes in the response curves, most noticeable in the phase (Fig. 3c); however, as the resistivity of the layer becomes sufficiently high, the effect on the phase also becomes negligible.

DISCUSSION AND CONCLUSIONS

It has been shown that the MT response, specifically the phase, has a large response to the presence of resistive units at the depth range corresponding to the known distribution of gas hydrate in the Mallik area. The anomalous response due to the presence of the resistor increases as the overall resistance of the layer increases, reflecting an increasing amount of frozen gas hydrate; however the anomalous response does not continue to increase with increasing presence of frozen material and therefore the ability of the MT method to delimit the true amount of gas hydrate is limited. It must also be borne in mind that the modelling done herein assumes the interval containing gas hydrate will act as a cohesive resistive unit. At present, there is limited information about the lateral and vertical continuity of gas hydrate. The borehole electrical logs shown in Figure 2 suggest that the vertical continuity of the gas hydrate is limited, i.e. the logs show thin resistive layers. If the gas hydrate deposits are present in only thin units throughout the entire depth interval of 800–1000 m then it is unlikely the MT method will detect the gas hydrate.

The magnetotelluric method is an inexpensive, deeply penetrating geophysical technique. It is inexpensive because it does not require the deployment of a transmitter. The MT method, however, requires the measurement of electric fields, which can be problematic in highly resistive surface environments such as permafrost and snow. As such, the utility of MT method for gas hydrate studies may be limited to summer measurements. Recently, Wannamaker et al. (2004) were able to make MT measurements in the Antarctic. The Geological Survey of Canada will be testing similar equipment to make electric field measurements in the region of the Mallik gas hydrate production research wells in late March and early April of 2007 with the view of making regional MT measurements one year later.

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