Interpretation of PP and PS seismic data from the Mackenzie Delta, N.W.T.

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ABSTRACT

The MKD-8 multicomponent seismic line was acquired in the spring of 2000 by the CREWES Project and Devon Canada Ltd. (formerly Anderson Exploration Ltd.). It was a six kilometre long line across a transition zone from floating to ground-fast ice in the Mackenzie Delta, N.W.T. The seismic data was processed to final stacked sections for both PP and PS wave. These sections have been interpreted in this work using logs from a neighbour well, Hansen G-07. The well is around 800 m away (southwest) from the MKD-8 line.

This represents the first known PS section in the Canadian Arctic. A very compelling correlation is found between the PP and PS sections. The Mackenzie Bay, Kugmallit, and Richards Sequences were interpreted in the well logs. Since the P sonic log from G-07 was limited to the depth range from 1200 m to 3200 m, the only sequences that could be interpreted in the seismic sections were the Kugmallit and the Richards. The P-wave synthetic matches the section very well. Some other dominant reflectors (K1 and K2), that correspond to lithological changes inside the Kugmallit Sequence were used to interpret the PS section.

Since the Hansen G-07 does not have a S sonic log, Vp/Vs values are inferred from Mallik 2L-38. These values are between 2.09 and 2.19 for the Iperk and Mackenzie Bay Sequences. Using this value as a reference it was found that the optimal Vp/Vs ratio to correlate PP and PS sections was 1.9, which corresponds to permafrost and ice.

INTRODUCTION

The Mackenzie Delta, N.W.T. has been an interesting area for oil and gas exploration. A large number of seismic surveys and well logs have been acquired in the last 40 years (Collett et al., 2002). Dixon et al. (1992) refer to the Beaufort-Mackenzie Basin as a major producer of hydrocarbons in the future. The demonstrated presence of methane hydrates (Dallimore et al., 1999) makes the Mackenzie Delta an even more attractive area for seismic exploration. A complete study, including downhole geophysics, has been completed in the Mallik 2L-38 well in the Mackenzie Delta, N.W.T. as part of the JAPEX/JNOC/GSC Mallik 2L-38 group, a collaborative agreement among the Japan National Oil Corporation, the Geological Survey of Canada and the United States Geological Survey (Dallimore et al., 1999). Gas hydrates may be broadly distributed in the Mackenzie-Beaufort basin (Dallimore et al., 1999; Collett et al., 2002).

A multicomponent seismic line was acquired in the spring of 2000 (Hall et al., 2002). A preliminary interpretation of this line is accomplished in this work using the Hansen G07 well log data.

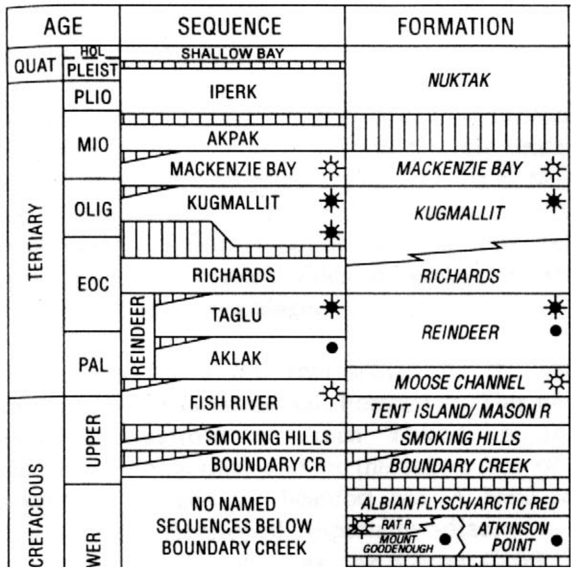

FIG 1. Stratigraphic column of the Mackenzie – Beaufort basin (Dixon et al., 1992). Observe that the Kugmallit Sequence has both oil and gas reservoirs.

Geology of the Mackenzie Delta

Consisting mostly of clastic rocks deposited in deltaic, shelf, slope and deep-water environments, the Upper Cretaceous to Holocene sediments in the Beaufort Mackenzie Delta is represented by 12 to 16 km of strata (Dixon et al., 1992). A large number of publications have described the geology of the Mackenzie Delta (reviewed by Dixon et al. 1992).

In the area of the Beaufort-Mackenzie Delta eleven regionally sequences have been identified, from the Upper Cretaceous to Holocene, figure 1. The structural basement is composed of Albian and older strata.

These sequences are (from older to younger):

- Boundary Creek (Upper Cretaceous)
- Smoking Hills (Upper Cretaceous)
- Fish River (Early Paleocene to Santonian or Campanian)
- Aklak (Late Paleocene to Early Eocene)
- Taglu (Early to Middle Eocene)

  The above sequences are not considered for this interpretation since there isn't any data available at those depths.

- Richards (Middle Eocene to Late Eocene)

  Only present as a thin delta complex in the Beaufort-Mackenzie Basin.

Thickness: Under the Mackenzie Delta and near-shore areas the sequence is 1000 to 2000 m thick.

Lithology: Under most of Mackenzie Delta, the Richards Sequence consists mostly of low-velocity shales. They are of variable thickness and the interval is easily identified on sonic logs.

Depositional environments: The depositional environment consists of pro delta deposits, mostly shale and siltstone.

Contacts: Upper boundary is conformable with overlying strata in the Mackenzie Delta. Lower boundary is conformable as well, with the exception of a few erosional unconformities.

Seismic and well-log character: consist of either a generally reflection-free interval or one in which there are only weak, discontinuous reflections.

- Kugmallit (Oligocene)

It has been identified only in the Beaufort-Mackenzie basin.

Thickness: up to 3000 m or 4000 m in thickness in the Issungnak area (Figure 2a).

Lithology: consist of conglomerates and gravels under the Mackenzie Delta.

Depositional environments: under Mackenzie Delta and the near-shore areas, delta plain deposits are prevalent in the sequence (Figure 2b).

Contacts: The lower boundary is abrupt throughout most of the basin but varies from apparently conformable (basinward) to an angular unconformity. The upper contact is also abrupt, but only erosional in the central shelf area. Mackenzie Bay Sequence overlies Kugmallit strata throughout most of the basin, although at the basin margins and some distal basin positions, the younger Iperk Sequence may rest erosional on Kugmallit beds.

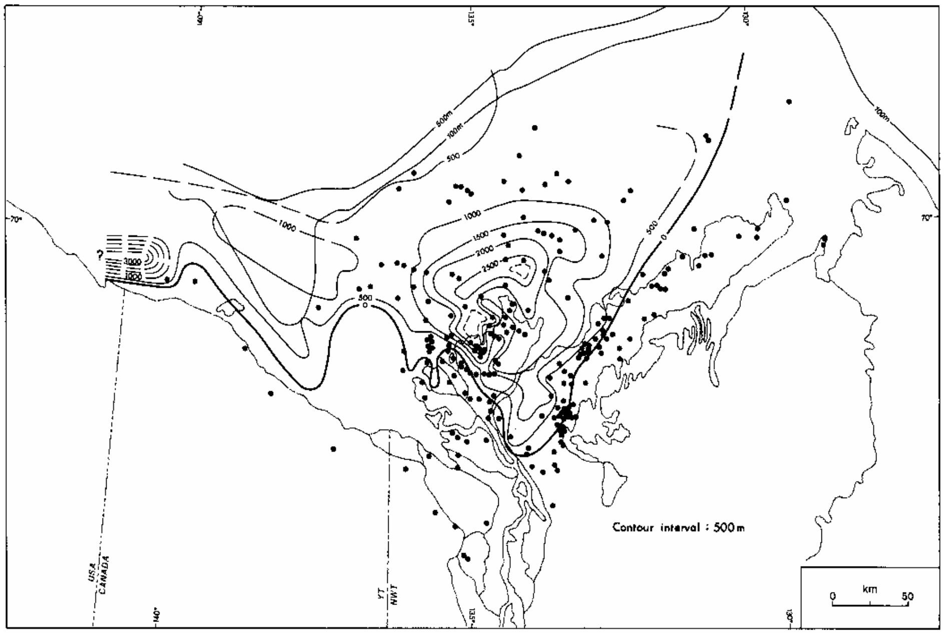

FIG 2a. Kugmallit Sequence isopach map. The thickness at Hansen Harbour G-07 is approximately 1800 meters (Dixon et al., 1992)

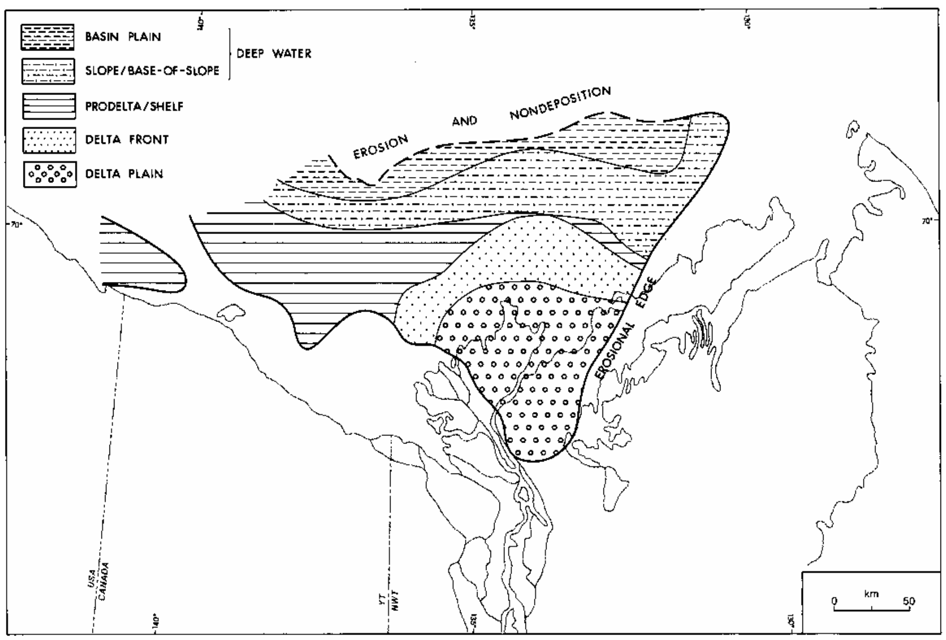

FIG 2b. Kugmallit Sequence interpreted depositional environments. Observe how the Kugmallit-sequence dominant environment is delta plain in the Hansen area (Dixon et al., 1992).

- <u>Mackenzie Bay (Miocene, Late to Middle Miocene)</u>

  Thickness: 2000 m in the western part of the Beaufort-Mackenzie Basin (Figure 3a).

  Lithology: shale is the dominant rock type in the central Beaufort area, but not in the Hansen Harbour area were deltaic sediments are dominant (Figure 3b).

  Depositional environments: the dominant environment in the Hansen Harbour area is delta plain to delta front, although to the north it becomes slope to deep water environment.

  Contacts: there is a marked lithological contrast between Mackenzie Bay shale and Kugmallit sandstones.

  Seismic and well-log character: The outer shelf and slope portions of the Mackenzie Bay Sequence are characterized by high-amplitude reflections and well-developed clinoforms, and are good examples of high-amplitude seismic facies developed in shale-dominant shelf sediments.

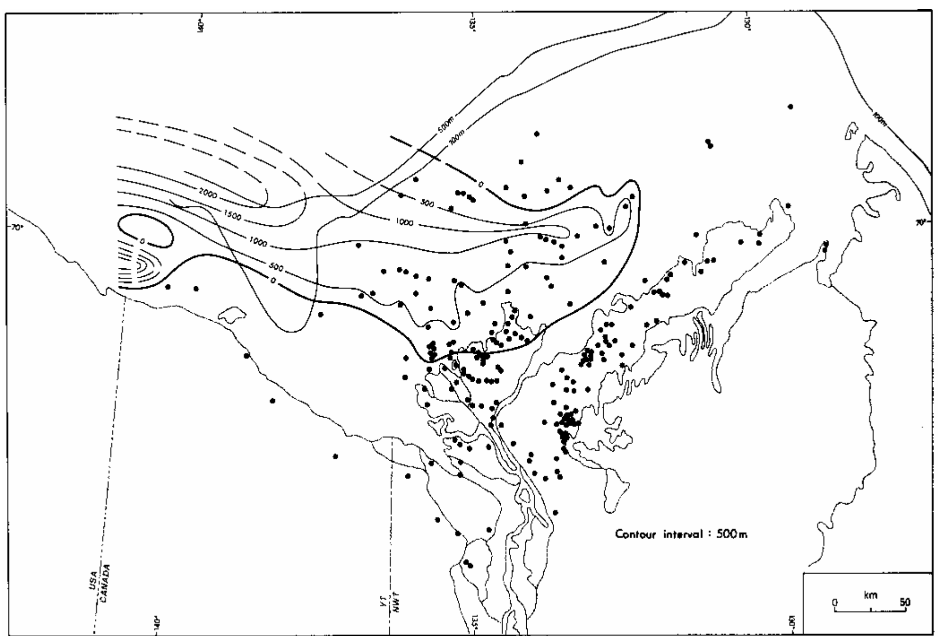

FIG 3a. Mackenzie Bay Sequence isopach map. The thickness at Hansen Harbour G-07 ranges from a few tens of meters up to 300 meters (Dixon et al., 1992)

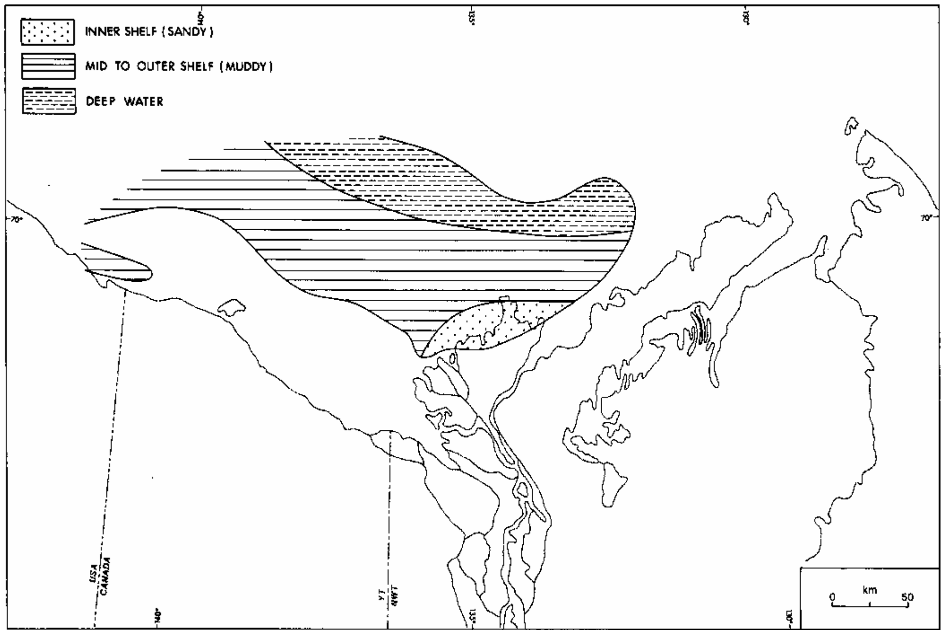

FIG 3b. Mackenzie Bay Sequence interpreted depositional environments. Notice how the sequence has an inner-shelf dominant environment in the Hansen area (Dixon et al., 1992)

- Akpak (Miocene, probably Late Miocene)

  This formation is not present in the Hansen Island area, since the isopach map indicates wedging to zero landward (Figure 4).

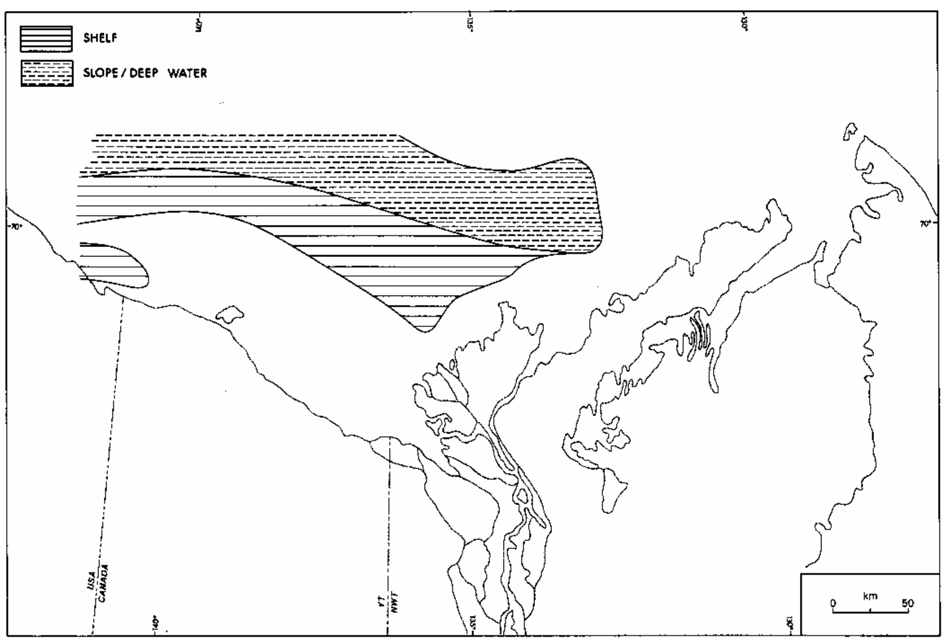

FIG 4. Akpak Sequence interpreted depositional environments. Observe how the sequence wedges towards the Hansen area (Dixon et al., 1992)

- Iperk (Pliocene to Pleistocene)

  Thickness: thickens from zero edge on the landward side of the basins to over 4000 m in the north Beaufort Sea (Figure 5a).

  Lithology: consists of weakly consolidated to unconsolidated sandstone and conglomerate at the basin margins, grading laterally into a succession with more shale. The Iperk Sequence was deposited as one, very large delta complex (centred over the eastern Beaufort Sea). The landward part of the sequence contains fluvial conglomerates and sandstones, grading laterally into deltaic and shelf sandstone and shale, in turn grading into and overlying slope shale and siltstone (Figure 5b).

  Contacts: Commonly difficult to separate Iperk from Shallow Bay strata. The base is a major erosional unconformity that can be traced throughout the Beaufort-Mackenzie and Banks Beaufort. The Iperk strata thin rapidly landward to a zero wedge.

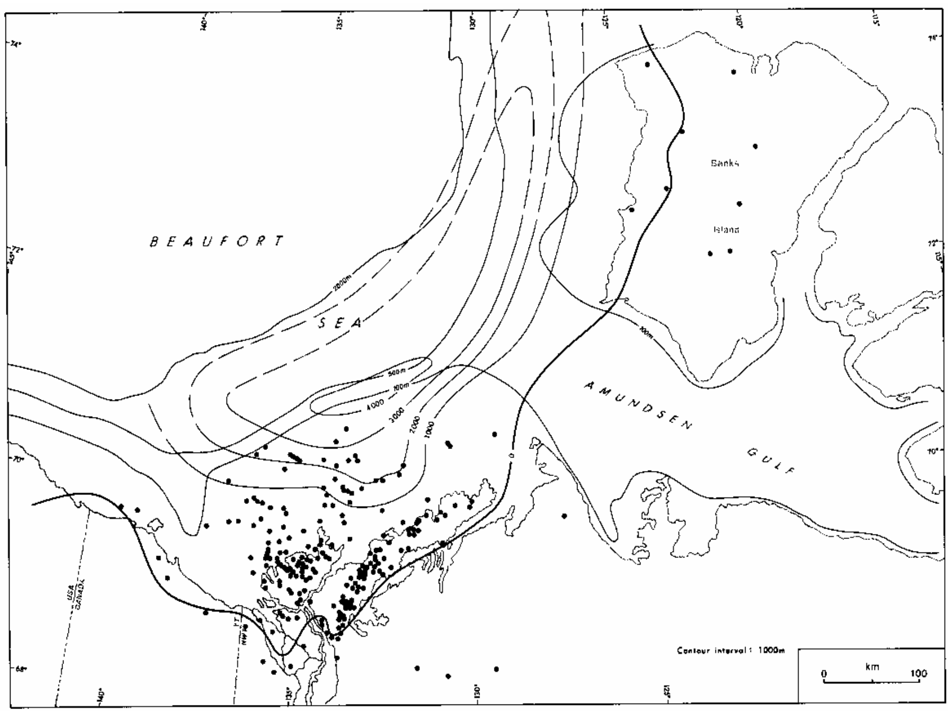

FIG 5a. Iperk Sequence isopach map. At Hansen Harbour G-07 is approximately 800 meters thick. (Dixon et al., 1992)

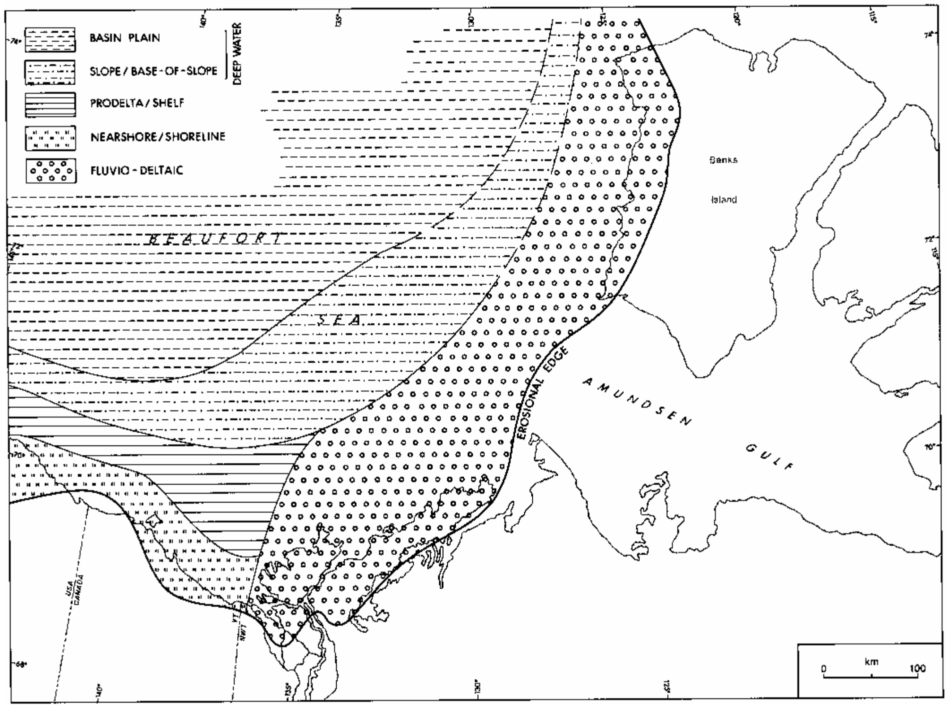

FIG 5b. Iperk Sequence interpreted depositional environments. The sequence has a fluvio-deltaic dominant environment in the Hansen area (Dixon et al., 1992)

- Shallow Bay (Cenomanian to Holocene)

  Seismic character: low-amplitude, discontinuous, subparallel reflections, but only in the Mackenzie trough. Elsewhere, is difficult to separate it from the underlying Iperk Sequence. Some other internal units could be defined using shallow, high-resolution seismic data.

  Depositional environments: characterized by oceanward prograding sequences, many of which are dominated by large delta complexes.

HANSEN G-07 WELL INTERPRETATION

A suit of 10 logs was acquired at the well Hansen G-07 (Figures 7a and 7b). This is an Imperial Esso well located in the Hadwen Island; Figure 6 shows the same location where the MKD-8 seismic line was recorded. It is reported as an oil and gas-producing well (Dixon et al., 1992). This well was logged to approximately 3250 m deep. Spontaneous potential, gamma-ray, caliper logs were acquired from 521.8 m to 3275 m depth. Sonic, density, resistivity (shallow, medium, deep) and porosity were acquired from 1196 m to 3275 m depth.

Using the GR and SONIC logs, three lithological boundaries separating four different lithological formations were identified (Figure 7a and Table 1). The notation used to define the mentioned lithology is Sequences A, B, C, and D, where A stands for the shallowest; and the contacts are L1 (between A and B), L2 (between B and C) and L3 (between C and D) (Figures 7a and 7b).

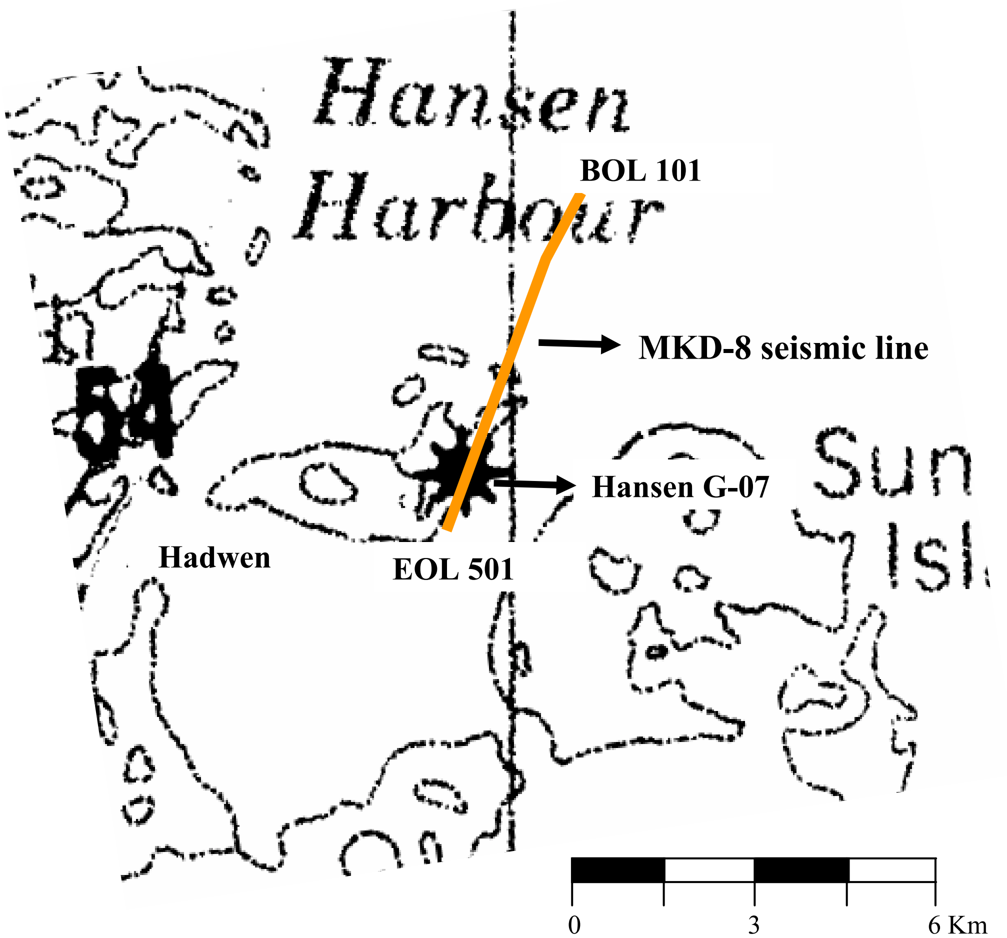

FIG 6. Hansen Harbour - Mackenzie Delta area, N.W.T. The six – kilometer MKD-8 seismic line is located along a transitional path from floating ice (BOL101) to ground-fast ice (EOL101). Hansen G-07 is an Imperial Esso well. It is classified as an oil & gas producing well, but no other information is available (Dixon et al., 1992).

Table 1 Depth and thicknesses for defined sequences in the Hansen G-07 well.

BOUNDARY	DEPTH [m]	SEQUENCE	THICKNESS [m]
[L1] TOP B	691.4	B	1180.1
[L2] TOP C	1871.5	C	765.4
[L3] TOP D	2636.9	D	n.a.
TOP TARGET 1	2372.9	TARGET 1	31.0
BASE TARGET 1	2403.9	TARGET 2	43.7
TOP TARGET 2	2548.8		
BASE TARGET 2	2592.5		

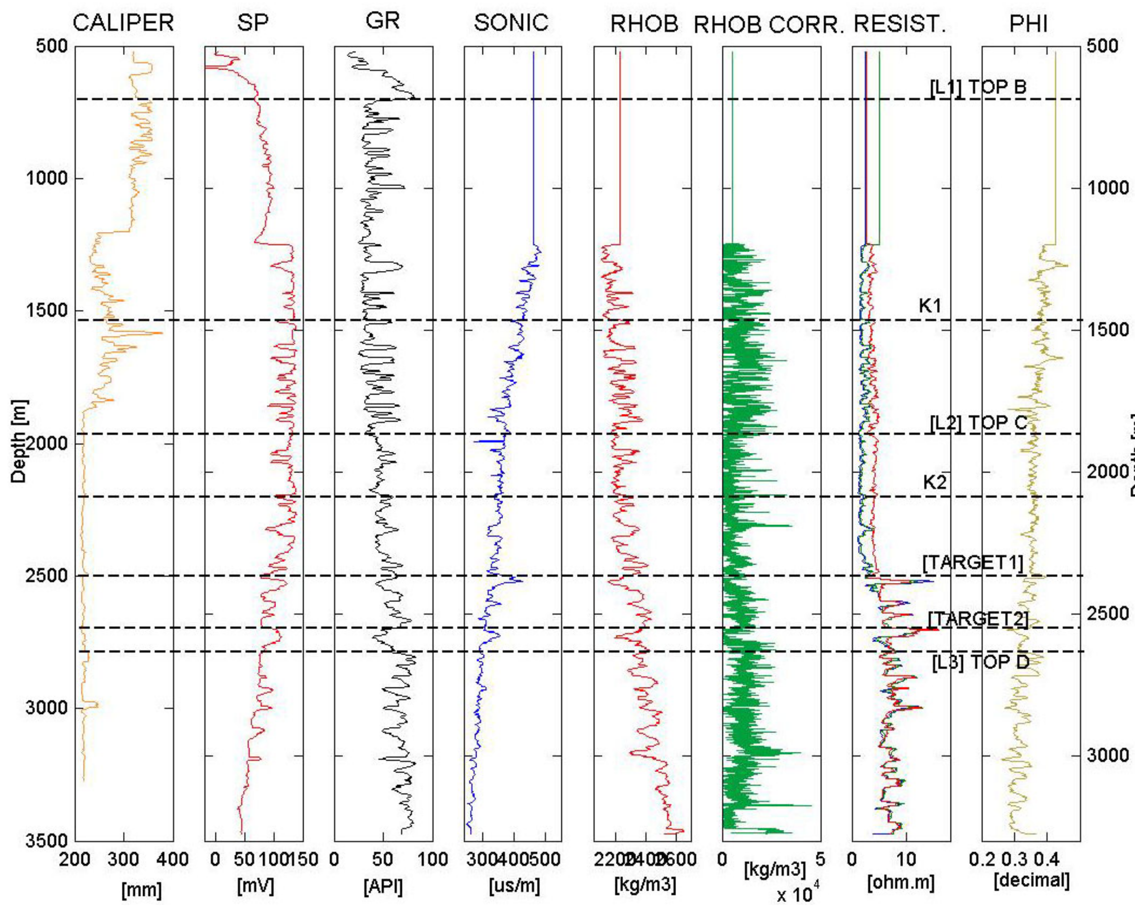

FIG 7a. Hansen Harbour G-07 well logs. Observe that the SP, gamma ray and caliper logs were acquired from 521.8 m to 3275 m, and the rest went up to 1196 m only. Based on the GR log the lithology of this well was separated into 4 sequences: A, B, C, and D, A being the shallowest and D the deepest sequence. Notice the two target zones defined in the sequence C.

- <u>Sequence A</u>

This sequence consists of a thick shale body and a sand interval over it (Figure 7a). The top of this sequence could not be defined since it is out of the logged interval. The caliper response for the shale body indicates a competent rock.

- <u>L1 boundary</u>

Defined as a lithological contrast at 691.4 m deep, it separates the shale body (Sequence A) from the underlying Sequence B, consisting of a succession of shale and unconsolidated to consolidated sands.

- <u>Sequence B</u>

The sequence ranges from L1 boundary (691.4 m deep) to L2 (1871.5 m depth). Thickness of this sequence is 1180.1 m. The lithology of this sequence is a succession of shale (from 10 to 40 m) and sand (10 to 90 m) bodies. The predominance of sand in this sequence is easily observed on the gamma-ray log.

At 1196 m the remaining logs (sonic, resistivity, density and porosity) were started to be recorded.

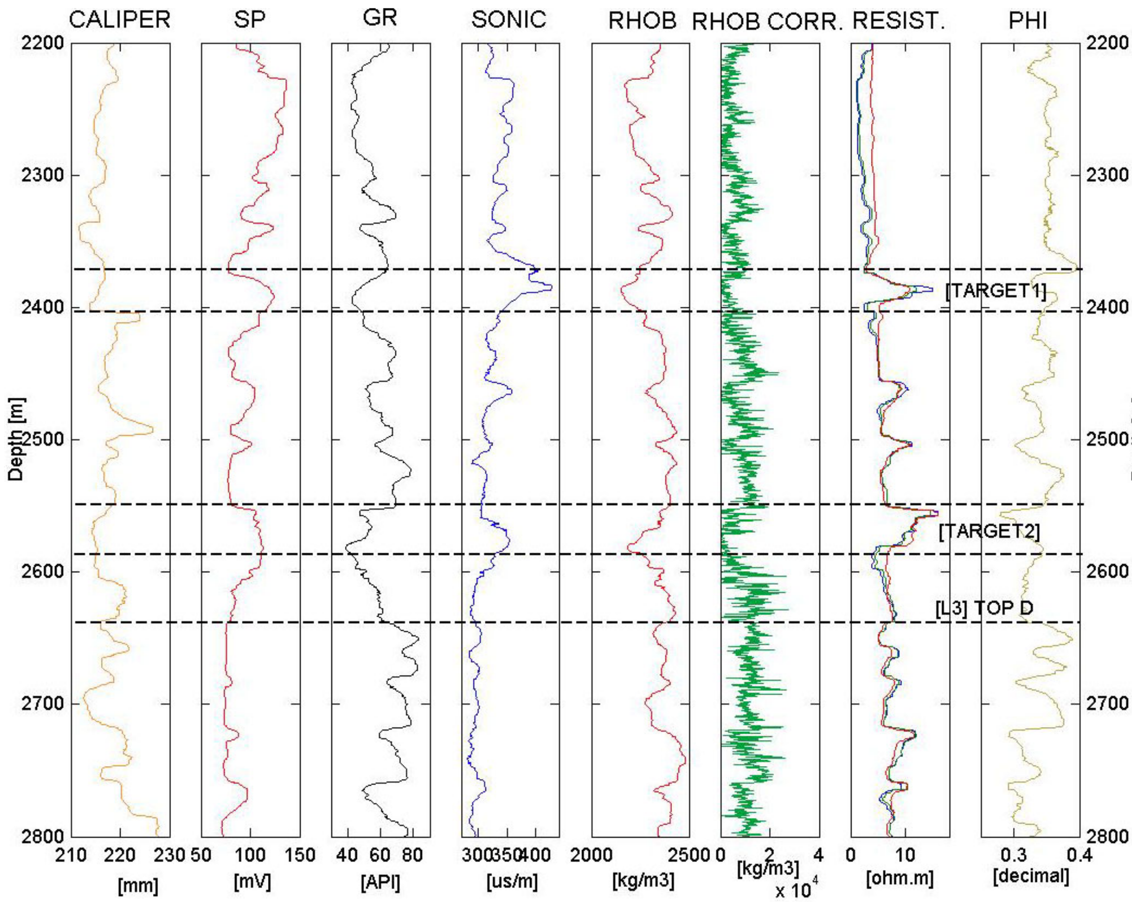

FIG 7b. Target zones in the Hansen G-07 well. Notice the two bodies defined in the sequence C as TARGET1 and TARGET2. These were marked because of their sonic and resistivity contrast which should be seismically recognizable.

- L2 boundary

It is defined at 1871.5 m deep. It separates two different lithological successions (B and C). The contrast in the gamma-ray log distribution gives an evidence of the contact, as well as a difference in the shape of the density and sonic log.

- Sequence C

It consists of a succession of thicker more competent sand (40 m to 100 m) and shale (10 to 50 m) layers, and a total thickness of 765.4 m. This sequence has more shale content than Sequence B (observe how the gamma ray values are higher in average (Figure 7a). Two seismically recognizable layers are present in this sequence, TARGET 1 and TARGET 2, (Figure 7b and Table 2). These bodies are attractive because of their high deep, medium, and shallow resistivity values (Figure 7b).

- L3 boundary

Defined at 2650-m deep, this contact divides sequence C and D. A thick low velocity layer (60 m approximately) lies over a sequence of shale dominant layers.

- Sequence D

It is more shally than the overlying sequence. The lithology of this sequence is mostly shale intercalated with a few thin sand layers (from 10 to 30 m thick).

Table 2 Statistics for TARGETS in Sequence C [Hansen G-07 well]

Sequence	Vp [m/s]				Density [kg/m3]			
	Mean	Median	Min.	Max	Mean	Median	Min.	Max
TARGET 1	2628.36	2594.71	2971.77	2340.28	2200.10	2199.12	2150.40	2276.37
TARGET 2	3029.55	3040.44	3306.88	2821.68	2294.02	2285.79	2187.32	2400.87

A model for the surrounding area of the Hansen Island was defined using the isopach maps (modified from Dixon et al., 1992) of all the geological sequences. This model consists of the following sequences:

- Iperk: due to the starting depth of logging, 500 m, the presence of this sequence is not expected to appear at this location. Even though, it should be present in the shallow times of the seismic section.

- Akpak: not present at this location as it wedges to zero thickness (Figure 4).

- Mackenzie: depending on the real thickness of this sequence at G-07, this sequence should be represented by the first 200 m of the well logs (Figure 3a).

- Kugmallit: a complete section of Kugmallit should have been logged at G-07, 1800 m approximately (Figure 2a).

- Richards: the presence of this sequence depends on the real thickness of the Kugmallit. If present, it should appear at the very bottom of G-07 with a total thickness of 1400 m approximately.

Correlating the interpretation of the logs from Hansen G-07, constrained with the theoretical depth model taken from the isopach maps, with the geological description it can be inferred:

- [L1] TOP B: Mackenzie Bay Sequence and Kugmallit Sequence contact

- [L2] TOP C: interface where the Kugmallit Sequence become shale-dominant.

- [L3] TOP D: Kugmallit Sequence and Richards Sequence contact

- Sequence A [*Mackenzie Bay Sequence*] thickness cannot be calculated.

- Sequence B and C [*Kugmallit Sequence*]: thickness of 1945.5 m
- Sequence D [*Richards Sequence*] thickness cannot be calculated.

SYNTHETIC SEISMIC SECTIONS

Using the “synth” application from the CREWES MATLAB Seismic Toolbox several synthetic sections were created (Figures 8 and 9). The objective was to interpret the PP and PS seismic sections obtained with the 3C geophones in the Hansen Harbour area. The parameters used to define the synthetic sections are:

- Type of section: NMO removed
- Maximum offset = 1500 m
- Offset increment = 100 m
- Offset/depth ratio = 1
- Vp/Vs ratio = variable from 1.6 to 2.8
- Ricker wavelet, 30 Hz dominant frequency
- No attenuation or geometrical spreading effects included

Since no shear-wave sonic log was acquired at Hansen G-07, several panels with different constant Vp/Vs ratios were created to define an appropriate Vp/Vs depth function.

An almost direct correlation was found between the PP synthetic stacked seismic section from Hansen G-07 and the PP migrated seismic section from Hanson (Figure 8). Although the indicators used to correlate the well data are not easily recognized, both the Kugmallit – Richards Sequence contact and the Target zones at the bottom of the Kugmallit Sequence were successfully identified in the PP seismic section.

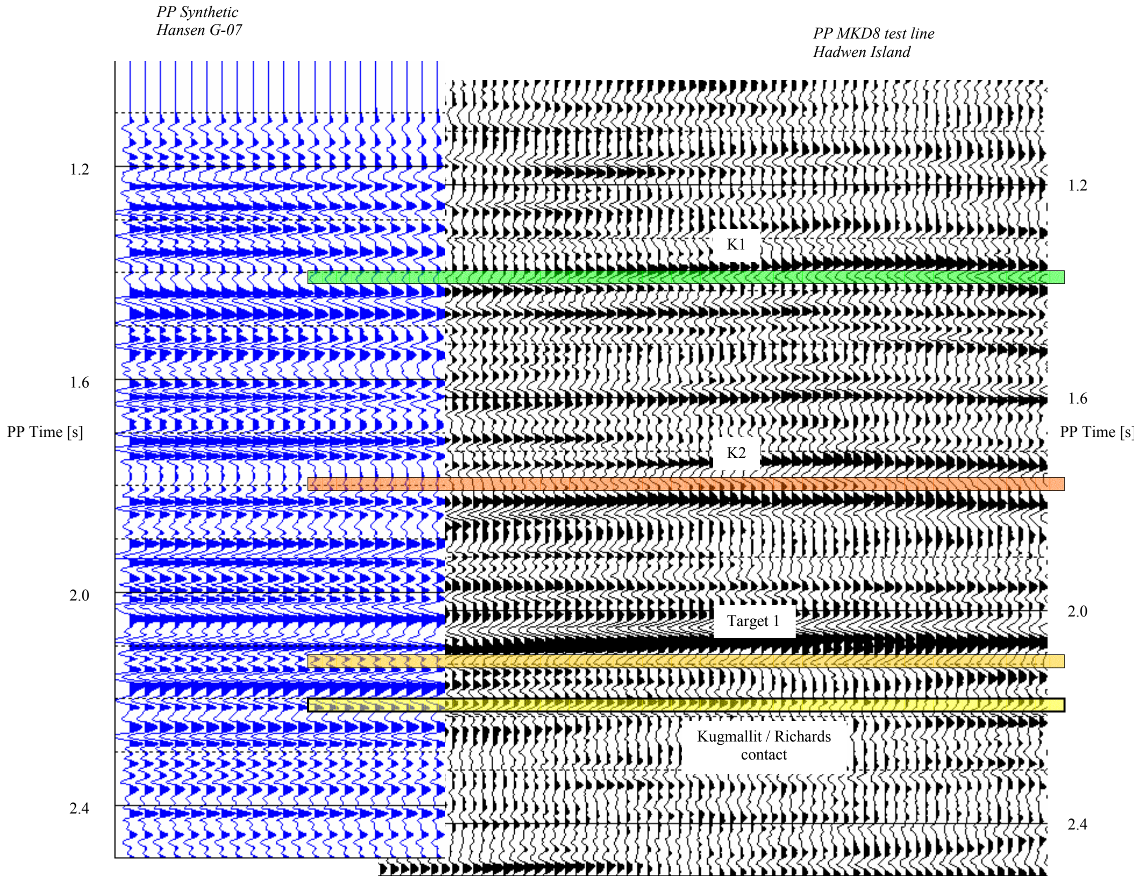

FIG 8. PP seismic data correlation. The traces displayed in the left panel correspond to the synthetic NMO removed seismic section. Observe that the targets are not easily recognized in the section. The absence of shallow data doesn't allow the interpretation of the Kugmallit / Mackenzie Bay boundary.

Once the PP section has been interpreted, the next thing to do is understand the PS section. The sequence used to do this consists in:

(1) Estimation of Vp/Vs ratio for different sequences from a relatively close well.

The closest well that had both P-wave and S-wave sonic logs, as well as other logs, and that has been extensively studied is the Mallik 2L-38 (Figure 9). The present sequences at this location are: Iperk, Mackenzie Bay, and Kugmallit. The base of the permafrost occurs at 640 m (Mi et al., 1999). The Vp/Vs curve was calculated from the sonic logs (Figure 9). An average ratio for each sequence was taken from this log (Table 3).

Table 3. Vp/Vs values for Mallik 2L-38 well

Sequence	Vp/Vs statistics			
	Mean	Median	Minimum	Maximum
Iperk	**2.19**	**2.17**	1.44	2.90
Upper Mackenzie Bay	**2.04**	**2.08**	1.31	2.62
Lower Mackenzie Bay	**2.41**	**2.46**	1.42	2.81
Kugmallit	**2.30**	**2.30**	1.98	2.69

Observe that the Mackenzie Bay has two very different zones, the upper and lower part. The reason the Vp/Vs changes across the sequence is the presence of permafrost (Figure 9). The upper part has a value of 2.04 and the lower 2.41. The value Vp/Vs for the Iperk Sequence is 2.19, which is larger than the Mackenzie Bay, indicating a change in lithology.

In general, the following values are good approximation of the Vp/Vs of the area: 2.1 for the permafrost section (upper Mackenzie Bay), and 2.4 below the permafrost (lower Mackenzie Bay and Kugmallit).

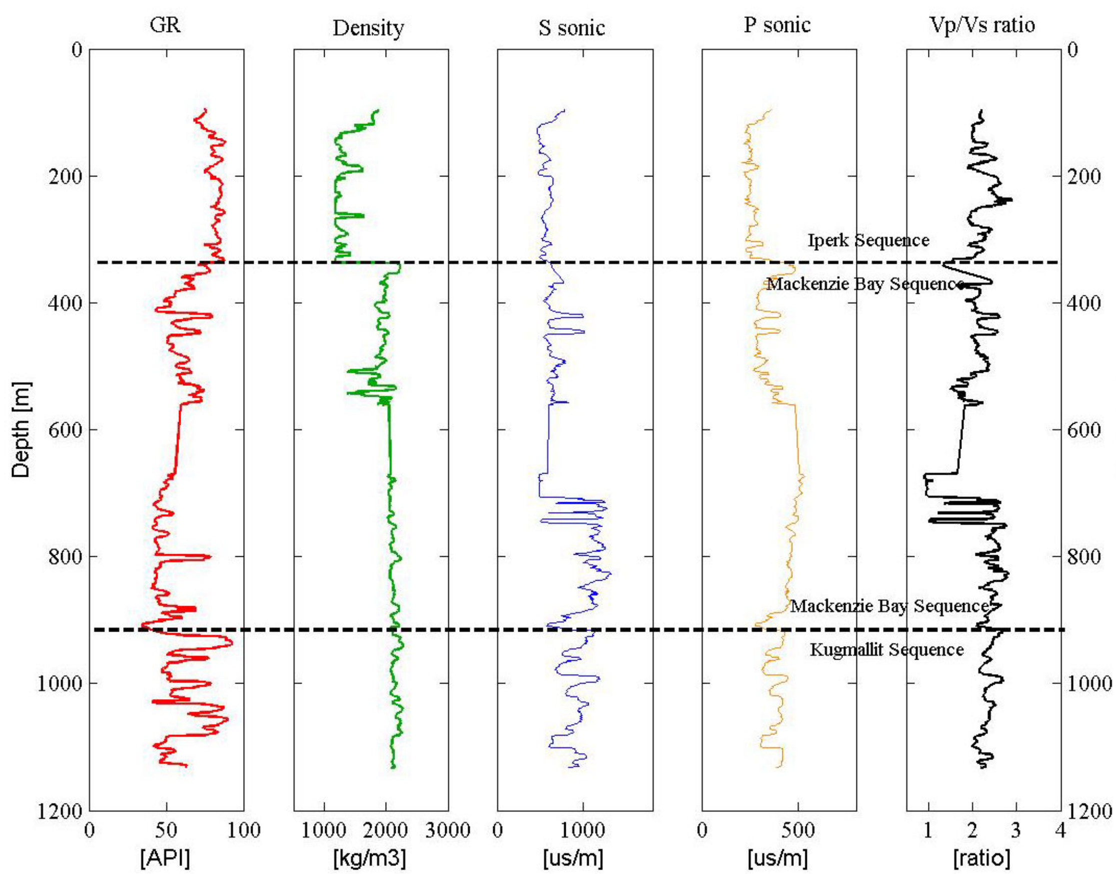

FIG 9. Mallik 2L-38 well logs (used by several authors to evidence the presence of gas hydrates in the Mackenzie Delta). The base of ice-bearing permafrost occurs at 640 m deep. The section from 550 m to 718 m was omitted when estimating the Vp/Vs ratio for the lower and upper part of the Mackenzie Bay Sequence.

(2) Comparison of real PP and PS sections using several Vp/Vs values

Two reflectors "K1" and "K2" were originally defined to help interpret the PS section, figure 7a. Both are part of the Kugmallit Sequence. The reason for that is to be able to use the good quality data in the shallow part of the line since the PS section does not have a good definition in the deep part.

Using the calculated Vp/Vs values and lower, the PS section was stretched by its respective factor in order to match the PP section. Based mainly on the seismic character (amplitude, continuity) of the reflectors K1 and K2 and omitting any structure around the edges, the PS section was successfully correlated with the PP section using a Vp/Vs ratio of *1.9*, figure 10.

A low pass frequency filter, 45 Hz, was used to correlate the events K1 and K2. Reliability of the interpretation in the deep area (K2 indicator) is not so high since there is no control of the shallow velocity and density values. This represents a preliminary approach, since the PS section loose seismic character under K1.

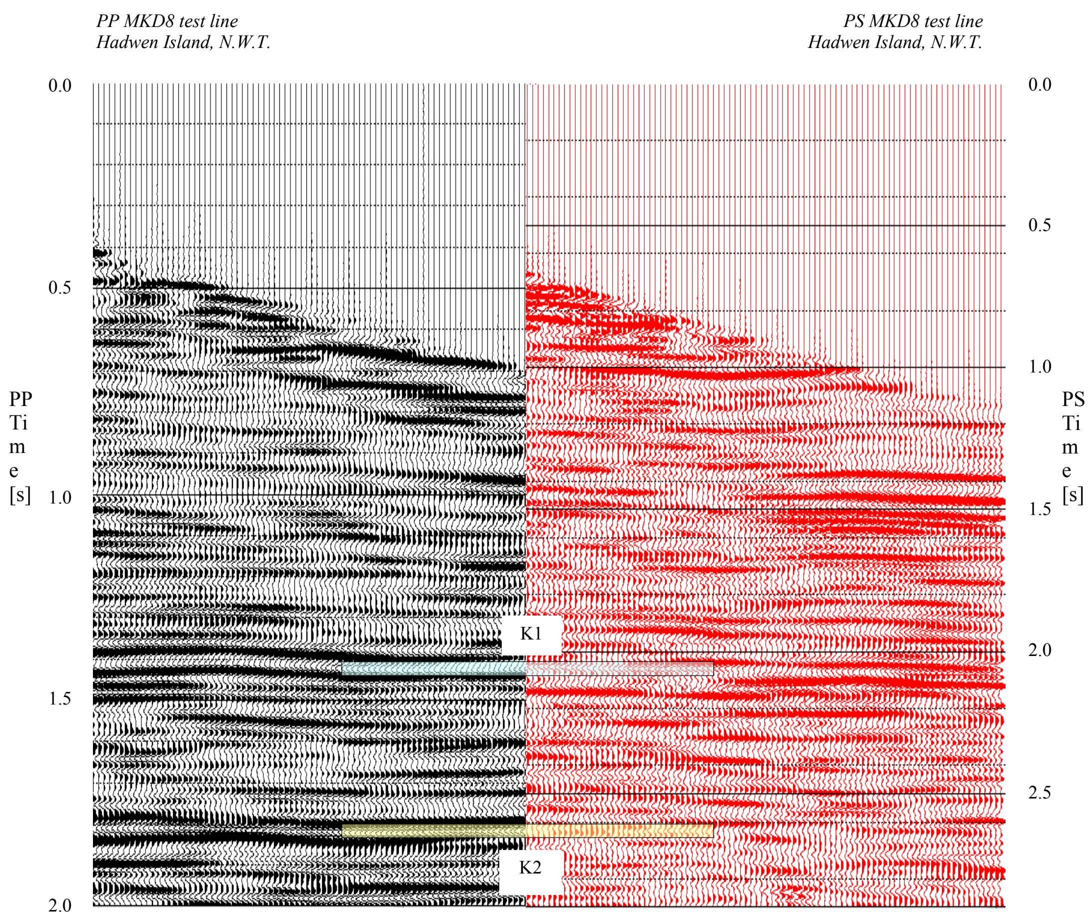

FIG 10. PS NMO removed seismic data correlation. The targets are not easily recognized in this section either, but the reflectors K1 and K2 serve as a reference in the Kugmallit Sequence.

(3) Including the PS synthetic section to finish the interpretation.

Using the Vp/Vs values mentioned before two PS synthetic seismic sections were calculated and correlated with the real PP and PS sections, reaffirming the interpretation of the data (Figure 11).

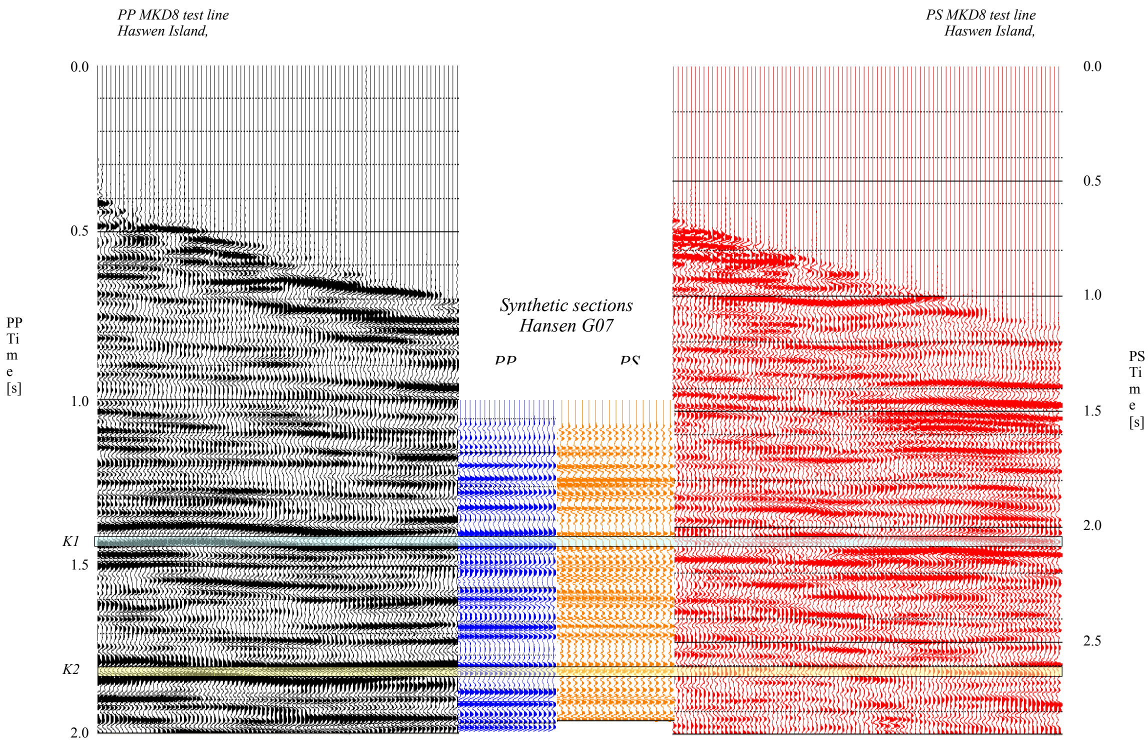

FIG 9. Final correlation of the PP and PS synthetic section with the MKD-8 seismic line. From left to right: MKD-8 PP seismic section (black); Hansen G-07 PP seismic section (blue), Hansen G-07 PS seismic section (orange); MKD-8 PS seismic section (red). The synthetics start at 1 sec PP time, equivalent to 1.5 sec PS time, approximately, due to the absence of the shallow part of the well logs.

CONCLUSIONS

A preliminary interpretation of the Hansen seismic line and Hansen G-07 well was achieved. It was interpreted that the Mackenzie Bay, Kugmallit, and Richards sequences are present in the G-07 well. The well-log response indicates that the target zones inside the Kugmallit Sequence are likely to be the producing oil and gas formations. The PP and PS MKD-8 seismic section were successfully correlated with the synthetic sections. The Vp/Vs function estimated from the Mallik 2L-38 was a good approximation to interpret the PS MKD-8 seismic section.

An important observation from the Hansen well-logs is that it should report gas hydrates around 1200 m deep. Since none of the G-07 logs used to discriminate the presence of hydrates were recorded at this depth, the integration of other well logs in the vicinity remains. A thorough analysis of amplitude variations is required as well in order to verify the presence or absence of gas hydrates.

An evaluation of Vp/Vs shallow values from well logs close to the area are required to obtain an estimate of this parameter. This would improve the accuracy of the interpretation.

ACKNOWLEDGEMENTS

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