Multicomponent seismic acquisition in the MacKenzie Delta, N.W.T.

Kevin W. Hall[1], Carlos E. Nieto[1], Eric V. Gallant[1], Robert R. Stewart[1], and Peter Cary[2] - [1]CREWES, Department of Geology and Geophysics, University of Calgary and [2]Sensor Geophysical Ltd.

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Introduction

The Mackenzie Delta, N.W.T. is the location of considerable seismic exploration activity. This exploration excitement is being driven by the possibility of discovering large hydrocarbon reservoirs as well as the intriguing promise of shallow methane hydrates, thus, the impetus for seismic acquisition and analysis. Work commitments (Polczer, 2001) and continental demand for more hydrocarbons indicate a continued interest. There are however, a number of challenges manifest in seismic acquisition and analysis. Aside from the extreme cold of day-to-day operation, permafrost presents a very heterogeneous complexion for the near surface. Surveying on floating ice is another major problem. The question is, what field acquisition techniques and ultimately processing procedures can be used to generate the best subsurface images?

In the spring of 2001, the CREWES project in conjunction with Devon Canada Ltd. (formerly Anderson Exploration Ltd.), and a seismic contractor acquired a six-kilometre test line (MKD-8), centred over a transition zone from floating to ground-fast ice in the Mackenzie Delta. Several different types of receivers, including a 750 m 3-C geophone receiver line were laid out, and the entire line was shot with two tracked Vibroseis vehicles, and again with dynamite. A series of sweep tests and noise strips were also recorded. A hammer seismic survey of thirty meters source line length was carried out, recorded by the 3-C geophones only. The hammer seismic survey included vertical hits on the ice, forty-five degree hits in opposite directions into forty-five degree V-shaped notches chopped into the ice, and tests hitting steel plates, wood blocks or the ice directly. Ice velocities from the hammer seismic profiles indicate P-wave values of 3137 m/s and S-wave velocities of 1900 m/s. We were also able to produce very promising P-S sections from the 3-C geophone spread for Vibroseis and dynamite sources.

A preliminary analysis of dynamite and vibrator gathers has been made. The transition from ground-fast to floating ice has a profound (and deleterious) effect on seismic data quality. The vertical and radial components of data recorded by the 3-C geophones for the vibrator and dynamite sources have been processed to migrated stacks, and show good reflectivity under the ground-fast ice. Reflections are also present under the floating ice, but have a poorer signal-noise ratio and less coherence. Frequencies up to at least 90 Hz are observed in the data. There is a distinct change in reflection character across the transition zone. A strong flexural wave was observed on all shot records, but is most pronounced for Vibe points on the floating ice. Interestingly, modeling studies have shown that dispersive waves (flexural waves) generated by a point source on floating ice can be strong enough to completely obscure reflections (Rendleman et. al., 1990). Proubasta (1985) observed that a flexural wave produced at a transition zone travelled many miles offshore through the pack ice. However, the flexural wave was attenuated when cracks, pressure ridges, or trenches were present between the source and receivers. A filter designed specifically to remove dispersive waves has been described by Beresford-Smith et.al. (1988).

Geologic setting and rock properties

The Beaufort-Mackenzie basin formed on a post-rift continental margin. The rifting episode began in the Jurassic and continued to the end of the lower Cretaceous. From then until the late Tertiary, compressional tectonics was predominant. Listric faults, folds, and thrust faults are present at various locations in the basin. The combination of significant sedimentation and these structures has resulted in numerous possible traps for hydrocarbons (Dixon et al., 2001).

Mi et al. (1999) have provided a detailed discussion of the stratigraphy in a neighbouring location – the Mallik 2L-38 well. They indicate that the upper sequence (Iperk from 0–346 m) is mainly composed of ice-bonded sand with occasional silt and clay layers. The Mackenzie Bay sequence (346-926 m) consists of sand and weakly cemented sandstone with silt/shale interbeds. The Kugmallit sequence extends below 926 m. The base of the permafrost is at about 640 m and gas hydrates occur between 897 m and 1110 m. VSP and full-waveform sonic logs give P and S-wave velocities of about 3300 m/s and 1500 m/s, respectively, above the base of the permafrost. There is a marked decrease in P and S velocities below the permafrost (to 2100 m/s and 700 m/s). In the gas-hydrate section, the velocities increase to about 2600 m/s for the P waves and 1100 m/s for the S waves. We note that the Vp/Vs value is significantly lower (about 2.4) in the permafrost and gas-hydrate bearing strata than the intervening region with a Vp/Vs value of about 3.1.

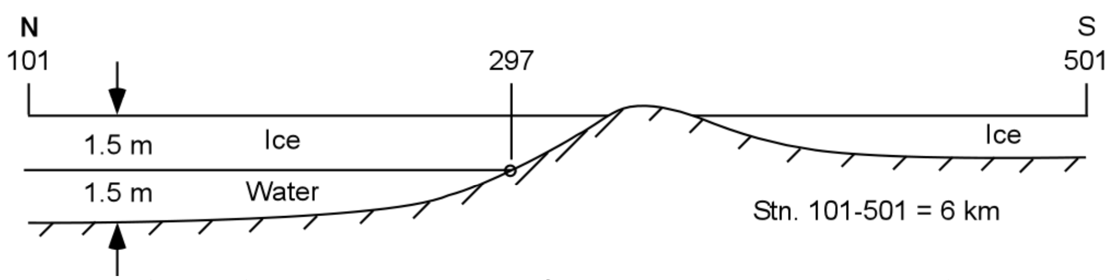

FIG. 1. Schematic diagram of near-surface conditions along the line. Station 297 is the approximate location of the transition from ground-fast to floating ice.

Near-surface conditions along the MKD-8 test line are shown in Figure 1. A transition from floating sea ice to ground-fast sea ice occurred about halfway along the line (Station 297, Figure 1). Just south of this point frozen sand, possibly the Iperk sequence, was observed at the surface. To the north of the transition, the seismic crew planting hydrophones and marshphones in the sea floor described it as muck, soft muck, and very soft muck.

Receiver geometry

The geometry of the MKD-8 2-D seismic line is as follows: The total line length was 6 km, with 3 km on floating sea ice and 3 km on the ground-fast ice. Station 101 was on the floating ice at the north end, and station 501 was on the ground-fast ice at the south end. There were a total of seven receiver lines (Figure 2). All receivers were live for all dynamite and Vibroseis shots.

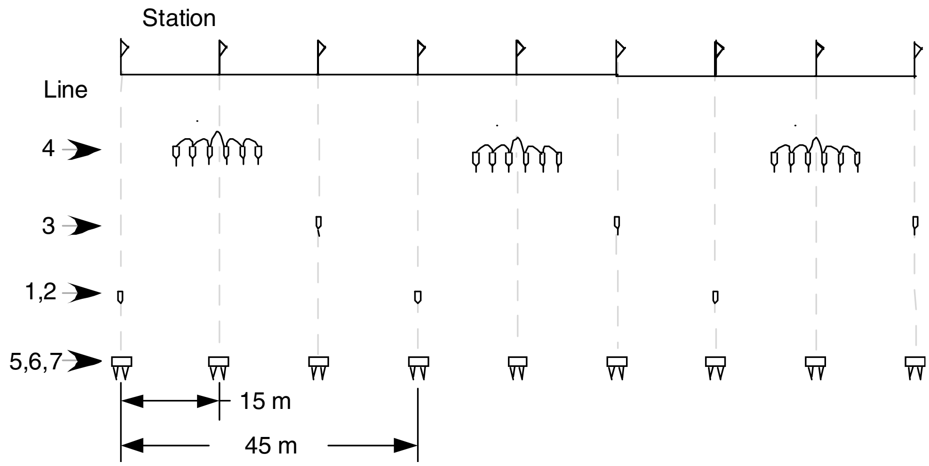

FIG. 2. Diagram of the receiver layout. Line 1: single Mark Products PE-44 hydrophones (under floating ice only). Line 2: single Oyo Geospace GS30CT marshphones, planted in sea floor/frozen ground below ice. Line 3: single marshphones in 0.30 m holes in ice. Line 4: six geophone arrays of marshphones, 2 m apart. Line 5: H1 component of Sensor 3-C geophones with SM-4 elements frozen into 0.15 m holes in the ice. Line 6: Vertical component. Line 7: H2 component.

Source geometry

The line was shot with three sources, 1) vibrator, 2) dynamite and 3) sledge hammer. The Vibroseis and dynamite surveys comprised the entire length of the line. The hammer survey consisted of vertical and forty-five degree hits on ice every meter for thirty meters, on the floating ice only.

Source line 1 was shot using two Mertz 18HD tracked vibrators, with a hold down weight of 50,000 pounds each. Vibe points were on every half station with the vibes centred in-line, from stations 101.5 to 501.5. The linear sweep used for this test line was 6-96 Hz over 32 seconds, and the correlated records are eight seconds long.

Source line 2 was shot with dynamite at 90 m station spacing. On the floating ice, an in-line five-hole pattern (north/south) with 2 kg per hole was used. If the charge could not be placed at least 7 m below the seafloor, that shot point was not used. On the ground-fast ice, single 20 kg charges at a depth of 20 m were used.

Source lines 3, 4 and 5, were twelve pound sledge hammer hits on the ice surface from station 285 to station 287, for a total source line length of thirty meters. Three shots were recorded every meter, 1) a vertical hit, 2) a 45^{O} hit into a V shaped notch in the ice towards the east, and 3) a 45^{O} hit on the opposite side of the notch, towards the west (Figure 3). An audible tone was transmitted from the recorder for timing, so time-zero depended on human reflexes, and is different for every shot record. The objective of this survey was to characterize ice properties by recording a large number of closely spaced shots with a single receiver. The resulting receiver gather(s) should allow very accurate characterization of ice properties.

Description of shot records

When the source is on/under the floating ice, energy in the direct arrivals crosses the transition zone for both Vibroseis and dynamite. However, a significant part of the energy on the horizontal channels of the 3-C geophones is reflected from the transition zone back towards the floating ice.

When the source is close to the transition zone, energy propagates towards land and out to sea equally well. However, a change in reflection character is visible, and the data on the floating ice part of the line are noisier. The horizontal channels show energy is reverberating through the ice sheet and water column, possibly bouncing off a ground/ice contact further to sea.

However, for sources on/under the ground fast ice, dynamite produced more interpretable first breaks on the floating ice (north of the transition zone). Energy on some Vibroseis shot records appears to stop at the transition zone, although there are some hints of energy being reflected back towards the ground-fast ice.

Figure 3 shows a hammer seismic shot record. Direct arrivals are seen on every 3-C geophone on the floating ice, but not south of the transition zone. Direct arrivals can be seen reflecting back to sea from the transition zone on line 7 (H2 component), particularly with a shear-wave source (Figure 3). A series of reverberations are preferentially recorded on line 5 (H1 component). Some of the hammer seismic shot records show distinctive noise trains, probably waves generated by ice cracking, which travel through the ice sheet and arrive before the hammer hit (not shown).

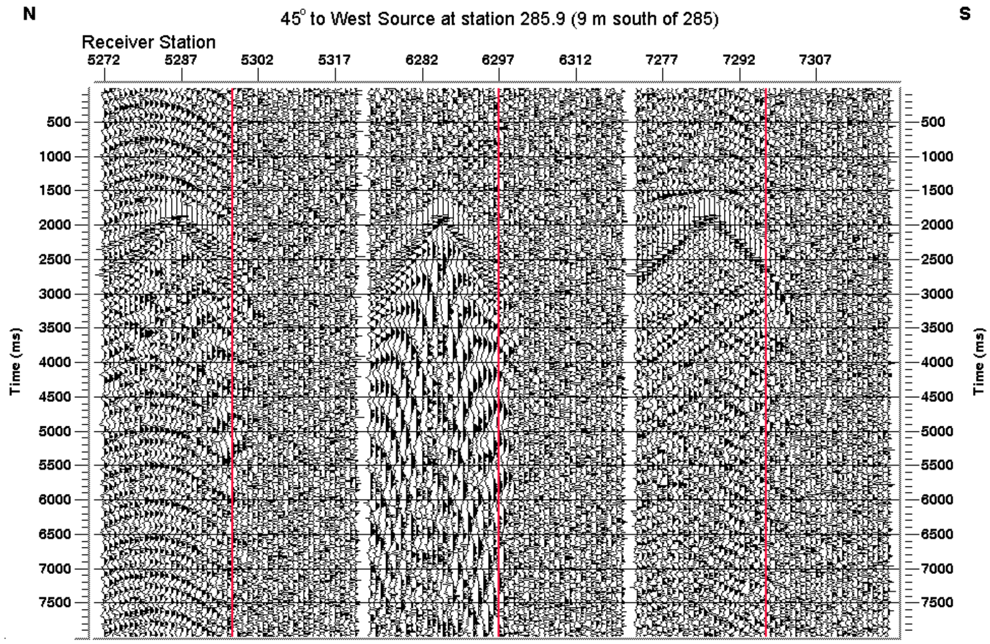

FIG. 3. Hammer source shot record, forty-five degree hit towards the west on the floating ice. H1(left), V(centre), and H2(right) components are shown. A red line shows the approximate surface location of the transition zone.

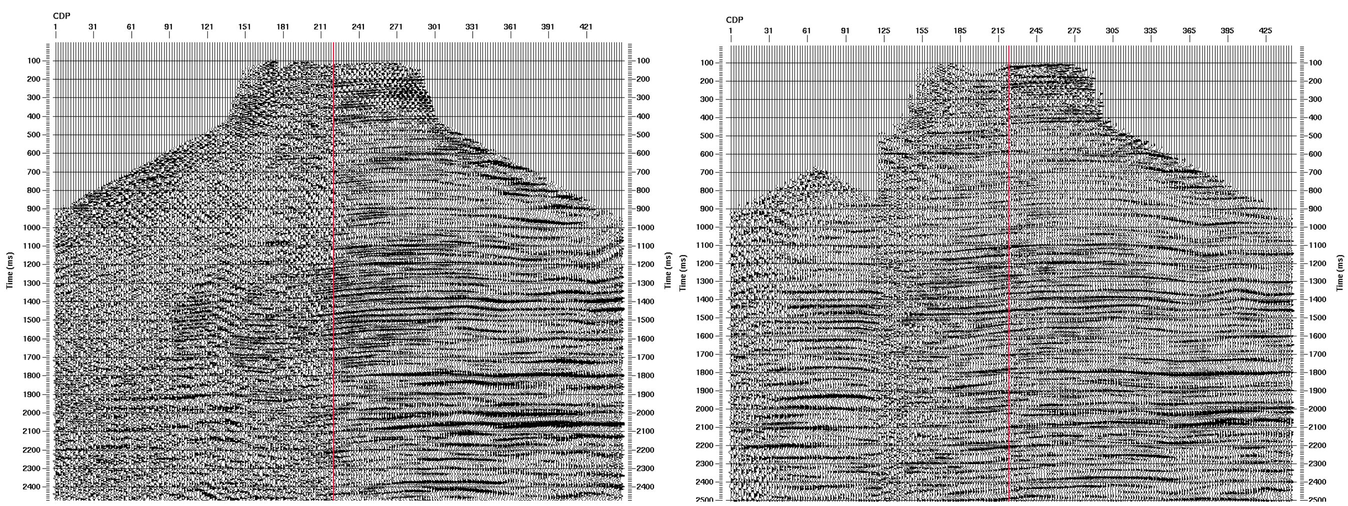

FIG. 4 Vertical component structure stack with f-x deconvolution for Vibroseis source (left) and dynamite source (right). A red line shows the approximate surface location of the transition zone.

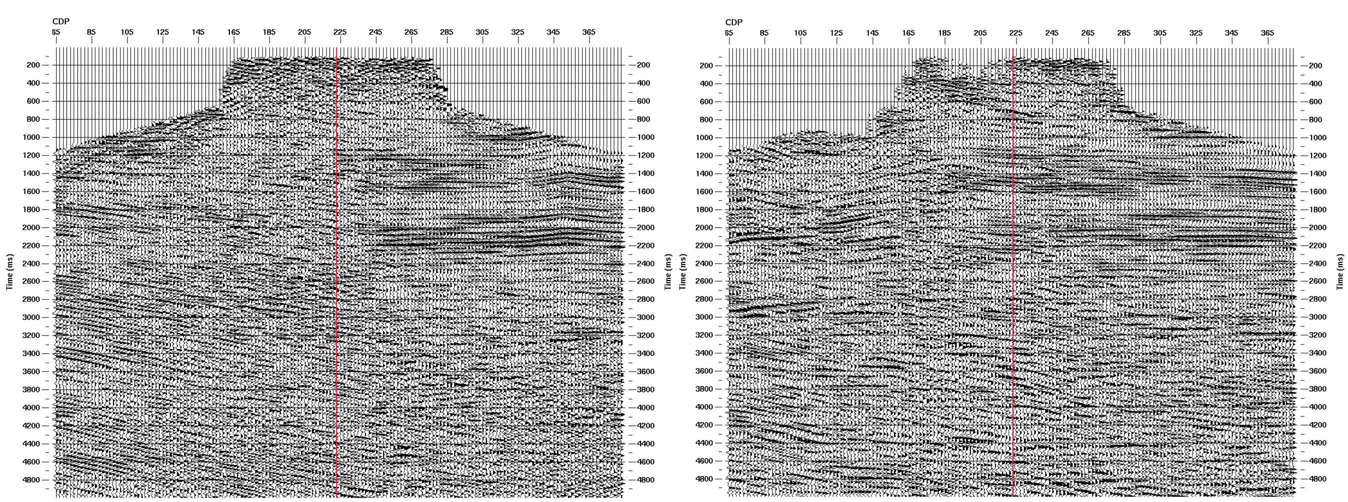

FIG. 5 Radial component structure stack with f-x deconvolution for Vibroseis source (left) and dynamite source (right). A red line shows the approximate surface location of the transition zone.

Ice velocities have been calculated from the hammer seismic shot records. The compressional-wave velocity is 3137 m/s (average of five measurements), and the shear-wave velocity is 1900 m/s (single measurement). These numbers compare well with 3164 m/s and 1916 m/s (Christensen, 1982). The data is presenting interesting processing challenges due to spatially aliased noise, noise on the shot records from the ice sheet cracking, and effects due to permafrost. Hopefully, the three-component data can be used to aid processing of the vertical data.

Vibroseis and dynamite structure stacks

Vertical and radial component data recorded on 3-C geophones for Vibroseis and dynamite sources have been processed to structure stacks with f-x deconvolution (Figures 4 and 5). The vertical component stacks have also been migrated (not shown). The stacks obtained clearly show a change in reflection character and continuity across the transition zone. In general, reflections below the ground-fast ice (right half of stacks, Figures 4 and 5) are more coherent and have higher amplitudes than those obtained below the floating ice (left half of stacks, Figures 4 and 5). However, after careful processing, reflections can be correlated across the transition zone with some degree of confidence.

Discussion and Future Work

Preliminary results show the profound effect that floating ice has on seismic data quality. Both dynamite and Vibroseis sources provide better data on ground-fast ice than floating ice. Other Vibroseis data acquired in the area by the same contractor can be of better quality. Data quality of final stacks is significantly improved by additional processing steps, such as deconvolution, statics and various types of filters.

We plan to process all receiver lines for all sources and make detailed comparisons, particularly in the area where vertical geophones are spatially coincident with the 3-C geophones. This data set also lends itself to studies of spatially aliased noise, permafrost effects, multiple removal, and improved processing of data from transition zones. It may be possible to use the data recorded on the horizontal channels of the 3-C geophones to improve processing of the vertical channel, and thus obtain better images of the transition zone and floating ice portions of the line.

Finally, at least two studies are possible based on the hammer seismic data. First, a comparison of data quality resulting from direct hits on the ice, versus hits on steel plates, steel I-beams, and wooden blocks that are frozen into the ice or loose on the surface. Secondly, a very accurate characterization of ice properties should be possible.

Acknowledgments

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