Multicomponent seismic survey over ground-fast and floating ice, MacKenzie Delta, N.W.T.

Kevin W. Hall, Carlos E. Nieto, Eric V. Gallant, and Robert R. Stewart.

ABSTRACT

In the spring of 2001, the CREWES project in conjunction with Devon Canada Ltd. (formerly Anderson Exploration Ltd.) and acquired a six kilometre test line (MKD-8), centred over the transition zone from floating to ground-fast ice in the Mackenzie Delta. Several different types of receivers, including 3-C geophones 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 length was also 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 give P-wave values of 3137 m/s and S-wave velocities of 1900 m/s.

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 component of data recorded by the 3-C geophones for the vibrator source has been processed to a brute stack, and shows 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.

INTRODUCTION AND SURVEY OBJECTIVES

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 the shallower methane hydrates, thus, the impetus for the seismic surveys. 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 to 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.

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 were 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).

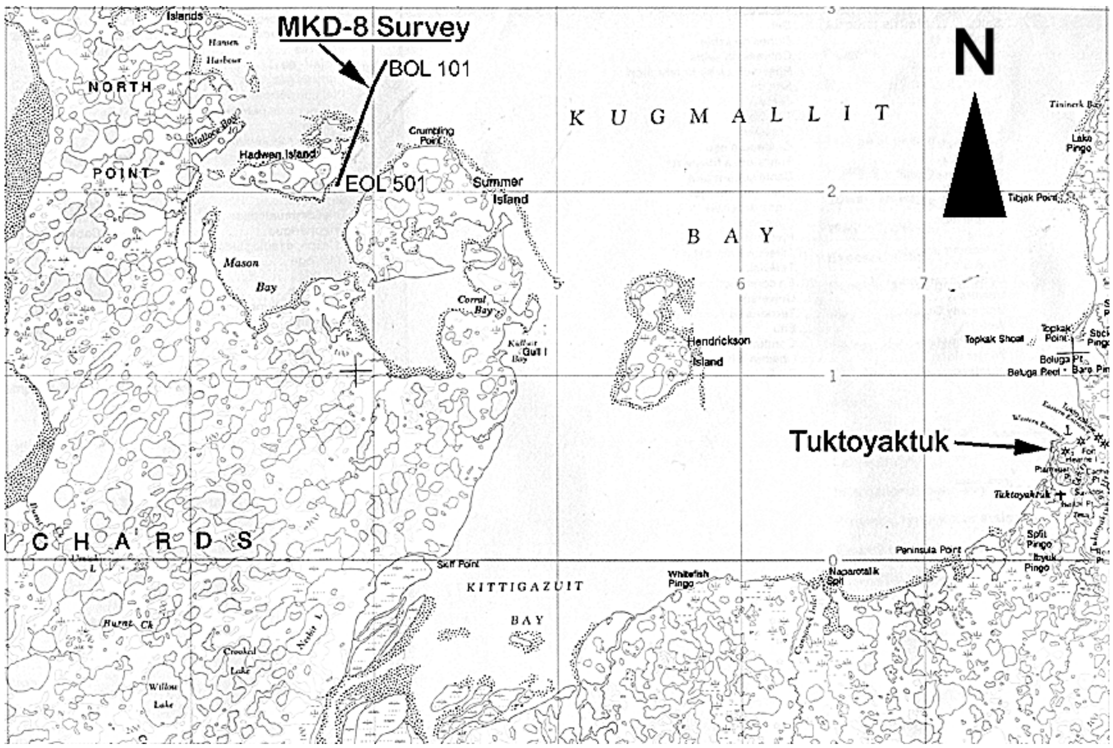


FIG. 1. Location of the MKD-8 test line. (base-map from Energy, Mines and Resources Canada, 1988).

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.

Near-surface conditions along the MKD-8 test line (Figure 1) are shown in Figure 2. A transition from floating sea ice to ground-fast sea ice occurred about half-way along the line (Figure 2). 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 geophones in the sea floor described it as muck, soft muck, and very soft muck.

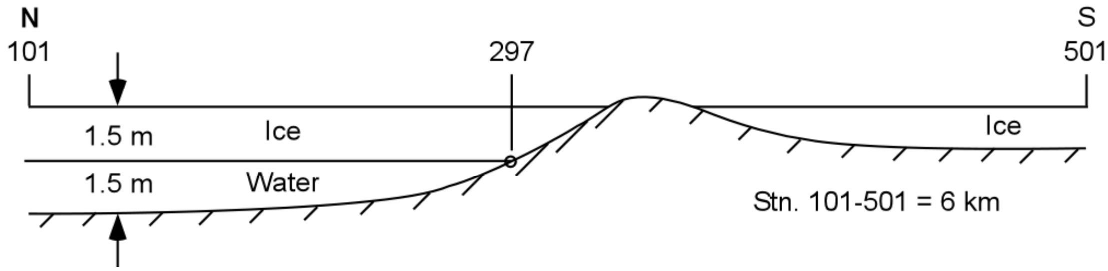


FIG. 2. Schematic diagram of near-surface conditions along the line. Station 297 is the approximate location of the transition from ground-fast to floating ice.

DESCRIPTION OF SURVEY GEOMETRY

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. All receivers were live for all dynamite and Vibroseis shots.

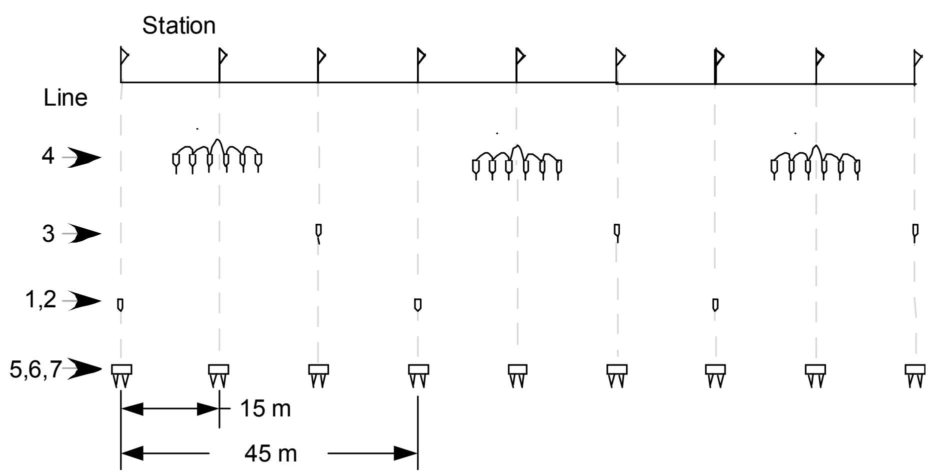


FIG. 3. Diagram of receiver layout: Line 1: single hydrophones. Line 2: single deep marshphones. Line 3: single shallow marshphones. Line 4: six geophone arrays of vertical geophones. Line 5: H1 component of 3-C geophones. Line 6: Vertical component. Line 7: H2 component.

Line 1 (see Figure 3) consisted of 64 Mark Products PE-44 hydrophones at a 45 m station spacing. These were inserted into the seafloor under the floating ice (north half of the line only).

Line 2 consisted of 132 Oyo Geospace GS30CT single marshphones. These were deployed every 45 m from stations 103 to 499 (Figure 3). They were inserted into the mud on the sea floor on the north part of the line, and into the frozen ground beneath the ground-fast ice to the south.

Line 3 consisted of 133 Oyo Geospace GS30CT single marshphones deployed between stations 102 and 501 at a 45 m receiver interval (Figure 3). These phones were planted just below the surface of the floating ice and the ground-fast ice in augured holes approximately 0.3 m deep.

Line 4 consisted of 133 six geophone strings of Oyo Geospace GS30CT marshphones 2 m apart. They were deployed between stations 101 and 500 at a 45 m group interval (Figure 3). These phones were planted on the surface of the ice using a cordless drill.

Lines 5-7 are H1, V, and H2 components for the fifty 3-C geophones. The geophones used were Sensor 3 Component with SM-4 elements (Figures 3 and 4). These geophones were deployed between stations 272 and station 321 every 15 m, centred on the transition zone. The spikes were removed from these geophones, and they were frozen into the bottom of ~0.4 m deep augured holes with fresh water.

FIG. 4. Typical 3-C geophone plant in an augured hole in the sea ice. Geophones were frozen in with fresh water.

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 (Figure 5). The hammer survey consisted of vertical and forty-five degree hits on ice every meter for thirty meters, on the floating ice only.

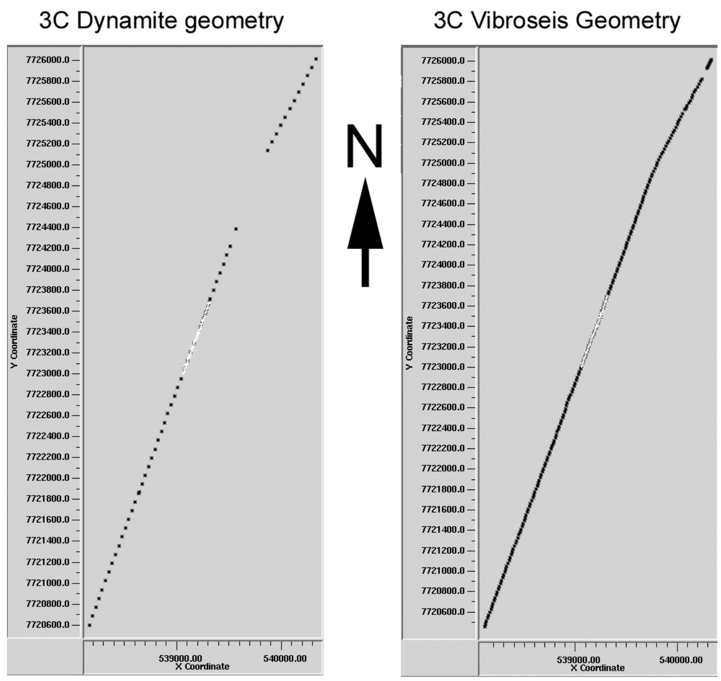


FIG. 5. *ProMAX* geometry for 3-C geophones, all shots. Shot locations are black, receiver locations are white.

Source line 1 was shot using two Mertz 18HD tracked vibrators (Figure 6), 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 a 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 7). An audible tone was transmitted from the recorder for timing, so time-zero depended on human reflexes, and is different for every shot record.

FIG. 6. Mertz 18HD tracked vibrators, heading north to the beginning of the line.

FIG. 7. CREWES personnel preparing V shaped notches in the ice for forty-five degree hammer hits. Notches were chopped every meter for thirty meters (bottom left of picture).

SHOT RECORDS

Figures 8, 9 and 10 are comparisons of Vibroseis and dynamite shot records with a 500 ms AGC for: 1) station 101.5 on the floating ice at the beginning of the line, 2) station 299.5 on a sand bar just south of the transition from floating to ground-fast ice (station 297), and 3) station 497.7 on the ground fast ice near the end of the line (EOL is at station 501). When the source is on/under the floating ice, energy in the direct arrivals crosses the transition zone for both sources. However, a significant part of the energy on the horizontal channels (lines 5 and 7, Figure 8) is reflected from the transition back towards the floating ice.

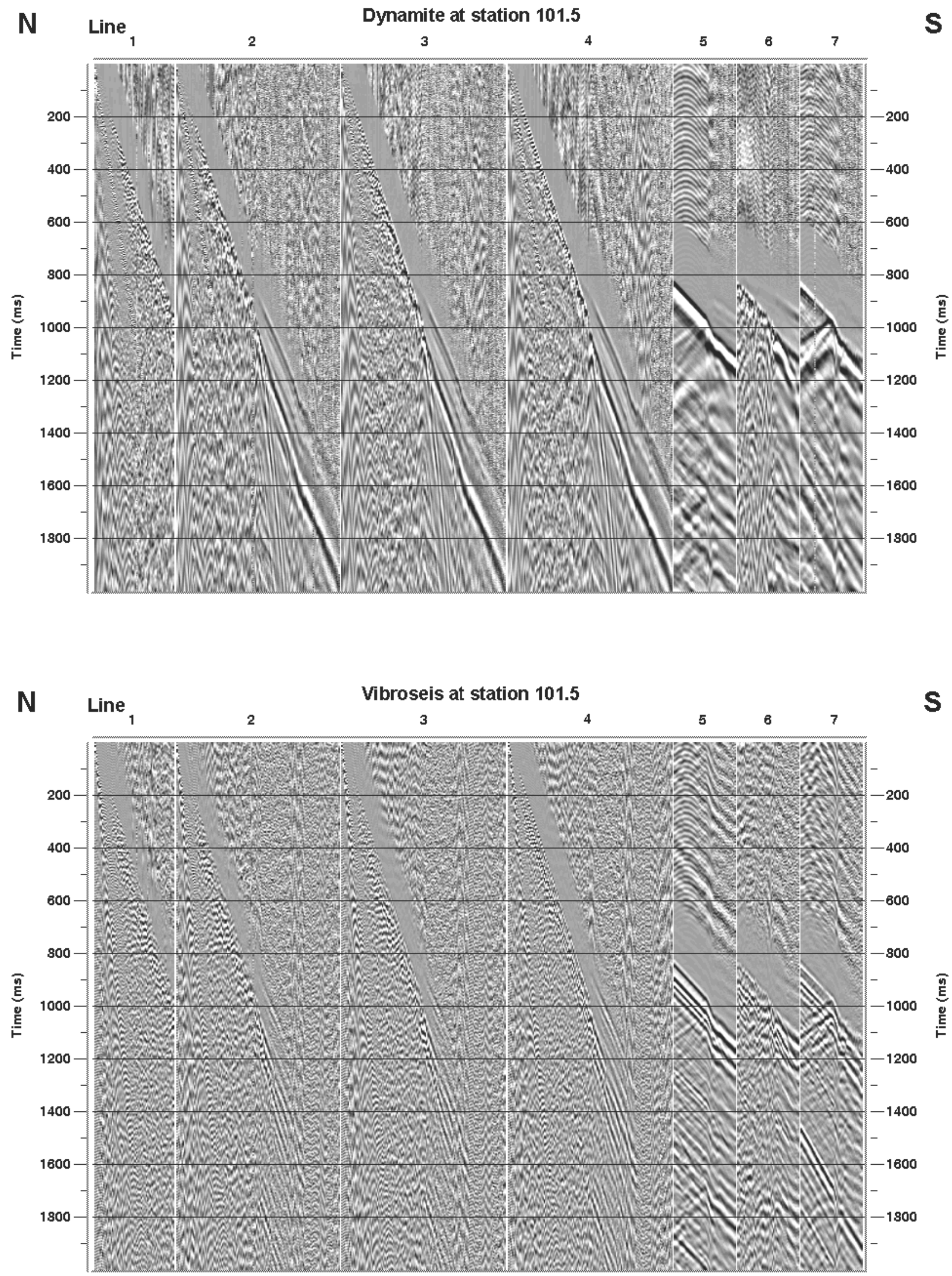


FIG. 8. Dynamite and Vibroseis shot records for SP/VP 101.5 on the floating ice at the north end of the test line. Line numbers refer to different receiver layouts (Figure 3). Lines 2-7 are centered on the transition from floating to ground-fast ice. Lines 2-4 are 6 km long at 45 m trace spacing, Lines 5-7 are 750 m long at 15 m trace spacing.

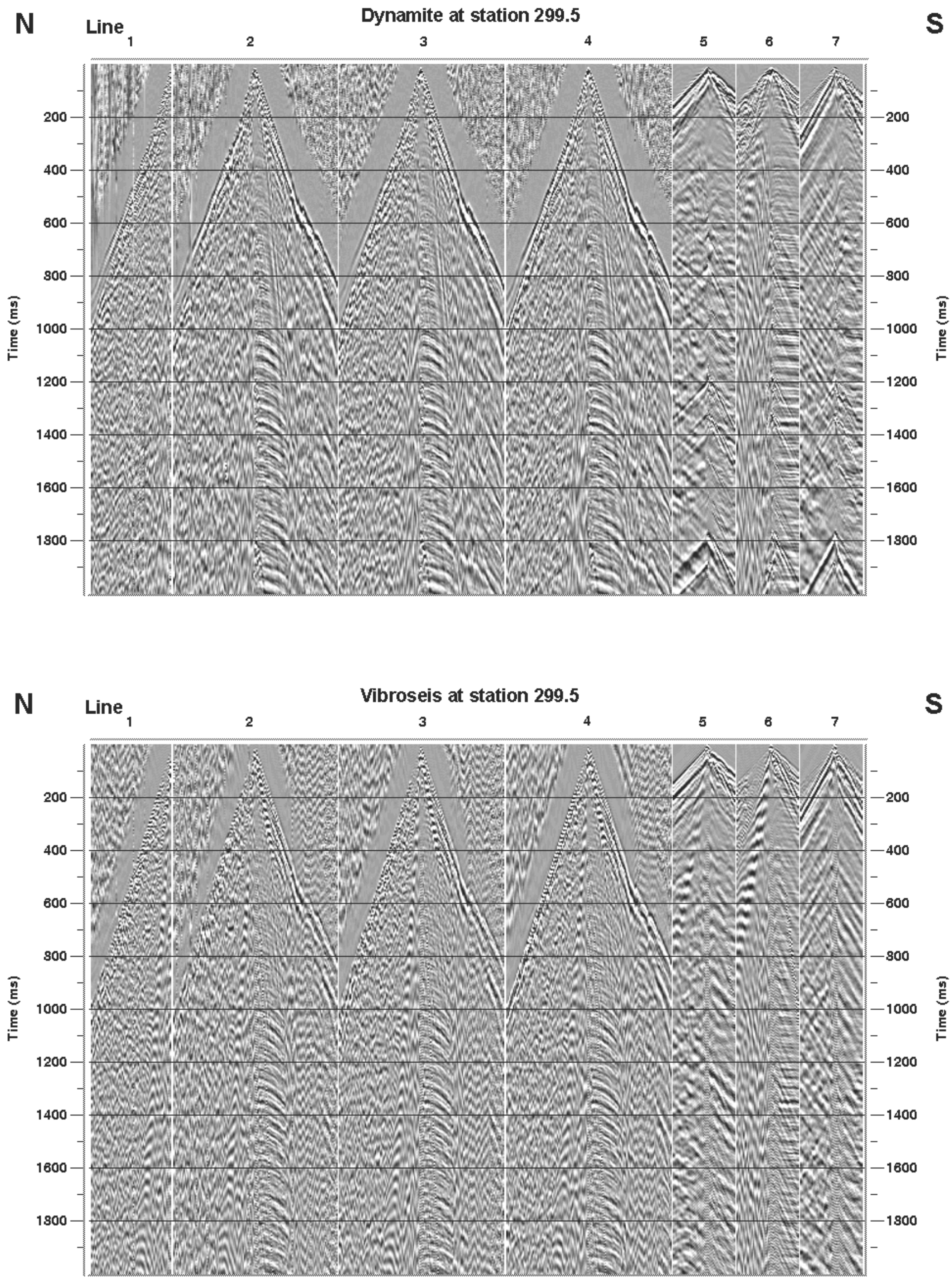
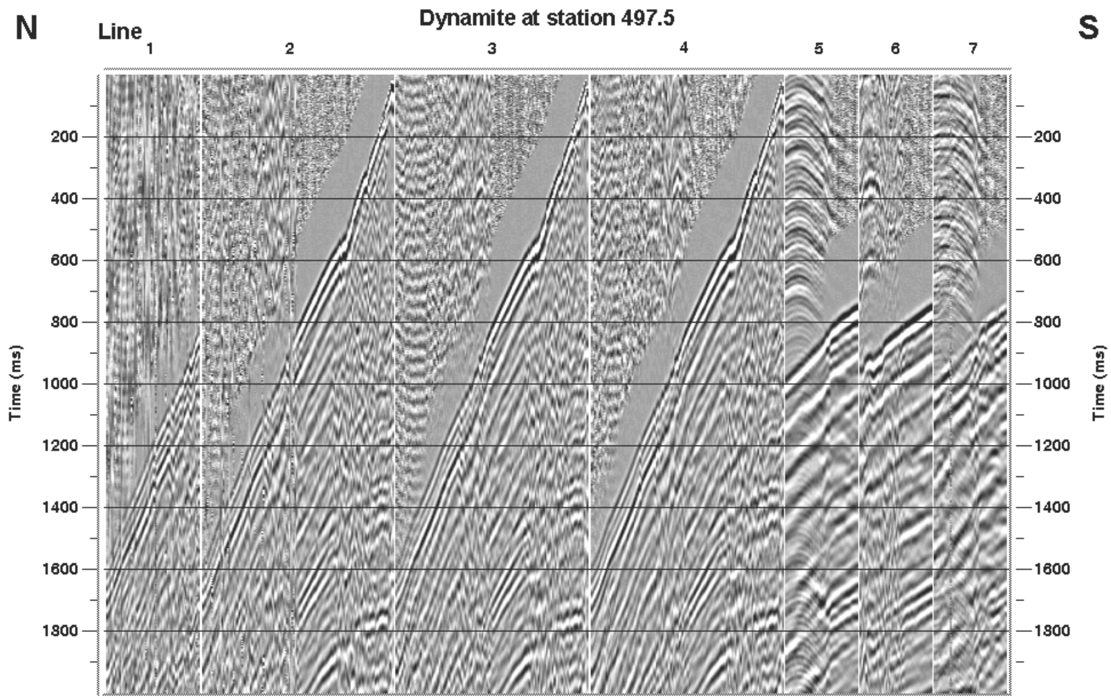


FIG. 9. Dynamite and Vibroseis shot records for SP/VP 299.5, on a frozen sand bar just south of the transition from floating to ground-fast ice (center of lines 2-7).



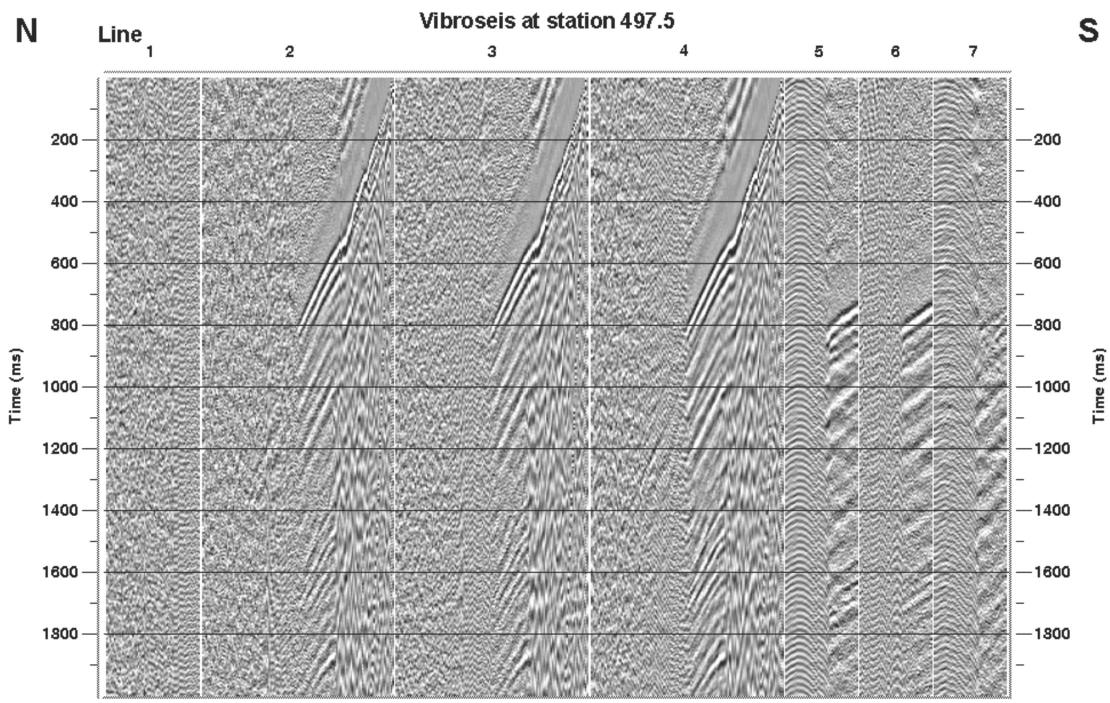


FIG. 10. Dynamite and Vibroseis shot records for SP/VP 497.5, near the south end of the line, on ground-fast ice.

The break in slope of the direct arrivals (best seen on the horizontal channels) correlates to a sandbar that was observed at the surface (compare with Figure 2).

When the source is close to the transition zone, energy propagates towards land and out to sea equally well (Figure 9). 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 the Vibroseis shot record appears to just stop at the transition zone, although there are some hints of energy being reflected back towards the ground-fast ice (Figure 10).

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.

HAMMER SEISMIC SHOT RECORDS

Figures 11, 12, and 13 show shot records from the hammer survey. 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.

Direct arrivals are seen on every 3-C geophone on the floating ice, but the energy is not seen south of the transition zone. The direct arrivals can be seen reflecting back to sea from the transition zone on line 7 (H2 component), particularly with a shear-wave source (Figures 12 and 13). A series of reverberations with a period of about 500 ms are preferentially recorded on line 5 (H1 component). Some of the hammer shot records show noise, probably waves generated by the ice cracking, traveling through the ice sheet and arriving before the hammer hit (not shown).

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 (page 140, Christensen, 1982)

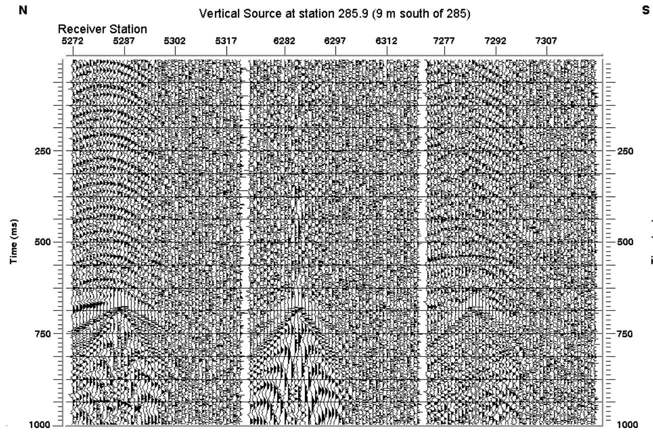


FIG. 11. Hammer source, vertical hit on the ice 9 m south of station 285, as recorded on lines 5, 6, and 7 (H1, V, and H2 components of the 3-C geophones).

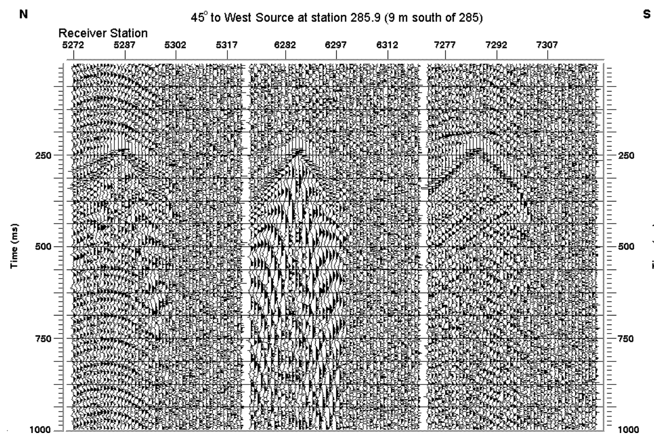


FIG. 12. Hammer source, forty-five degree hit towards the west on the ice, 9 m south of station 285

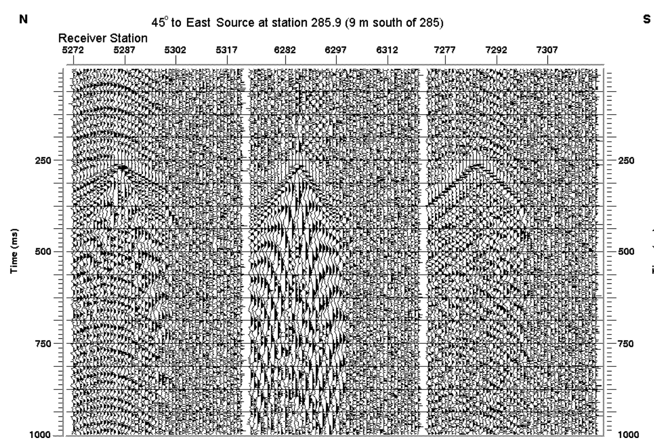


FIG. 13. Hammer source, forty-five degree hit towards the east on the ice, 9 m south of station 285

PRELIMINARY PROCESSING

The vertical channel from the 3-C geophones (receiver line 6) for the Vibroseis source has been extracted from the field records and processed to a preliminary brute stack using *Vista*. The geometry for line 6 is shown in Figure 5.

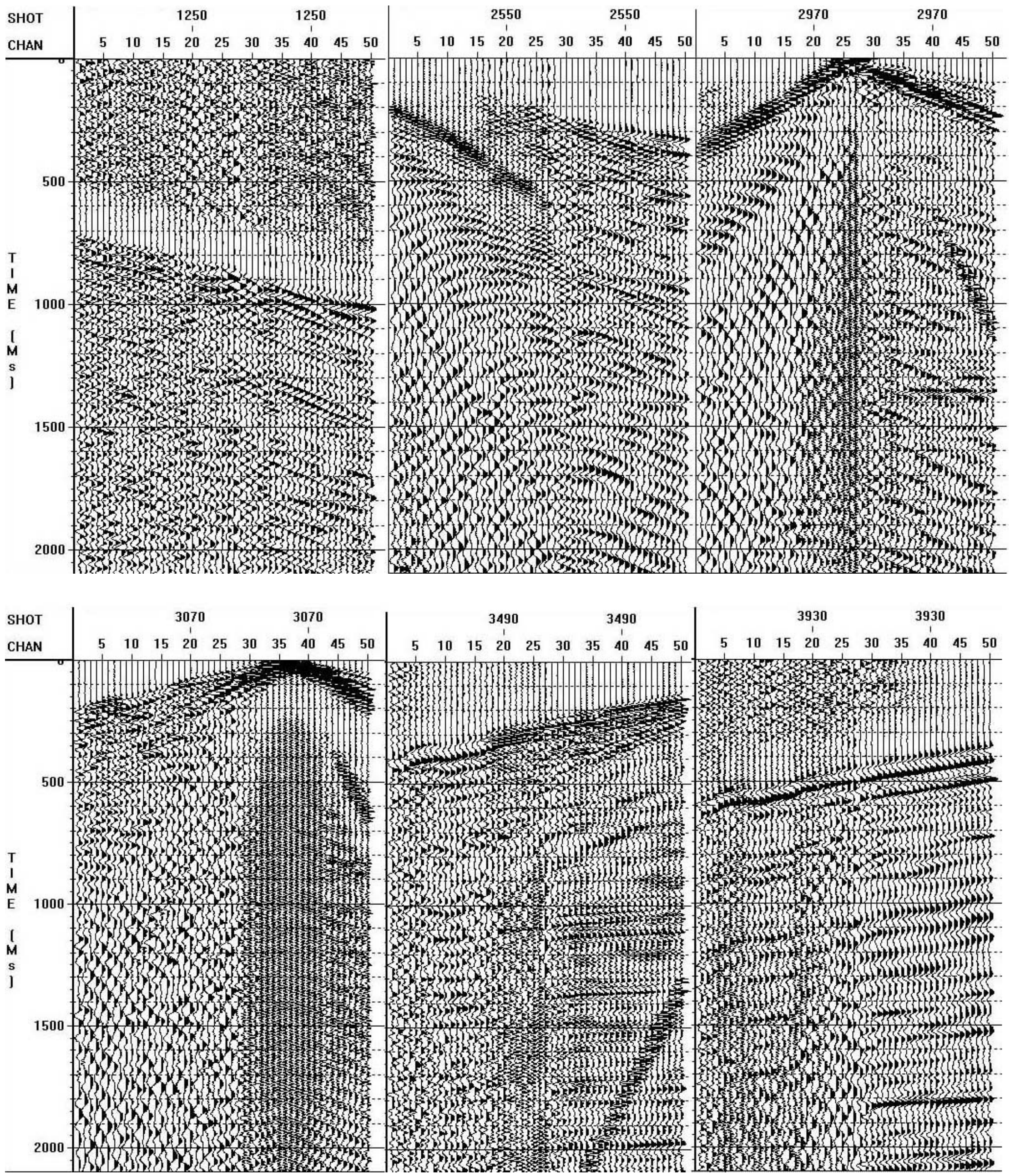


FIG. 14. Shot gathers for VPs 125, 255, 297(top), 307, 349 and 393 (bottom). North is to the left, the transition zone is at channel 27. Note: 1) the presence of spatially aliased near-source noise, and 2) the difference in character of the direct arrivals and reflections between shots on the floating ice (125,255), and shots on the ground-fast ice (307, 349, and 393).

Figure 14 shows some shot records for line 6. Data quality is significantly better for vibrators on ground-fast ice and receivers on floating ice, than for the opposite case (compare shots 255 and 349, Figure 14). A simple processing flow was designed to create a brute stack (Figure 15). The line was processed using a straight-line geometry with 7.5 x 200 m bins, for a maximum fold of 25 traces per bin.

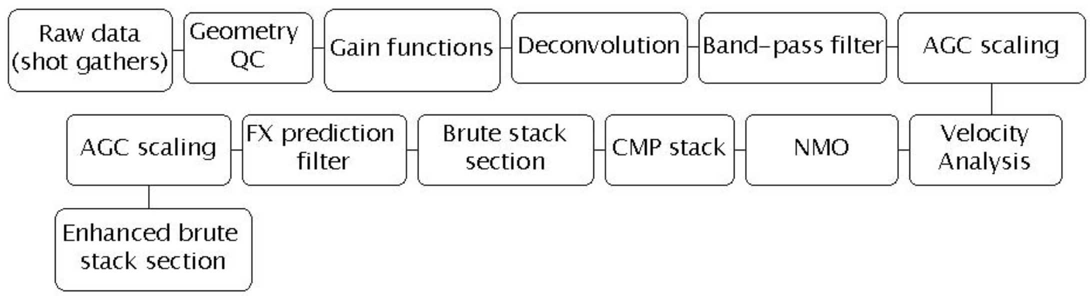


FIG. 15. Processing flow applied to vertical component of 3-C geophones (Line 6)

Traces were gained by applying an exponential time power function with an exponent of 1.2. Mean scaling of the shot gathers was also necessary due to the geometry of the line. The amount of energy recorded when the vibrators were in the proximity of the geophones is much larger than when they were at the ends of the line (compare with Figure 5).

A zero-phase deconvolution operator was designed on a 1500-2500 ms time window. The length of the operator was set to 120 ms and 1% pre-whitening. The deconvolved shot gathers were then filtered using an Ormsby band-pass operator with a pass band of 20-25-65-70 Hz, which is based on 10 Hz filter panels generated for VP 349 (Figure 16). Finally, a 300 ms AGC was applied. Figure 17 shows a comparison of the raw and processed shot gather for vibe point 349.

The gained, deconvolved and filtered shot gathers were used as input for semblance and constant velocity stack based velocity analysis (Figure 18), which was performed on every twenty-fifth CMP (every 187.5 m).

NMO corrections and mutes were then applied to the data using the velocity functions to obtain a CMP brute stack. A frequency-offset prediction filter and an additional AGC (300 ms window) were used to enhance linear events on the section to obtain an enhanced brute stack (Figure 19).

The brute stack obtained clearly shows a change in reflection character and continuity across the transition zone. Reflections below the ground-fast ice are more coherent and have higher amplitudes than those obtained below the floating ice.

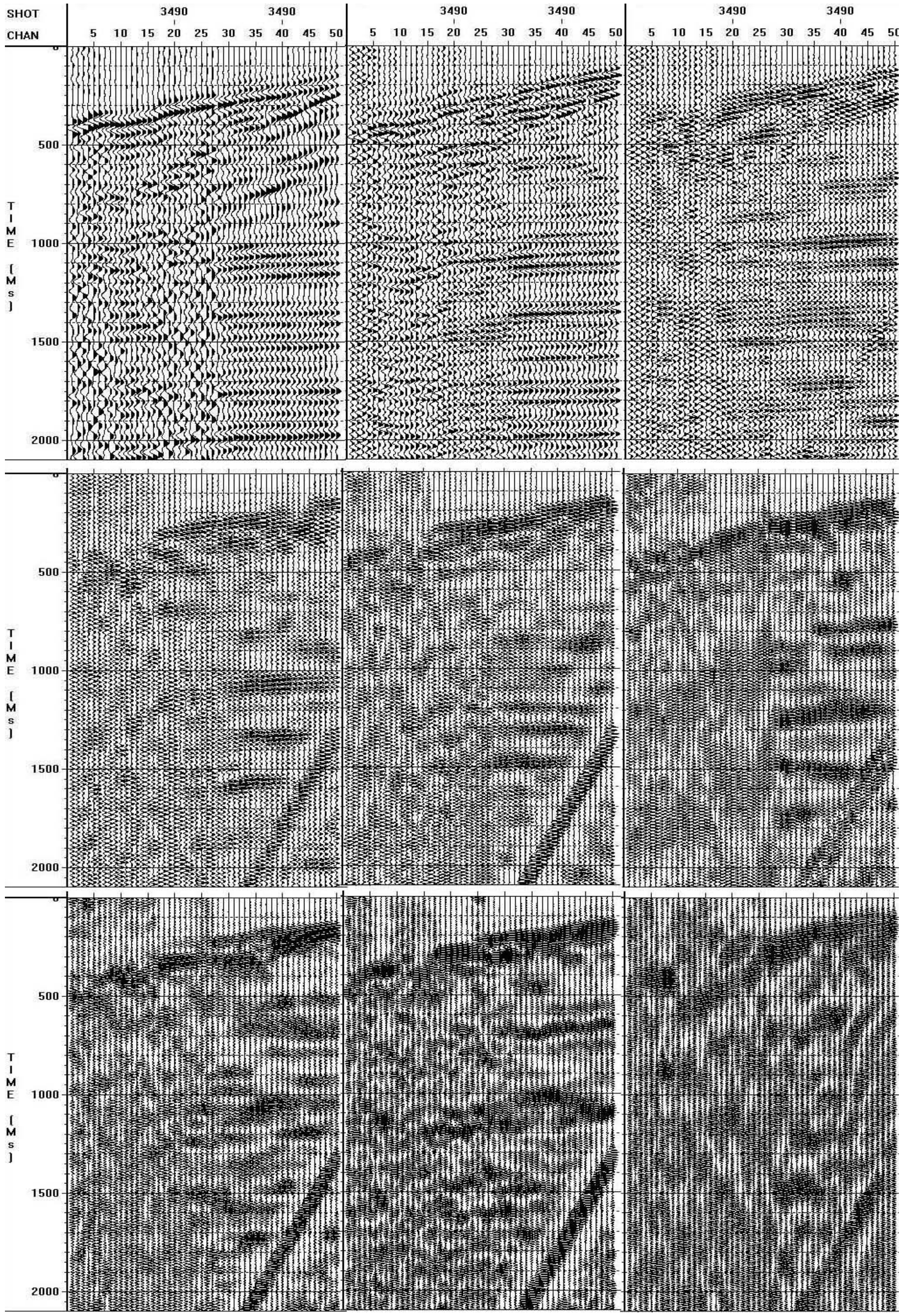


FIG. 16. Filter panels of shot gather VP 349. From left to right: 10 – 20 Hz, 20 – 30 Hz, and 30 – 40 Hz (1st row); 40 – 50 Hz, 50 – 60 Hz, and 60 – 70 Hz (2nd row); 70 – 80 Hz, 80 – 90 Hz, and 90 – 100 Hz (3rd row).

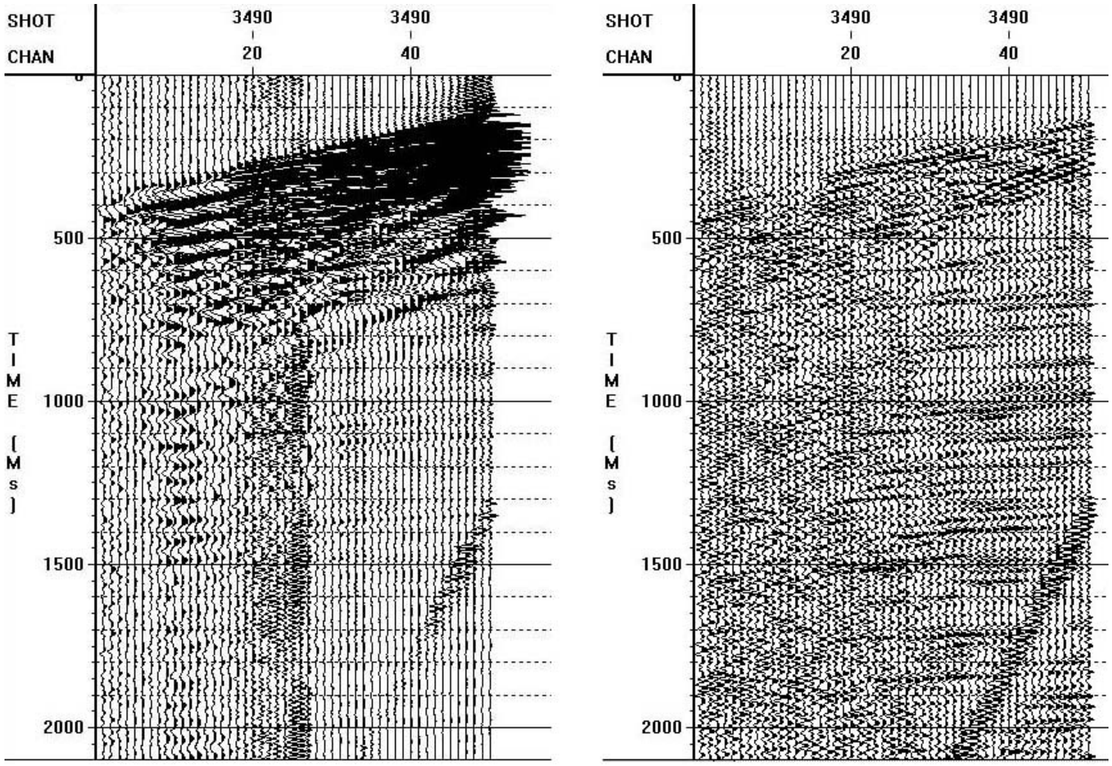


FIG. 17. Raw (left) and processed (gained, deconvolved and bandpassed, right) shot gather for VP 349.

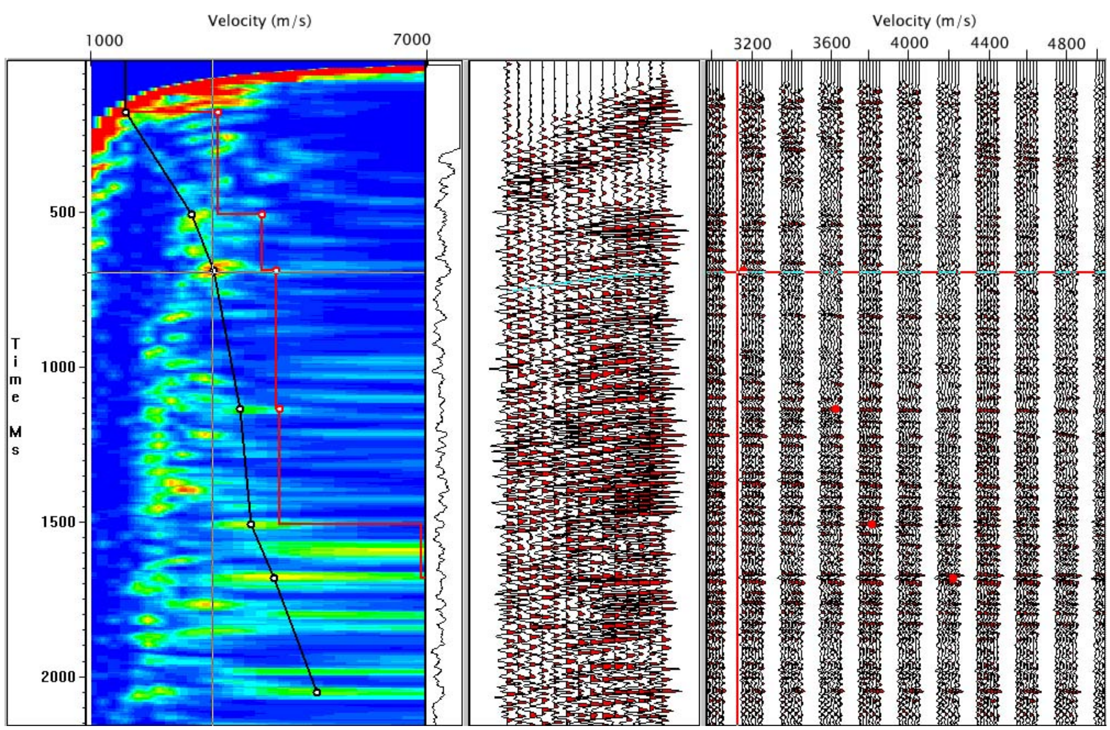


FIG. 18. Velocity analysis for CMP 450. Semblance panel (left), uncorrected CMP gather (center) and constant velocity stacks (right).

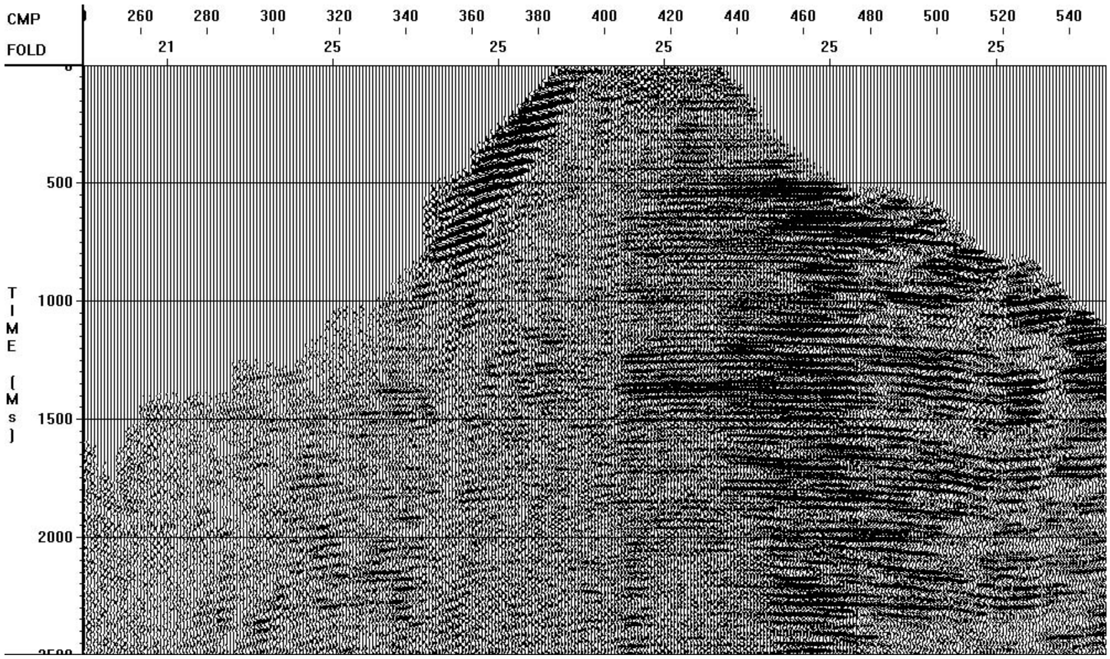


FIG. 19. Enhanced brute stack section. Floating ice (north, to the left) is located towards small CMP numbers while the ground-fast ice (south) is located towards high CMP numbers. The transition zone in this section is located on CMP number 390, approximately.

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 are of significantly better quality. As such, it would be premature to make any final conclusions about source suitability for other surveys based on the brute stack shown. Data quality of final stacks is significantly improved by additional processing steps, such as statics and various types of filtering (Peter Cary, 2001, personal communication).

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 were 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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