

Ultra high-resolution seismic imaging of permafrost, Devon Island, Nunavut

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ABSTRACT

In July-August, 2002, several shallow multicomponent seismic surveys and ground-penetrating radar traverses were conducted near the NASA Houghton-Mars Project camp on Devon Island, Nunavut. Geophones and hammer impacts in three different orientations (vertical, horizontal inline, and horizontal transverse) with different acquisition parameters were acquired successfully. Two different locations were selected to conduct seismic surveying, the Von Braun Valley and the Gemini Hills. The analysis of the ultra-high resolution seismic lines allowed the characterization of the saturated silt layer (top layer).

A compressional velocity of 260 m/s and a shear velocity of 168 m/s were obtained from the first break arrival times. We observe that the direct compressional wave changes its polarity with offset sign and with hammer impact orientation. The direct shear wave does not change polarity with the offset sign but it does with the hammer impact orientation. A more complex situation occurs with the head wave arrival. An estimated velocity of 3050 m/s was obtained from first break arrival times for a pure compressional head wave. Its polarity remains unchanged with offset. Variation of the velocity suggests layering in or over the permafrost, and lateral changes. What appears to be shear wave refraction was identified on the horizontal elements. An average velocity of 2250 m/s was obtained from first break arrival times. It was found that the polarity of this event changes with offset sign.

INTRODUCTION

The Houghton structure on Devon Island, Nunavut at 75°22'N longitude and 89°41'W latitude, is a 24 km diameter, 23 Ma old impact crater in the high Canadian Arctic (Osinski et al., 2001). Host rocks are gently dipping (to the west) Ordovician and Silurian carbonate sediments mostly of the Allen Bay formation (Scott and Hajnal, 1988). The northwest corner of the outer middle rim hosts the base camp for the Houghton Mars Project (Long, 1999; Lee, 2002). Surveying conditions can be severe due to the high winds of the polar area (up to 70 km/hr during this field survey), low summer temperatures (5°C to +5°C), sleet, rain, and snow— even though this is characterized as a desert (Cockell et al. 2001), and significant ultraviolet radiation (Cockell et al., 2002).

We dug several test pits near the base camp to investigate the composition of the near surface. We found a tan-coloured, saturated silt with small clasts down to depths of about 45 – 65 cm. We then encountered solid and uniform permafrost with the appearance of frozen silt. We note that the soil smelled strongly of hydrocarbons.

We used an EG&G Startaview 60-channel seismic recorder with omni-geophones (used in a vertical and horizontal configuration). A small sledgehammer was employed as a source. Conventional seismic, results from the 10 cm lines Von Braun Valley 1m lines and Gemini Hills 1m lines.

Previous work on shallow seismic analysis

The refraction method yields valuable information about the near surface geology, and sometimes it can also be useful aids in interpreting shallow reflecting data (Reynolds et al, 1990). Shear wave reflection has had success in shallow weathering/bedrock interface at 60 m deep (Pullan et al, 1990). They found success with shear wave reflection in the areas where the ground roll energy was quickly attenuated and did not interfere with reflection events. The method is optimal when the top layer is unconsolidated.

Norminton (1990) shows by computer modeling that both SH and SV reflections from the bedrock interface should be observable at small angles of incidence, depending on the elastic parameters ratio and the type of incident wave P or SV. The SH wave has an advantage when designing field arrays; it only has one critical angle of incidence. Dufour et al. (1996) managed to detect shear head wave arrivals in shot records by analyzing their polarization. They showed how the P and S head waves have both rectilinear polarizations in the vertical and radial component respectively and the Rayleigh waves have elliptical polarization. The use of FK filters was key enhance the shear head waves in the radial component.

Analyzing several shot records from different locations Jolly et al. (1971) demonstrated that the surface wave is greatly diminished when the source is located below the weathered layer. Bachrach et al. (1998) concludes in his work that there is still need to better understand the seismic response of the near surface. They showed how the velocity profile is pressure dependent in the first few meters. Their work is based on the fact that Rayleigh waves attenuate in the presence of surface roughness. They were able to recognize very shallow reflections, up to 1 m deep, in unconsolidated sediments by applying only a low cut filter.

Xia et al. (1999) mentions a pitfall when estimating SH wave from shear wave refraction methods. They found with in a real case example that the SH wave undergoes a wave-type conversion along an interface of non-horizontally layers. Shear and compressional head wave velocities where approximately the same. By assuming that SH displacement produces compressional wave motion along non-horizontal interface, they addressed this observation. The most important conclusion is that the shear wave reflection will be possible depending on the dispersion of the unconsolidated layer, eg if the packet is dispersive resulting from strong velocity gradients near the surface, the groundroll will mask much of the viewing window.

SURVEY OVERVIEW

A number of seismic experiments were recorded at two different locations on Devon Island. The first area of study was in the “Von Braun Valley” and the second at “Gemini Hills”. We describe the acquisition of all lines, but only the small spread in the Von Braun Valley will be analyzed (Figure 1). Table 1 summarizes the seismic test in Devon Island.



FIG. 1. Vertical receivers deployed in the Von Braun Valley, with student R. Birch checking the seismic recorder.

Table 1. Survey description. A total of 9 different lines were recorded, obtaining a full set of orientations for both receivers and sources.

Location	File number	Total files	Line name	Receiver direction	Hammer Hit direction	Time sample rate (usec)
Von Braun Valley	1001-1046	46	VVS1	Vertical	Vertical	31.25
Von Braun Valley	2001-2092	92	VVS2	Transverse	Horizontal (both transverse directions) (1) Transverse hit away from camp (2) Transverse hit towards camp	31.25
Von Braun Valley	3001-3046	46	VVS3	Inline	Vertical	31.25
Von Braun Valley	4001-4092	92	VVS4	Inline	Horizontal (both inline directions) (1) hit towards increasing channel number (2) hit towards decreasing channel number	31.25
Von Braun Valley	5001-5046	46	VVL1	Vertical	Vertical	250.00
Von Braun Valley	6001-6092	92	VVL2	Inline	Vertical, horizontal (inline) (1) Vertical hit (2) Inline hit towards increasing channel number	250.00
Von Braun Valley	7001-7013	13	VVL3	Vertical	Vertical	250.00
Von Braun Valley	8001-8046	46	VVL4	Vertical	Vertical	250.00
Gemini Hills	9001-9051	51	GG1	Vertical	Vertical	500.00
Gemini Hills	9101-9196	92	GG2	Transverse	Horizontal (both transverse directions) (1) Transverse hit towards east (2) Transverse hit away towards west	500.00

The recording parameters were defined to sample the total wavefield at different spatial and temporal scales: 10 cm, 100 cm; 31.25 usec, 250 ms, 500 ms; vertical, horizontal (inline and radial in both directions) impulse sources.

We excavated several pits near the camp and on the seismic lines. We found that the contact between the permafrost and the saturated silt layer is at about 60 cm deep (Figure 2).



FIG. 2. Depth to the permafrost layer is approximately 60 cm in the Von Braun Valley. The soil is mainly composed of silts with the presence of some clasts. Permafrost can be observed in the bottom of the hole.

VVS1, VVS2, VVS3, VVS4 seismic lines:

A complete set of source and receiver directions were recorded in this experiment (Table 2). The maximum offset was 450 centimeters for all of them. This experiment was conducted in the Von Braun Valley (Figures 1 and 3).

The shot gathers of this survey are displayed using the following parameters:

- *Trace excursion*: 1 (max 5)
- *AGC filter*: 15 ms operator length
- *Gain*: 8 dB (for scaled shot gathers)
- *Mean scaling per ensemble*: scale factor 1

These were used in order to balance the energy per shot gather, and observe clear wave arrivals. For some of the shots these had to be changed in order to enhance some interesting events.

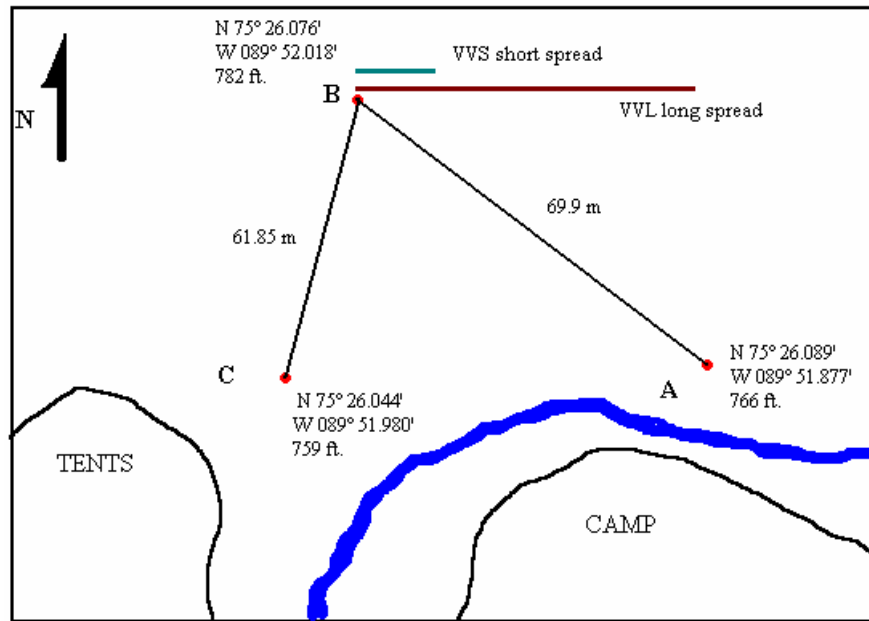


FIG. 3. Location map of VVS survey in the Von Braun Valley. Points A, B and C are the coordinates of GPR surveys. The ultra-high resolution survey was acquired at location B. The blue curve indicates the path of running water.

Table 2. Source hit and receiver orientation and recording parameters for the small spread survey

Line	Receiver direction	Hammer Hit orientation	Time sample rate (usec)	Receiver interval (cm)	Source interval (cm)	Recorded time (ms)	Delay time (ms)
VVS1	Vertical	Vertical	31.25	10	10	64	10
VVS2	Transverse	Horizontal (both transverse directions) (1) Transverse hit away from camp (2) Transverse hit towards camp	31.25	10	10	64	10
VVS3	Inline	Vertical	31.25	10	10	64	10
VVS4	Inline	Horizontal (both inline directions) (1) Hit towards increasing channel (2) Hit towards decreasing channel	31.25	10	10	64	10

VVS1

The receivers were deployed every 10 cm as well as the source points. The position of the receivers in this line are vertical and the hammer impact was vertical as well (Figure 4).

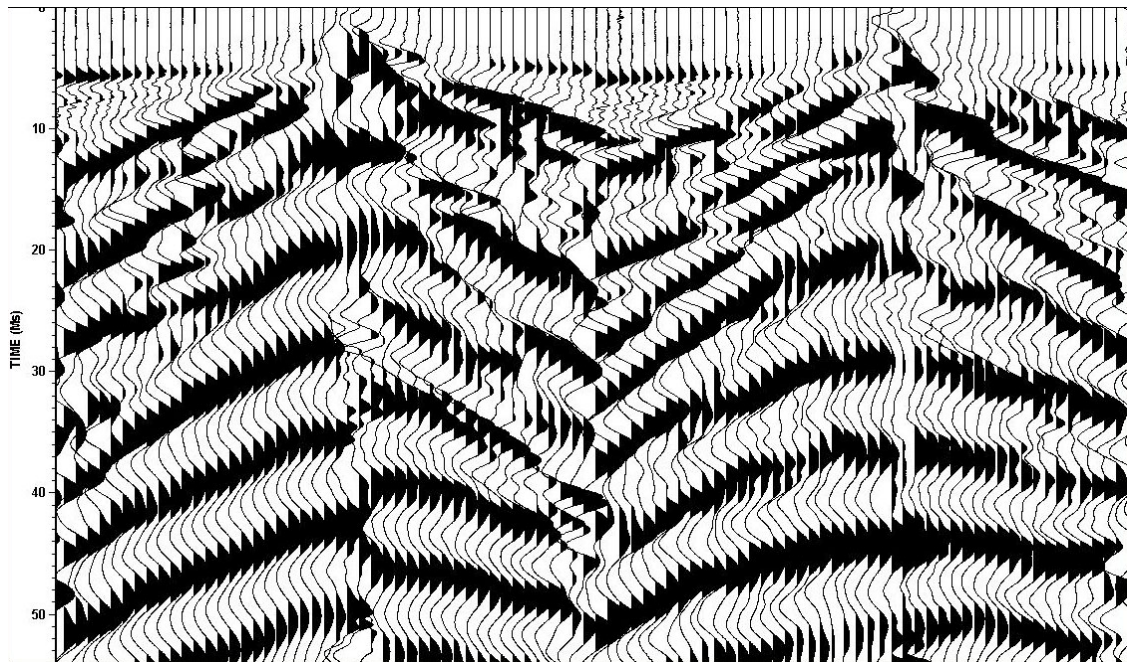


FIG. 4. Two consecutive scaled shot gathers VVS1. Trace and shot spacing are 10 cm. Vertical geophones and vertical hammer impact was used.

VVS2

This line corresponds to horizontal receivers, perpendicular to the seismic line (it will be referred as *transverse* in the rest of the paper), and hammer impacts parallel to the receivers orientation (*transverse impacts*). Two hits were recorded per shot point, opposite to each other (Figures 5a and 5b). The first hit away from the camp, and the second towards the camp (Figure 3).

VVS3

Receivers were deployed horizontally but in the same direction of the seismic line. This position will be defined as *inline* in the rest of the paper. One vertical hammer impact per shot was recorded (Figure 6).

VVS4

The receivers were left in the same position as for VVS3, but two inline horizontal hits were recorded. The first shot recorded corresponds to a hammer hit towards increasing channel numbers, and the second in the opposite direction (Figures 7a and 7b respectively).

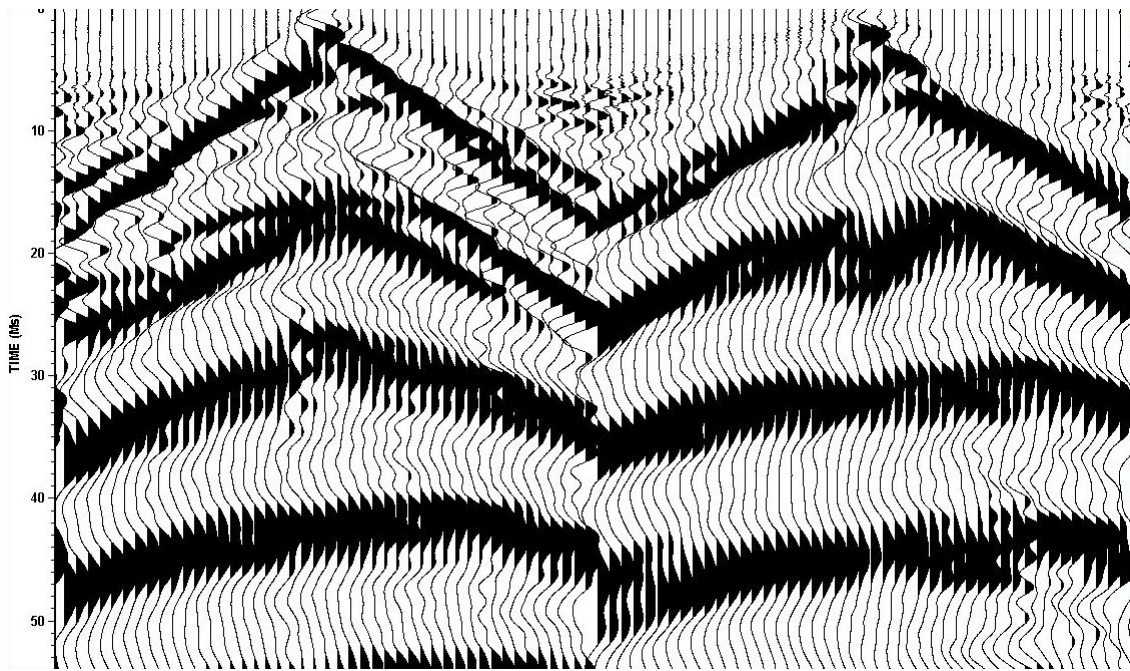


FIG. 5a. Two consecutive scaled shot gathers from VVS2(1). Trace and shot spacing are 10 cm. The hammer impact was transverse towards camp, and the receivers were transverse as well.

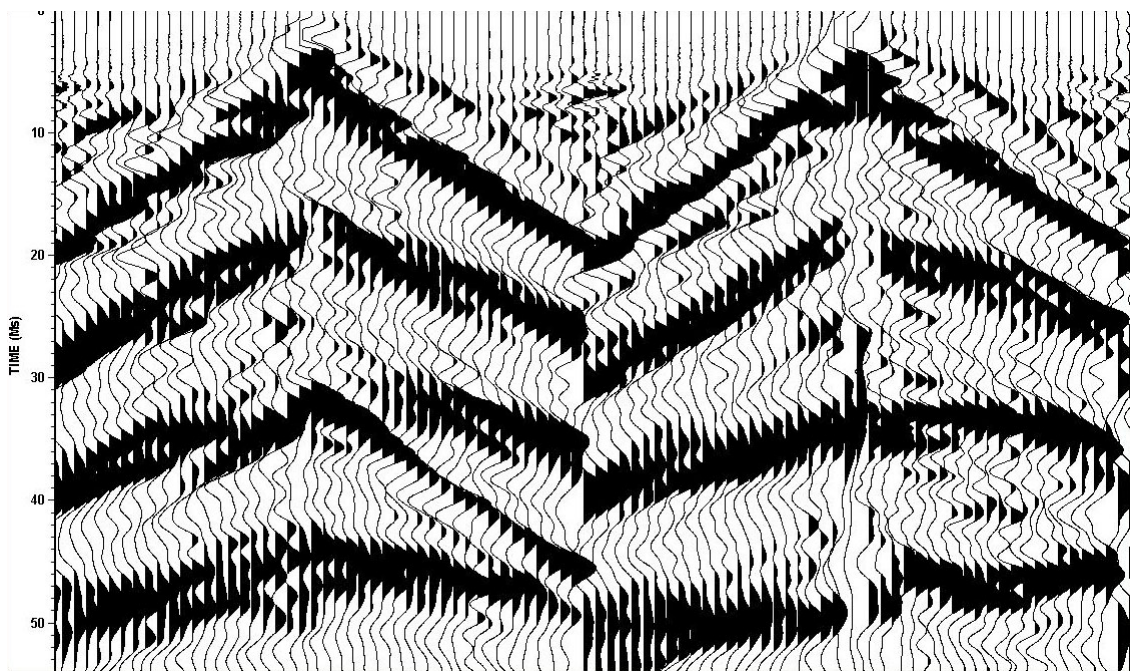


FIG. 5b. Two consecutive scaled shot gathers from VVS2(2). Trace and shot spacing are 10 cm. The hammer impact was transverse away from the camp, and the receivers were transverse as well.

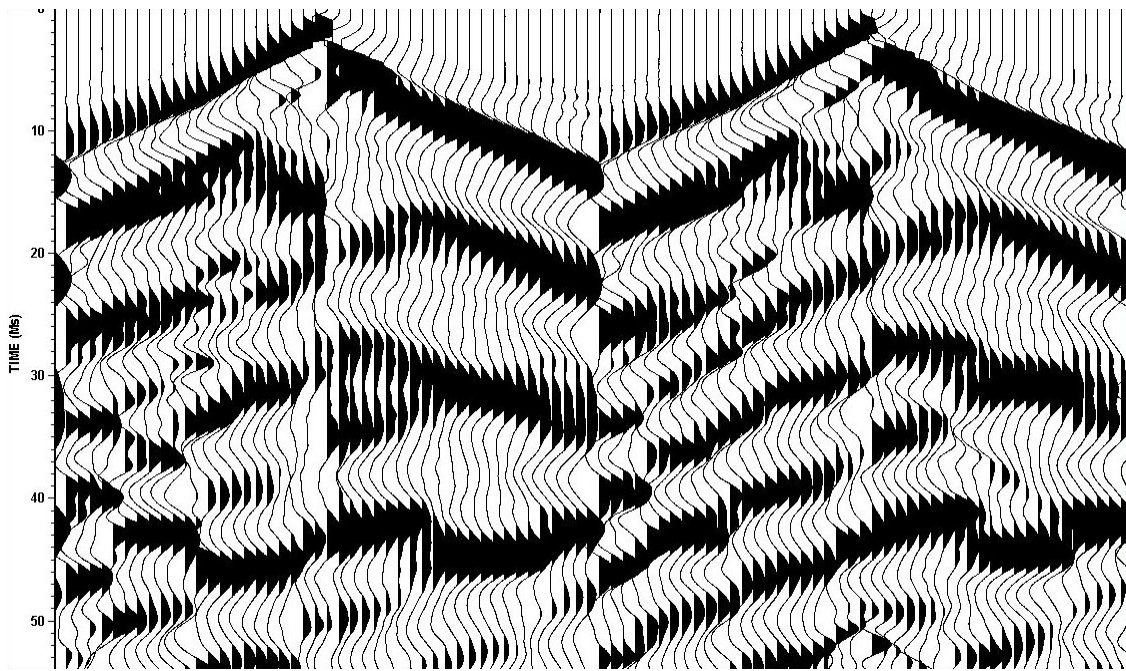


FIG. 6. Two consecutive scaled shot gathers from VVS3. Trace and shot spacing are 10 cm. The trace and shot spacing were 10 cm. For this line the hammer impact was vertical and the geophones horizontal (*inline*).

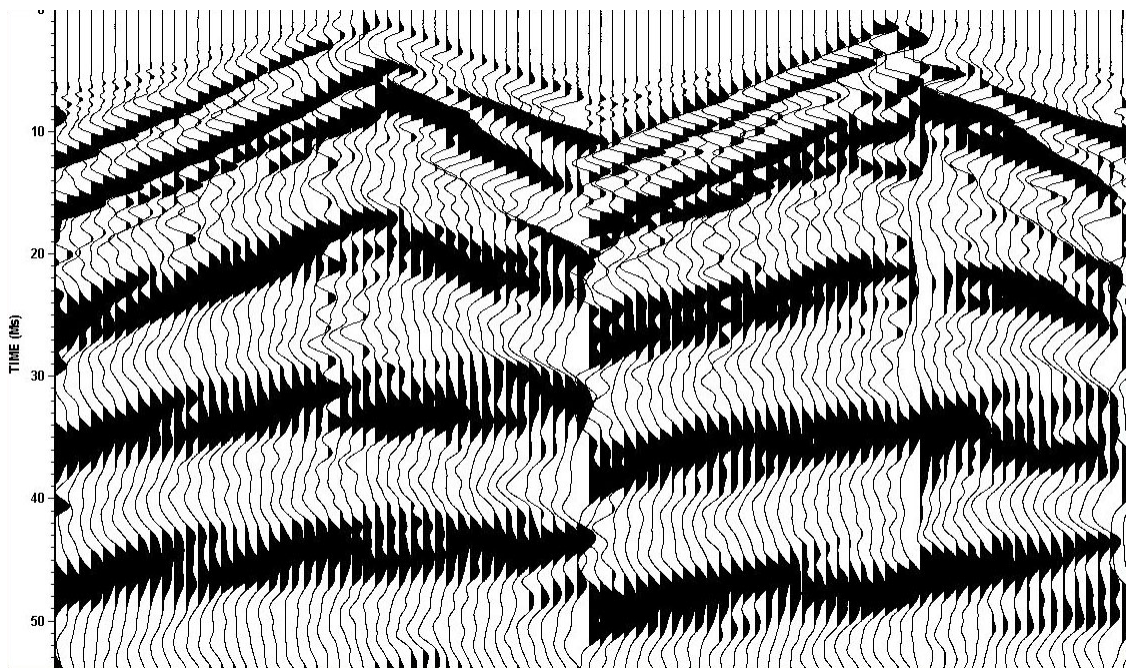


FIG. 7a. Two consecutive scaled shot gathers from VVS4(1). Trace and shot spacing are 10 cm. Inline receivers and inline hammer impact towards *increasing* channel was used.

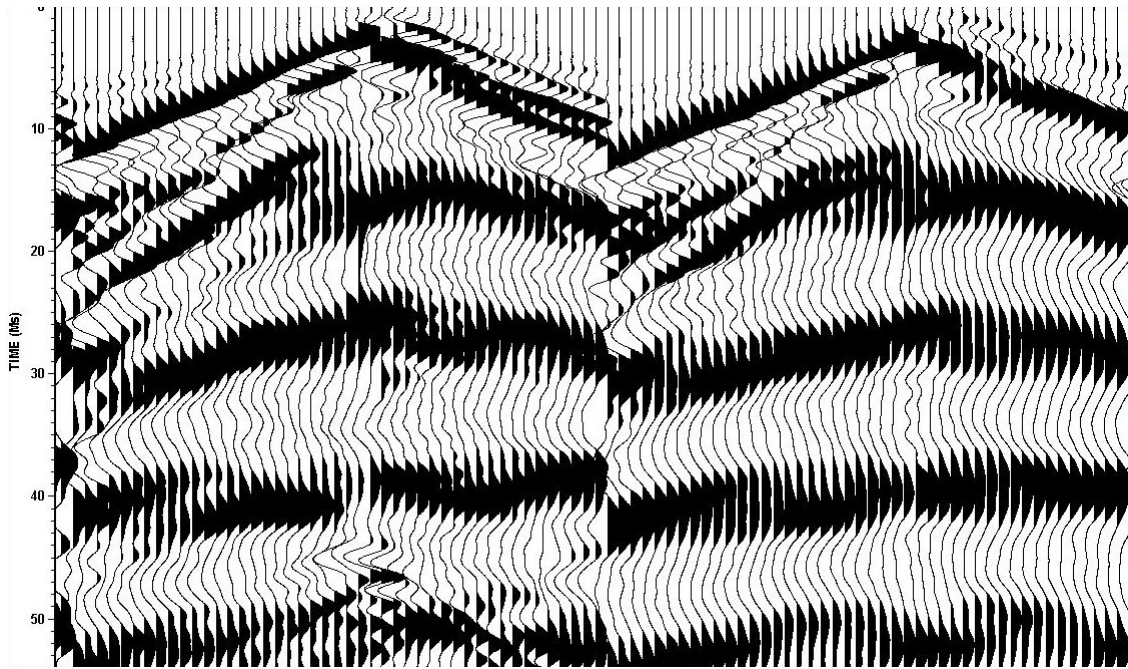


FIG. 7b. Two consecutive scaled shot gathers from VVS4(2). Trace and shot spacing are 10 cm. Inline receivers and inline hammer impact towards *decreasing* channel was used.

VVL1, VVL2, VVL3, VVL4 seismic lines:

This experiment was recorded with similar parameters but using *larger* time and spatial sample rates than the ones from VVS, and extended from the short spread (Figure 3). The trace spacing is now 100 cm, and the time sampling rate is 250 μ sec (Table 3).

Table 3. Survey description of the seismic lines recorded using 150 microseconds sample rate.

Line name	Receiver direction	Hammer Hit direction	Time sample rate (usec)	Number of samples	Receiver interval (cm)	Source interval (cm)	Recorded time (ms)	Delay time (ms)
VVL1	Vertical	Vertical	250.00	2048	100	100	512	10
VVL2	Inline	Vertical, horizontal (inline) (1) Vertical hit (2) Inline hit towards increasing channel number	250.00	2048	100	100	512	10
VVL3	Vertical	Vertical (HAMMER TEST)	250.00	2048	100	100	512	10
VVL4	Vertical	Vertical (softer impact)	250.00	2048	100	100	512	10

To display the shot gathers of this experiment the same scaling corrections previously explained was used but with different parameters:

- *Trace excursion*: 1 (max 5)
- *AGC filter*: 150 ms operator length
- *Gain*: 4 dB
- *Mean scaling per ensemble* (shot gather): scale factor 1

VVL1

This line was recorded using vertical positioned receivers and vertical hammer impacts (Figure 8).

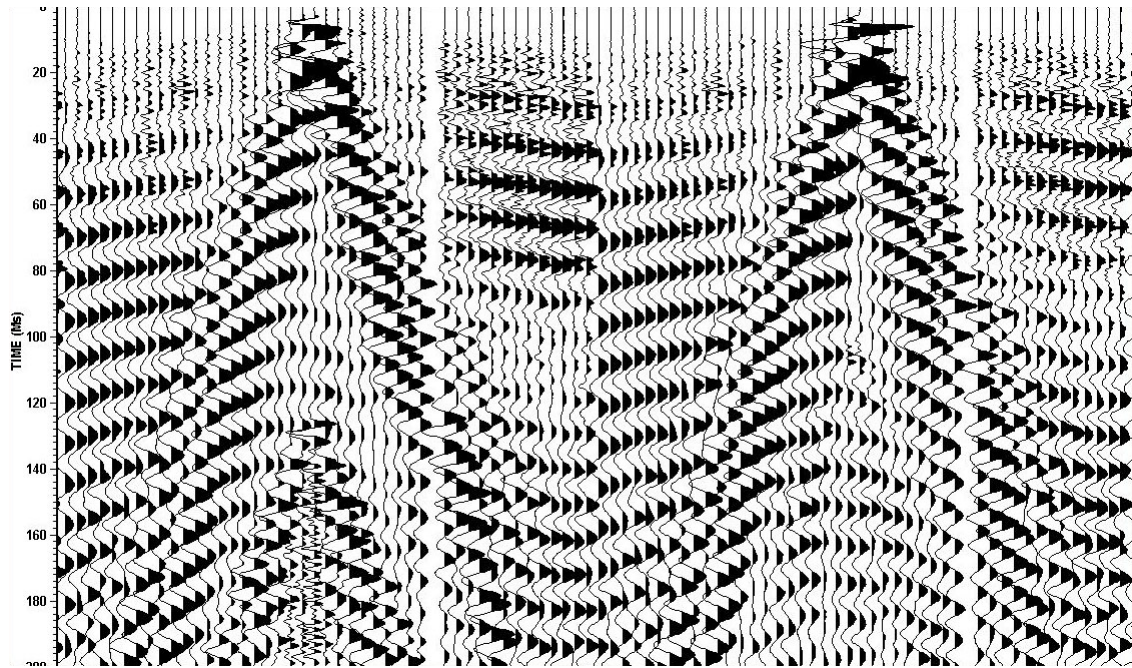


FIG. 8. Two consecutive scaled shot gathers [VVL1] Trace and shot spacing are 100 cm. Vertical geophones and a solid vertical hammer impact was used.

VVL2

The receivers were positioned in the inline direction. Two hits were recorded per shot point. The first impact was vertical and the second was inline towards increasing channel number (Figures 9a and 9b).

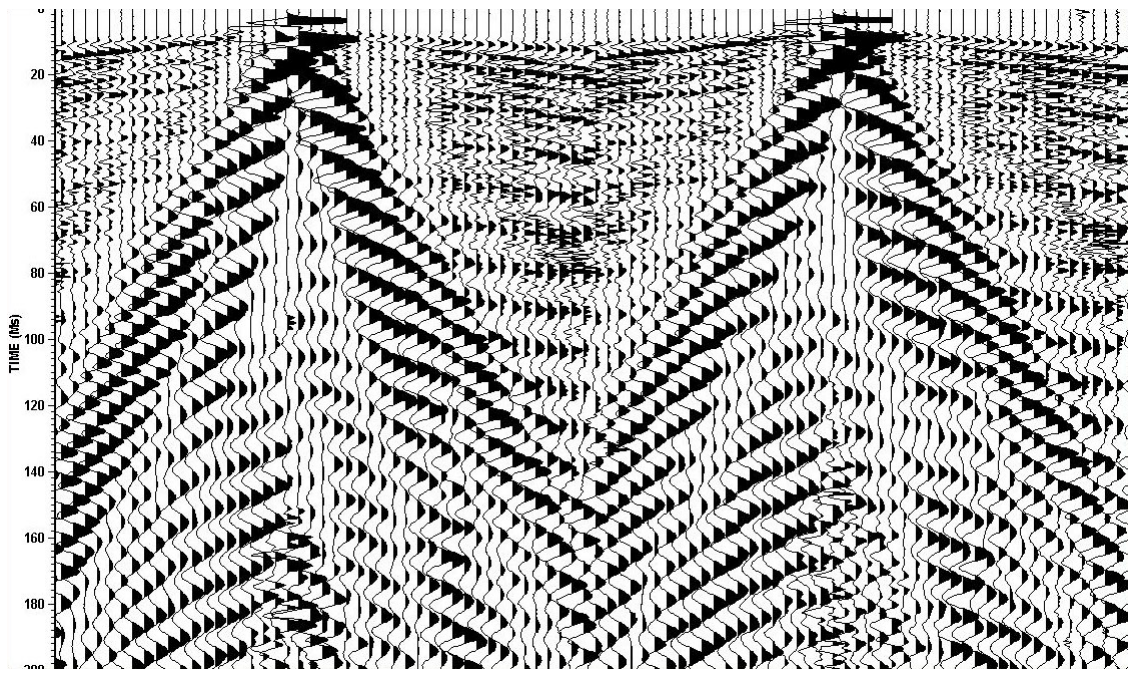


FIG. 9a. Two consecutive shot gathers from VVL2(1). The hammer impact was vertical and the receivers were horizontal in line.

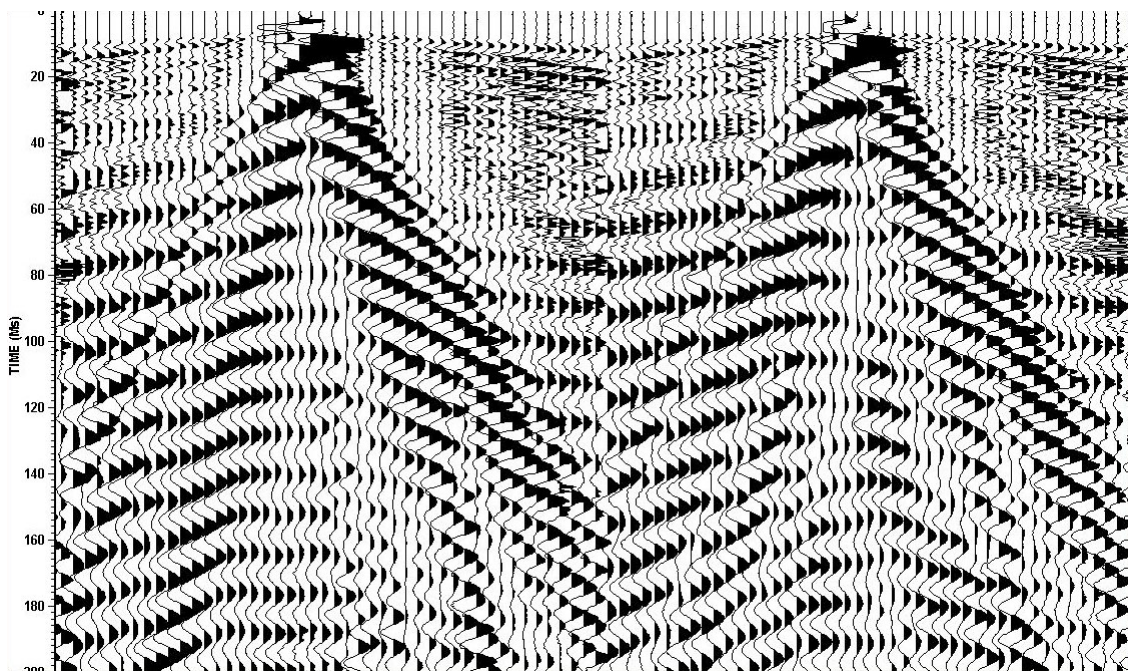


FIG 9b. Two consecutive shot gathers from VVL2(2). The hammer impact was inline towards increasing channel number and the receivers were horizontal in line.

VVL3

Several source devices were tested in this line (Table 4). The presence of the unconsolidated top weathered layer (Figure 2) introduces a number of unwanted seismic events like surface waves and guided waves, that mask the desired reflections. These tests

were all recorded at the same location, shot point station 999.5 approximately. The purpose of these tests was to observe how much the gather is improved one the impact is done directly into the permafrost (Figures 10a, 10b, 10c, and 10d).

Table 4. Hammer impact tests description.

FFID	Hammer impact description
7001	Hammer hit in test pit directly on permafrost at 51 cm depth
7002	Coring tool wacker into trigger geophone
7003	Wacker drop again
7004	6" lift a wacker weight drop
7005	Hammer tap in pit on permafrost
7006	Hammer impact on round plate in pit
7007	Vertical hammer on toothod plate
7008	Wacker on surface, just drop by itself
7009	Forceful wack into wacker on surface
7010	Round base plate
7011	Toothod base plate
7012	Hammer on hammer
7013	Hammer on inverted hammer

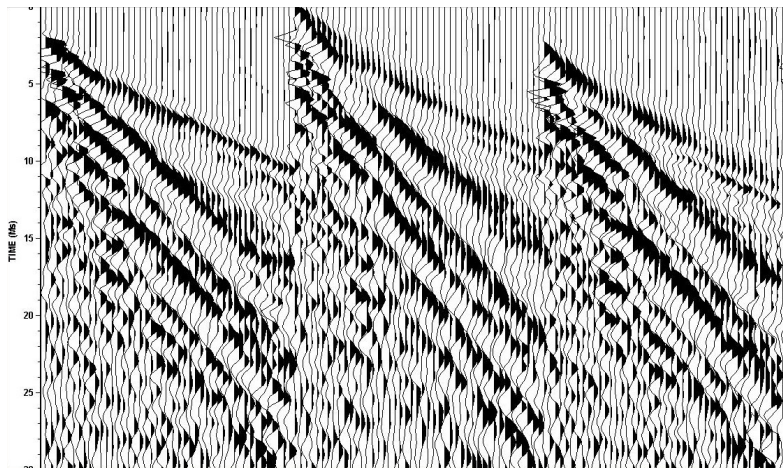


FIG 10a. Shot gathers from testing the hammer impact parameters in the Von Braun Valley. From left to right: FFID 7001, 7002, and 7003.

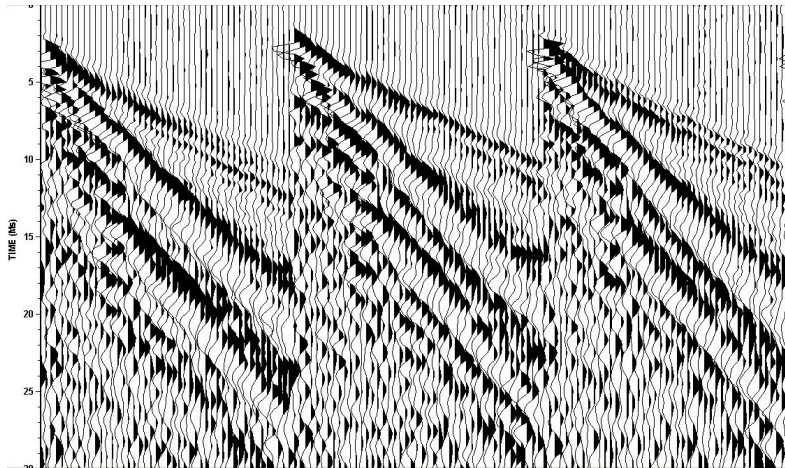


FIG. 10b. Shot gathers from testing the hammer impact parameters in the Von Braun Valley. From left to right: FFID 7004, 7005, and 7006.

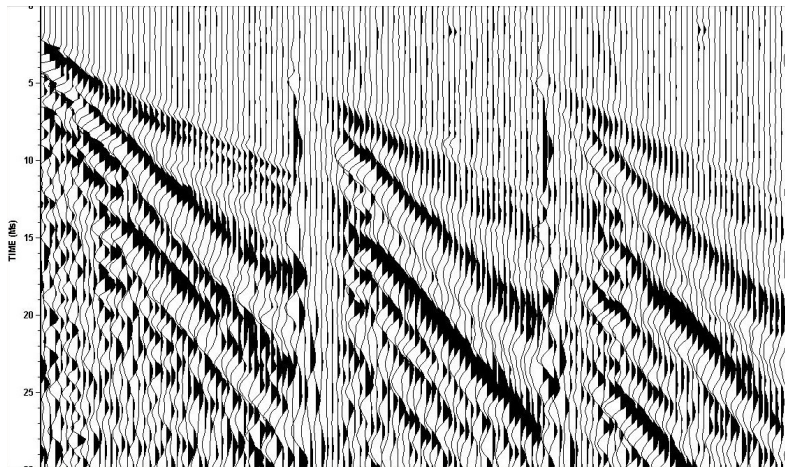


FIG. 10c. Shot gathers from testing the hammer impact parameters in the Von Braun Valley. From left to right: FFID 7007, 7008, and 7009.

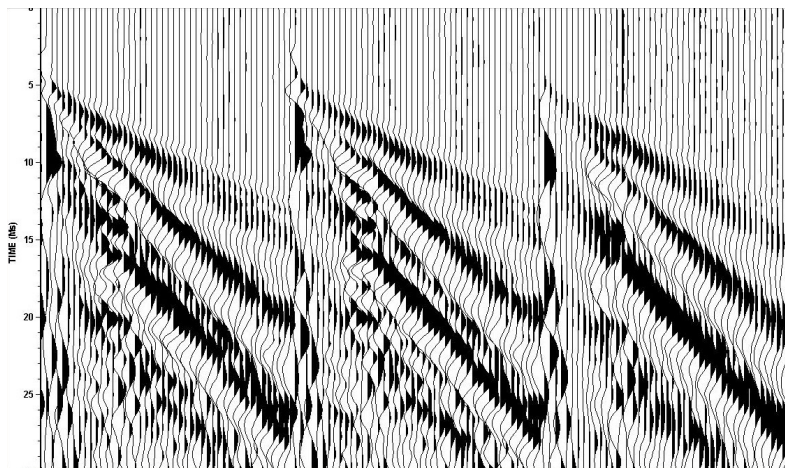


FIG 10d. Shot gathers from testing the hammer impact parameters in the Von Braun Valley. From left to right: FFID 7010, 7011, and 7012.

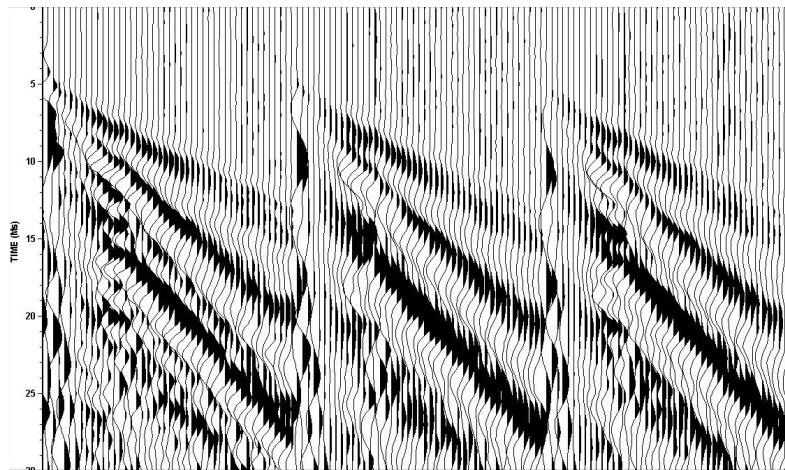


FIG 10d. Shot gathers from testing the hammer impact parameters in the Von Braun Valley. From left to right: FFID 7011, 7012, and 7013.

VVL4

The line was recorded using vertically oriented geophones, and vertical hammer impacts, just as VVL1. The difference between them was the force applied with the hammer. VVL4 is the same line as VVL1 but with a softer hammer impact (Figure 11).

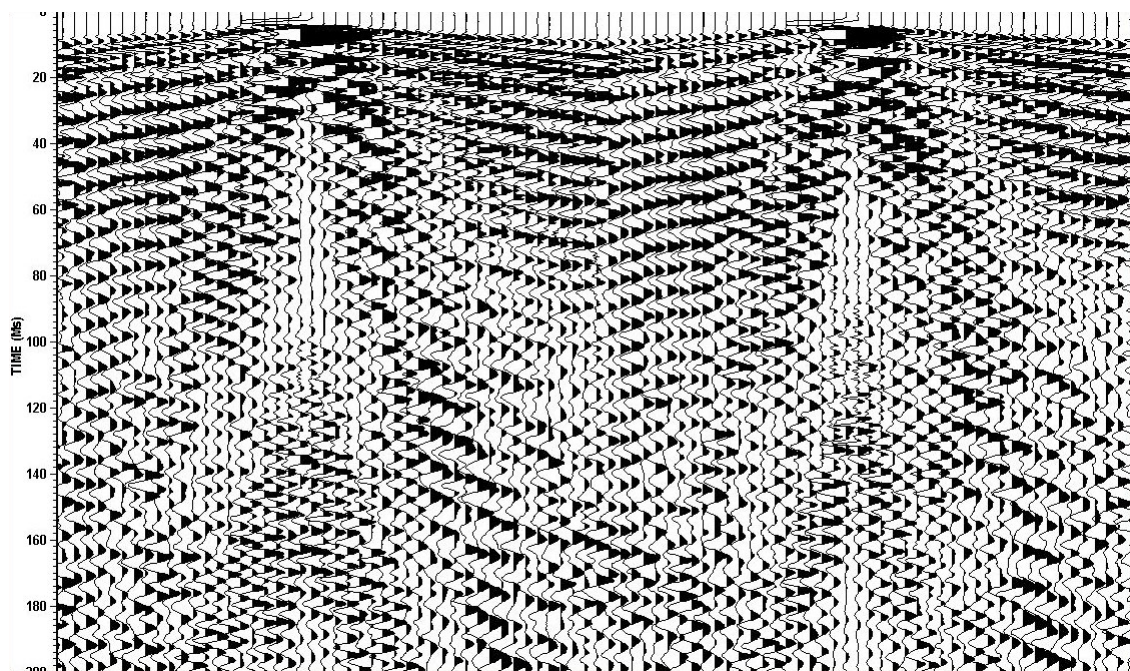


FIG. 11. Two consecutive shot gathers from VVL4. The geophones were in a vertical position as well as the hammer impact. The amount of energy laid in this time is smaller than for VVL1.

Analysis of the ultra-high resolution survey [VVS]

Analyzing the direct (compressional and pure shear motion) and head waves arrival times in the three different geophone orientations yields important information of the near-surface structure.

VVS1 and VVS3 analysis

The parameters used to analyze and display the shot gathers includes:

- *Trace excursion:* 2 (max 5)
- *AGC filter:* 30 ms operator length
- *Gain:* 2 dB
- *Mean scaling per ensemble* (shot gather): scale factor 1

A direct compressional arrival is observed with more consistency when the hammer impact was vertical and the geophones were layed out horizontally in the inline direction (VVS3, Figure 6) rather than when the geophones were vertical (VVS1, Figure 4). The polarity of the direct compressional wave changes its sign with offset sign as expected, (Figures 13a and 13b).

A strong and consistent head refracted wave is observed in the vertical geophones (Figure 12) with a velocity of 3000 m/s approximately. The velocity of the head wave varies for different hammer impact locations. Possibly reason being lateral changes of the elastic properties of the permafrost or the presence of layering inside or over it.

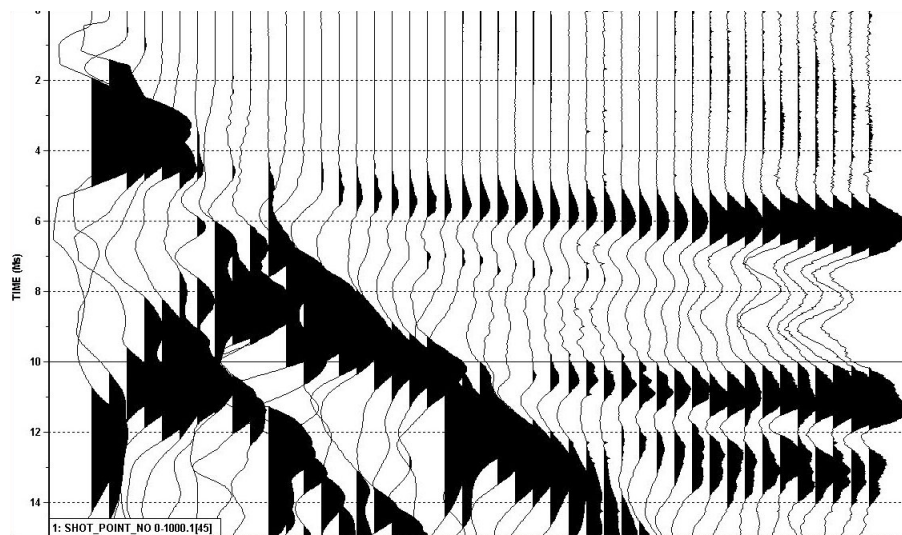


FIG 12. Vertical hammer impact 1000.05 and vertical geophones VVS1. The refracted arrival observed has a velocity of 3000 m/s approximately and a 90 degree phase wavelet (similar to the wavelet of an impulsive source). This velocity varies little from 2900 to 3200 m/s along the different shots.

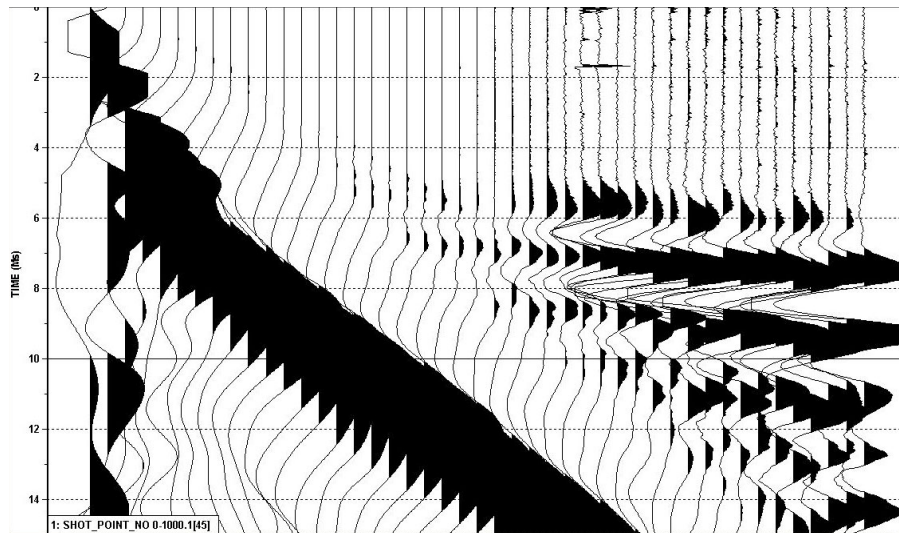


FIG 13a. Vertical hammer impact 1000.05 and inline geophones VVS3. The length of the agc operator was reduced to 10 ms enhance the linear refracted event. The wavelet of this event is zero phase, and changes its polarity for a shot in the other end of the line (Figure 13b). Its velocity ranges around 2400 m/s. This velocity varies from 1900 to 2600 m/s along the different shots.

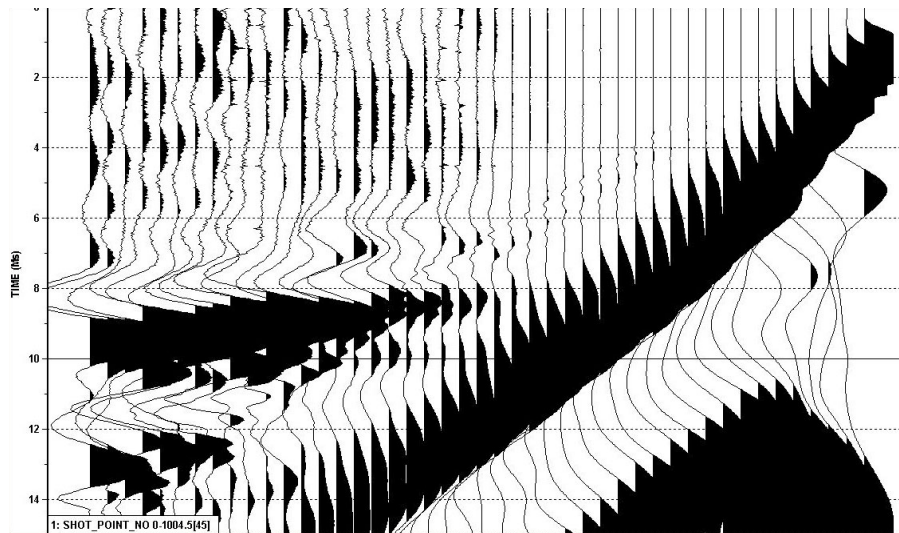


FIG 13b. Vertical hammer impact 1004.45 and inline geophones VVS3. The wavelet signature is zero-phase but it shows a polarity reversal from the shot 1000.05. Comments mentioned in the previous figure applies here as well.

There is an observable difference in wavelet signature, arrival times, velocity and polarity changes between the vertical VVS1 and inline VVS3 geophones (Figures 12, 13a and 13b) indicating that perhaps these are not the same event. A logical explanation is that the event in VVS1 line is a refracted compressional (Figure 12) and in the VVS3 line is a refracted shear wave (Figures 13a and 13b).

VVS2 and VVS4 analysis

The parameters used to analyze the shot gathers are:

- *Trace excursion: 2 (max 5)*
- *Gain: 4 dB*
- *Mean scaling per ensemble (shot gather): scale factor 1*

A variation of the recording start time for consecutive shot points observed in both lines VVS2 and VVS4 suggest a general problem with the trigger system when the impact is horizontal. There is small variation of the direct shear wave arrival times in VVS2 line where both the source and receivers were transverse horizontal (Figures 14a, and 14b). The head wave was not analyzed in this line due to its poor consistency and low amplitude from trace to trace.

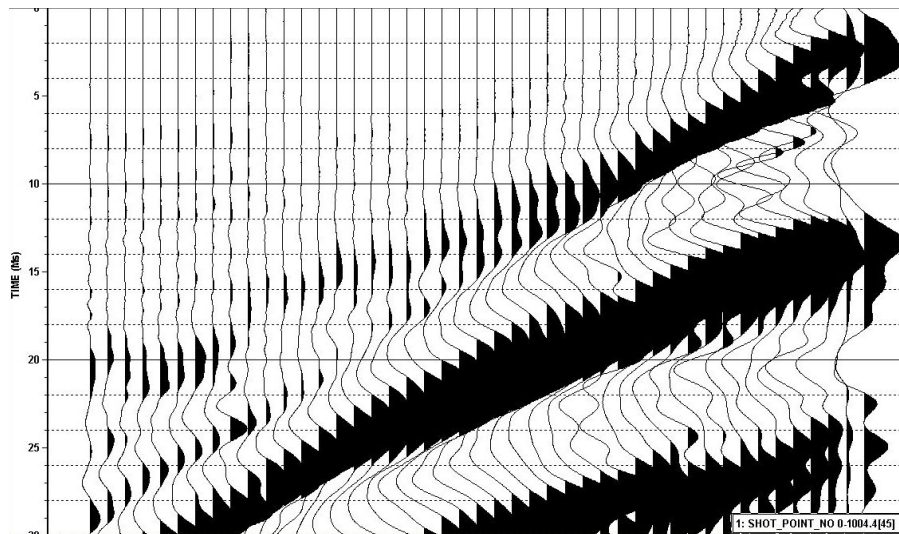


FIG 14a. Transverse *away from the camp* hammer impact 1004.35 and transverse geophones VVS2(1). The velocity of the direct shear arrival is 160 m/s approximately.

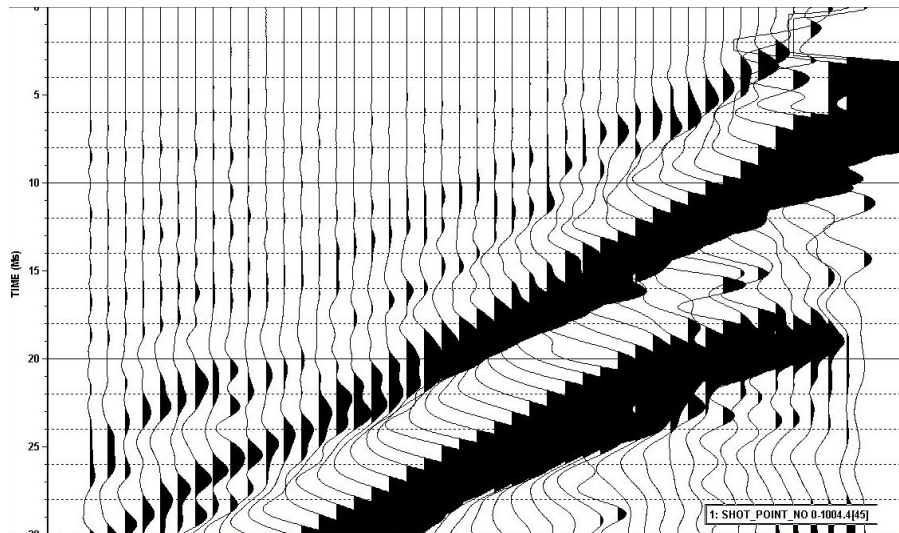


FIG 14b. Transverse *towards the camp* hammer impact 1004.35 and transverse geophones VVS2(2). The velocity of the direct shear arrival is 160 m/s approximately.

The direct SH wave arrival does not change its polarity from positive to negative offsets, but it does change polarity for different hammer hit directions, as expected (Figures 14a and 14b). The velocity estimated from these records varies between 155 m/s and 180 m/s.

VVS4 line has both horizontal *inline* receivers and hammer impacts. This line shows a strong amplitude and consistence of the direct compressional wave arrival in all records (Figures 15a, 15b, 16a, 16b). There are several relevant characteristics found in these records. In order to observe these characteristics the display parameters will include and AGC filter of 15 ms operator length.

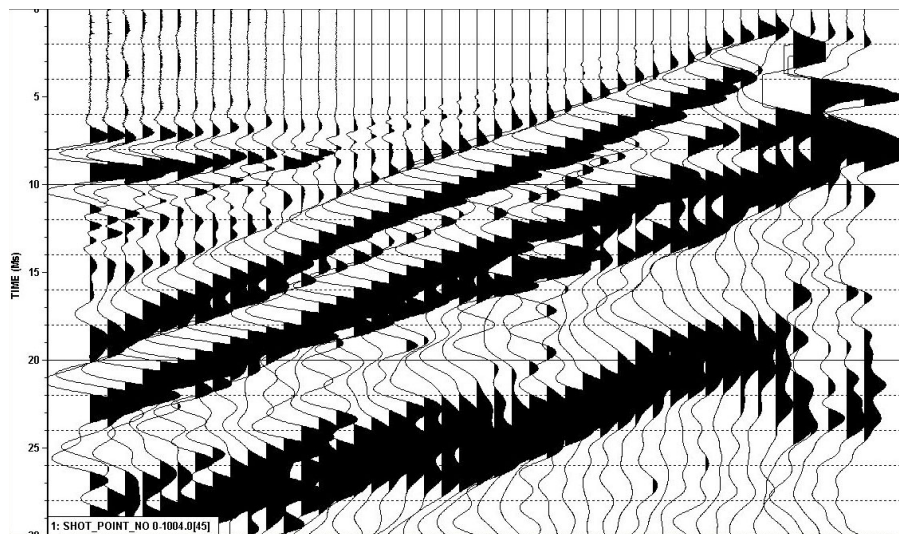


FIG 15a. Inline *towards increasing* channel number hammer impact 1003.95 and inline geophones VVS4(1). The direct wave has a velocity of 260 m/s and the head wave of 2080 m/s approximately. The polarity of the direct wave changes with both offset and hammer impact direction. The signature of the head wave wavelet is zero-phase type and its polarity does not change with offset or hammer impact direction (Figure 16b).

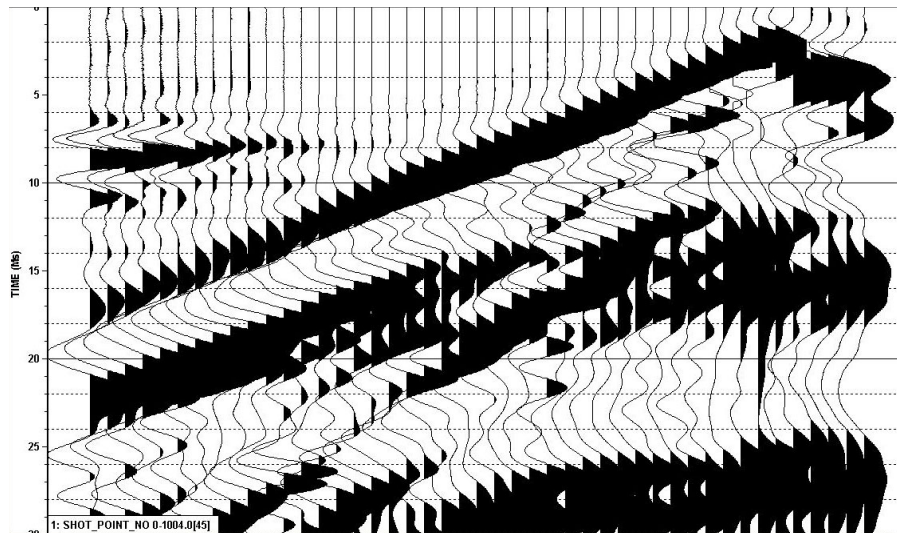


FIG 15b. Inline towards *decreasing* channel number hammer impact 1003.95 and inline geophones VVS4(2). The direct wave has a velocity of 260 m/s and the head wave of 2080 m/s in average. Observe the polarity reversal of the direct wave arrival from the impact towards *increasing* channel number (Figure 16a).

The first one is that the direct arrival changes its polarity from positive offset to negative offset, and changes also for the two different hammer impacts orientations as expected (Figures 15a and 15b).

The second is that the head wave arrival *does not change* polarity for two opposite hammer impact orientations (Figures 15a and 15b) or from positive offsets to negative offsets, (Figures 16a and 16b). This is opposite to what occurs in the VVS3 where the head wave changes polarity from positive to negative offsets (Figures 13a and 13b).

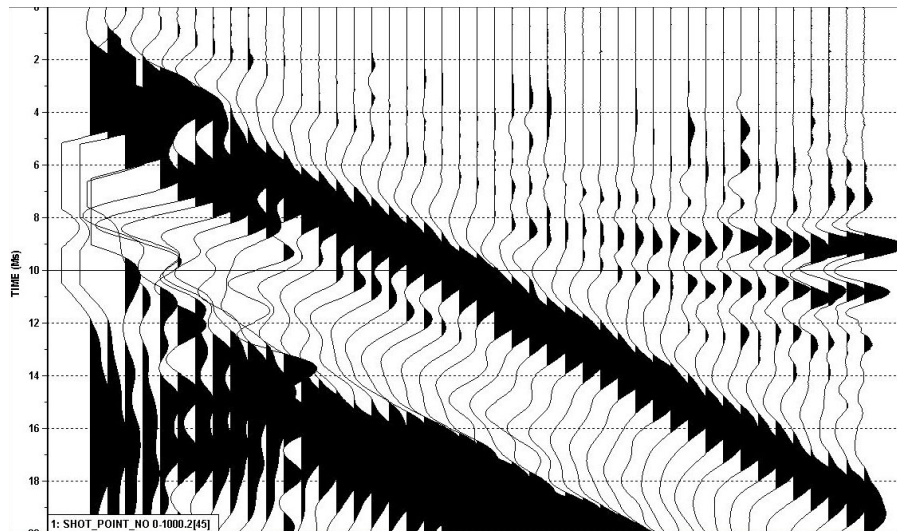


FIG 16a. Inline towards *decreasing* channel number hammer impact 999.95 and inline geophones VVS4(2). The parameters for display includes a 20 ms agc filter.

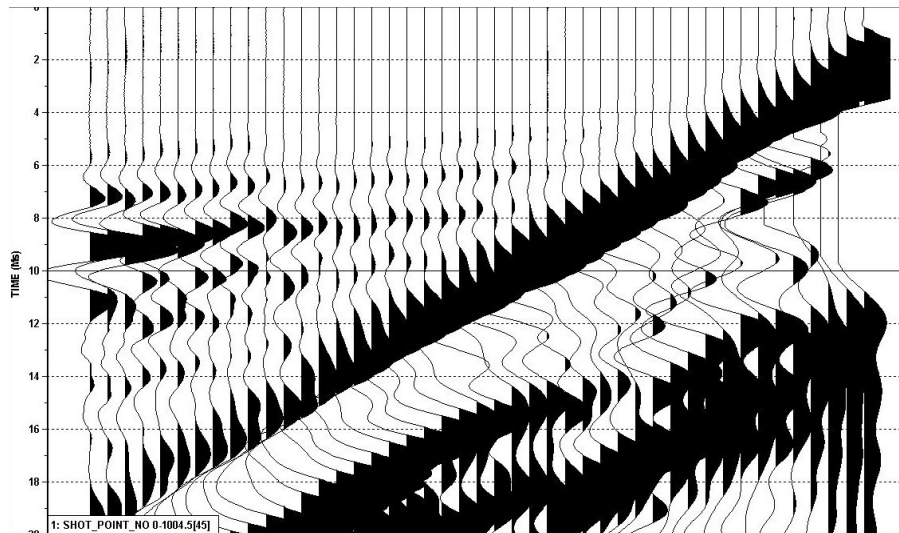


FIG 16b. Inline towards *decreasing* channel number hammer impact 1004.45 and inline geophones VVS4(2).

Table 5 presents a summary of the observations from the ultra-high resolution lines.

Table 5. Summary of the results from the VVS lines.

Line	Direct wave arrival			Head wave arrival		
	Vel. [m/s]	Polarity	Comments	Vel. [m/s]	Polarity	Comments
VVS1	200	No	Inconsistent direct wave arrival	3050	No	Velocity varies for different shot gathers {2900 to 3200 m/s}
VVS3	260	Yes	Very consistent arrival. Polarity changes with offset sign	2250	Yes	Polarity changes with offset. Inconsistent "head wave arrival". Velocity varies from 1900 to 2600 m/s
VVS2(1)	168	Yes	Changes polarity for opposite hammer impact orientations but not with offset sign. Velocity varies from 155 m/s to 180 m/s	---	---	Not analyzed
VVS2(2)						Not analyzed
VVS4(1)	260	Yes	Very consistent compressional wave arrival. Changes polarity both with offset, and with hammer impact orientation	2080	No	Inconsistent head wave arrivals
VVS4(2)						

CONCLUSIONS

A preliminary display of all the seismic lines recorded in the Von Braun Valley, Devon Island, Nunavut, is shown. Complete analyses of the compressional and shear motions were obtained from the analysis of the first break arrivals of the VVS seismic lines. Both compressional and pure shear motion direct arrivals are identified on their respective lines.

Compressional wave motion presents a velocity of 260 m/s in the saturated silt (top layer). It changes polarity with offset sign and with hammer impact orientation (VVS3 and VVS4) as expected. Shear wave motion shows a slower velocity of 168 m/s in the same layer. This motion was recorded in the VVS2 line. Its polarity changes with the hammer impact orientation, but remains the same with the offset sign.

The later events include compressional, and/or possibly shear wave refraction. VVS1 line shows the most consistent head wave arrival. Its velocity changes for different shot gathers, and also with offset suggesting possibly layering inside the permafrost or over it and lateral variation as well. An estimate of 3050 m/s was obtained from the first break times. The polarity remains unchanged with offset sign.

VVS3 line presents a later arrival with a zero-phase wavelet, very different than the impulsive 90-degree wavelet seen on VVS1. The velocity of this event is 2250 m/s. It varies from 1900 to 2600 m/s, and its polarity changes with offset sign. A third estimate of 2080 m/s is calculated from the VVS4 line, but there is not much confidence due to arrival time fluctuation.

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