Integrated well-log, VSP, and surface seismic analysis of near-surface glacial sediments: Red Lodge, Montana

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ABSTRACT

We conducted a series of geophysical surveys to characterize a glacial bench deposit and underlying strata near Red Lodge, Montana. Well logs and VSP data were acquired in a PVC-cased, 115m deep borehole. The multi-offset VSP was undertaken using surface sources (an accelerated weight drop and sledge hammer) with a hydrophone string and downhole, wall-clamping, 3-component geophone. The well logs included measurements of conductivity, radioactivity (gamma ray), temperature, and sonic velocity. Sonic and VSP velocities ranged from 1500m/s in the very near surface to 3000m/s at 85m depth. A distinct black clay layer (with high conductivity, high gamma ray, and low velocity) was penetrated at 85m. High-resolution 2D and 3D seismic surveys, using a sledge hammer source, showed a number of reflectors to about 150ms two-way traveltime. On the L-plot composite displaying well log data, synthetic seismograms, and the VSP corridor stack, a reflection at 80ms correlated with the 85m interface Various other reflections in the VSP and surface seismic data were interpreted to represent glacial deposit layers and water zones (from the perforation logs).

INTRODUCTION

The study area, near Red Lodge Montana, lies in front of the Beartooth Mountains which locally comprise an overturned sequence with a thrust fold (Foose et al., 1961; Wise, 2000). During the last glacial maximum (approximately 12,000 to 20,000 years ago, and called the Pinedale), mountain glaciers formed in the Montana area (Fig.1). Slow-moving glaciers picked up and transported rock fragments (glacial till). The glacial benches in the area were formed during earlier glacial melts depositing sediment and the erosional scarps were formed by a later glacier outwash. In the western part of glacial valley, called East Rosebud Creek, there are three layers of glacial till deposits (Pers. comm. J. Sisson, 2010 - Fig.2). The total thickness of glacial bench is around 23m (Ritter, 1964).

Rock properties from the drillers log and our subsequent well logs in Well GB-1 indicate that the top 13m is soil and gravel. The gravel may be the youngest pulse of glacial deposits (Fig.3). From 15m to 25m, there is the red-color rock with an intersecting red fracture zone which may be interpreted as another pulse of glacial deposit. Below that, there is a 15m thickness red rock zone, which could be Amsden bedrock (Fig.4). To assess the thickness of the overlying till and provide information on the underlying stratigraphy, we have undertaken geophysical measurements.

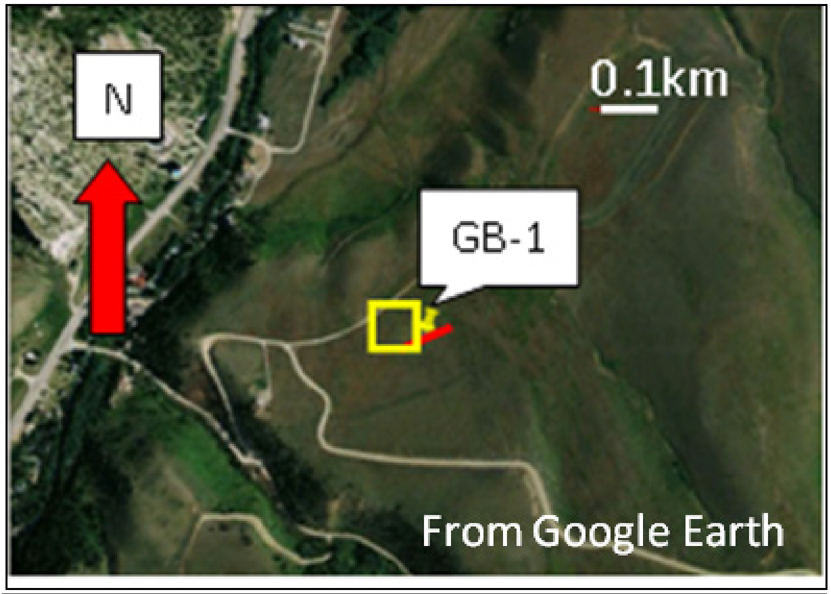

FIG. 1: Base map showing the location of well GB-1 and the 2D and 3D seismic surveys (the red line indicates the 2D seismic location; the yellow square outlines the 3D seismic area).

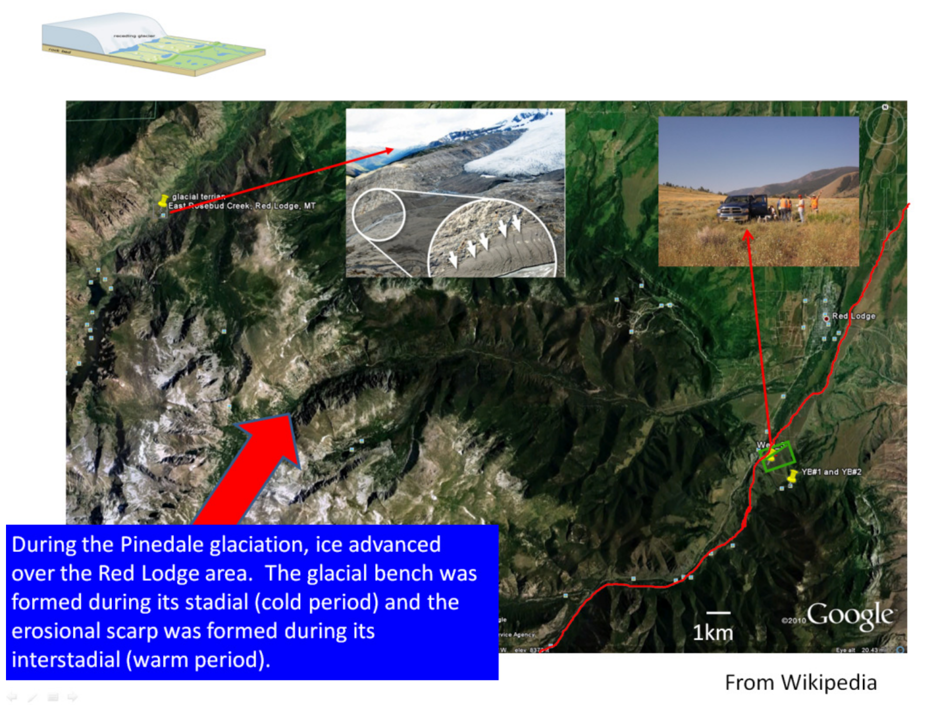

FIG 2: Geology background of glacial bench.

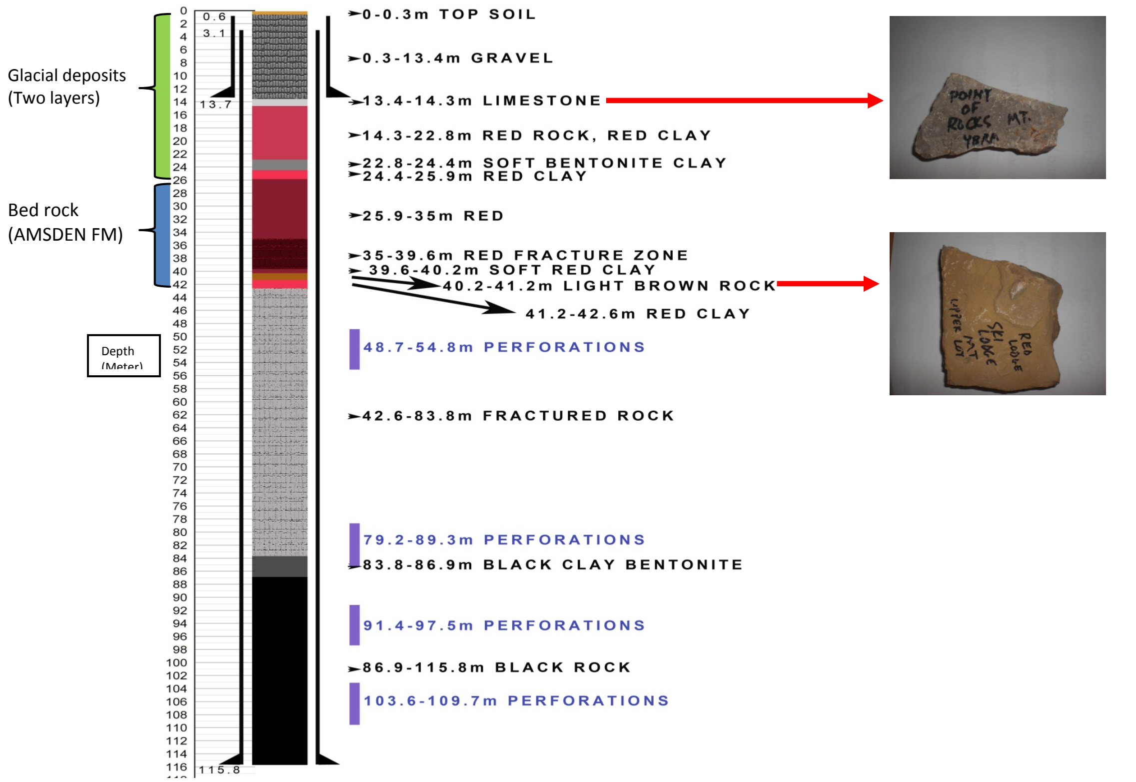

FIG. 3: Lithology and casing program of the GB-1 well (from the drilling report).

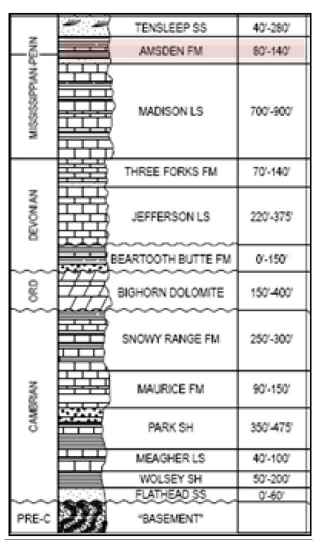

FIG. 4: General stratigraphic column, near Red Lodge, Montana, with regional thicknesses.

DATA AVAILABLE (WELL LOGS, VSP, 2D/3D SURFACE SEISMIC)

At the 2010 Geophysical Field Camp, the University of Houston (with help from University of Calgary, GEDCO, and UT-Austin personnel) conducted a VSP in the 115m-deep, PVC-cased water well, GB-1, located on the glacial benches. The suites of cased-hole geophysical logs (conductivity, gamma, temperature, full wave sonic) were acquired in GB-1. Gamma ray and resistivity logs delineated the shale/sandstone bedding. The character of the full-waveform sonic first arrival times bore similarities to the gamma ray log (Fig.5). A hydrophone string covered the depths from 6m to 112m with half-meter intervals. We also shot 2D (Fig.6) and 3D (Fig.7) seismic and the design of this 3D survey is shown in Figure 8. From the surface seismic, there is an obvious reflection at the red fracture zone. The well encounters about 13m of unconsolidated overburden and then goes through Red rock and a fracture zone. Vertical seismic profiles (VSPs) were acquired in the Red Lodge GB-1 using an accelerated weight drop (AWD, or wacker) and hammer as sources with a wall-clamping 3-component (3C) geophone and hydrophones as receivers (Fig. 9). The wall-clamping 3C geophone was placed at depths ranging from 4m to 114m with half-meter intervals. The 3C geophone and hydrophone VSPs with hammer source and accelerated weight drop source are compared on Figure 10. Figure 11 shows a selection of the walkaway VSPs with hydrophone array.

The purpose of this study is to interpret the VSP, surface seismic, and well log data and tie them to the glacial till thickness and other near-surface features. The 3m east offset VSP with accelerated weight drop source and 3C geophone was selected in this study. Low signal-to-noise ratios characterized the hammer source VSP data, so we did not use them in this study. The locking geophone with the AWD source gave data with good signal-to-noise ratios, but the hydrophone results appear unstable, especially at further offsets, where more than half the traces were dead traces. The best VSP, shown on Figure 10, is the one with the 3C geophone and the AWD source at 5.2 offset.

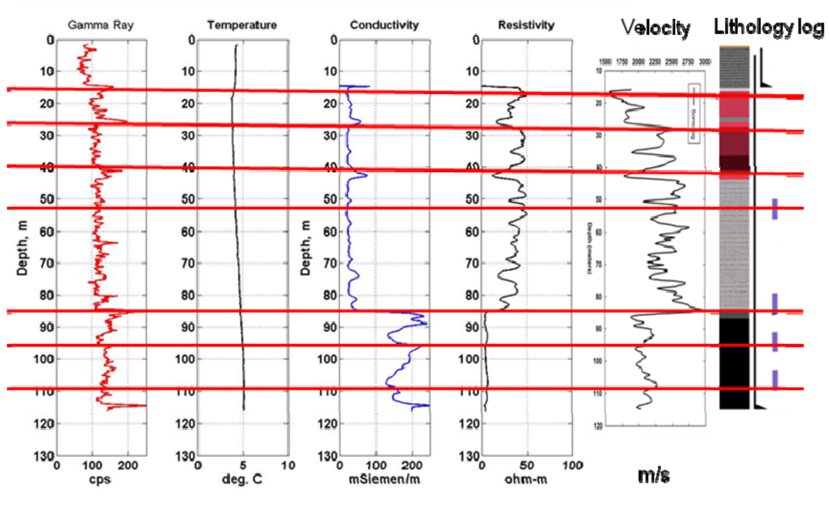

FIG. 5: Geophysical logs from the GB-1 as acquired in 2010.

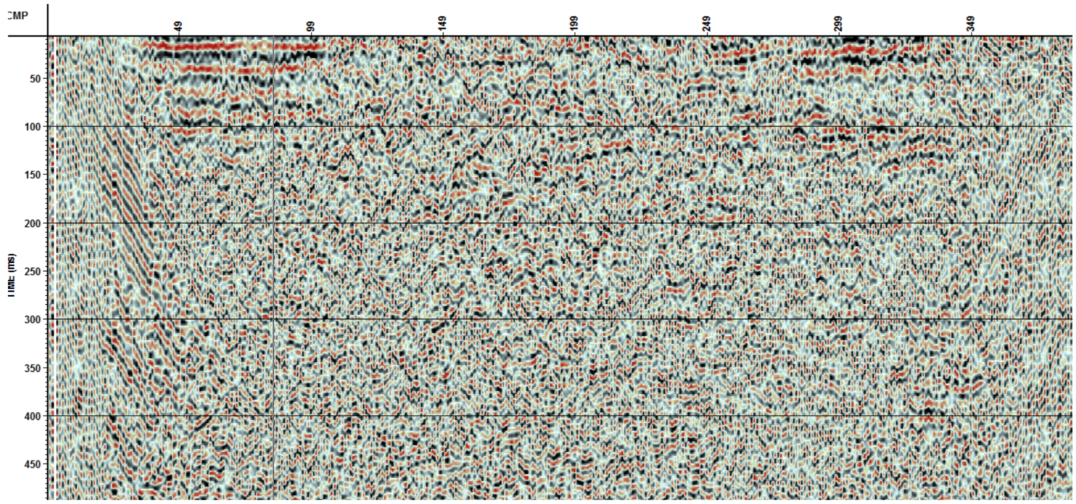

FIG. 6: 2D seismic section (brute stack only) on the glacial bench from 2010 field survey. Data are stacked with constant velocity 2500m/s.

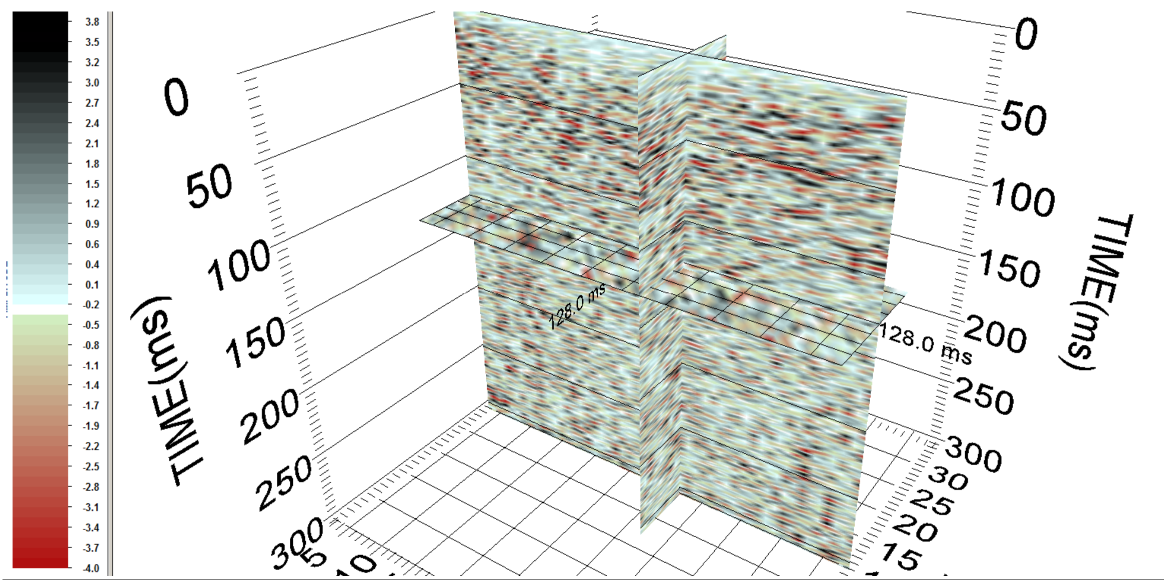

FIG. 7: 3D seismic brute stack cube at the glacial bench from 2010.

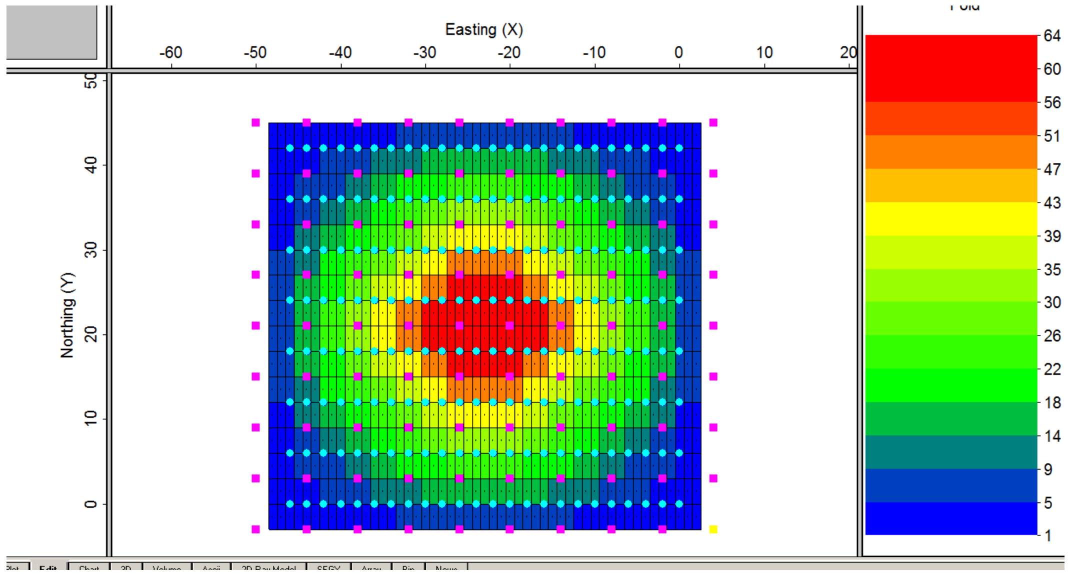

FIG. 8: 3D seismic survey design using the OMNI program.

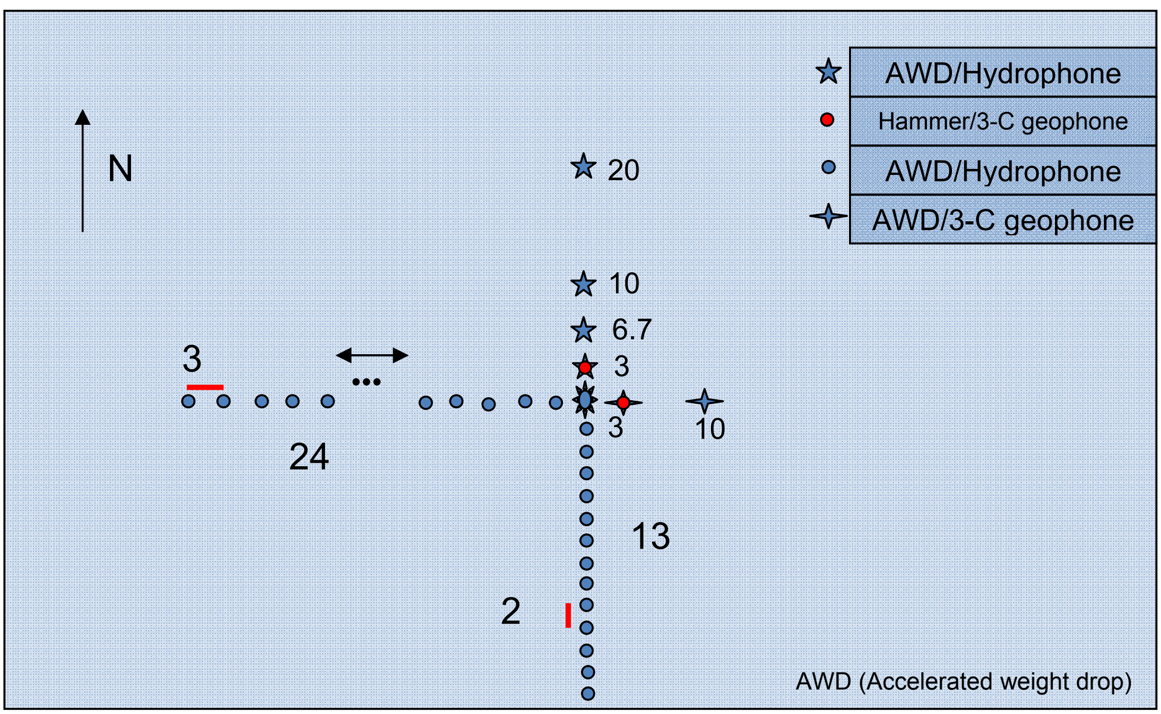

FIG. 9: Base map of the GB-1 VSP surveys.

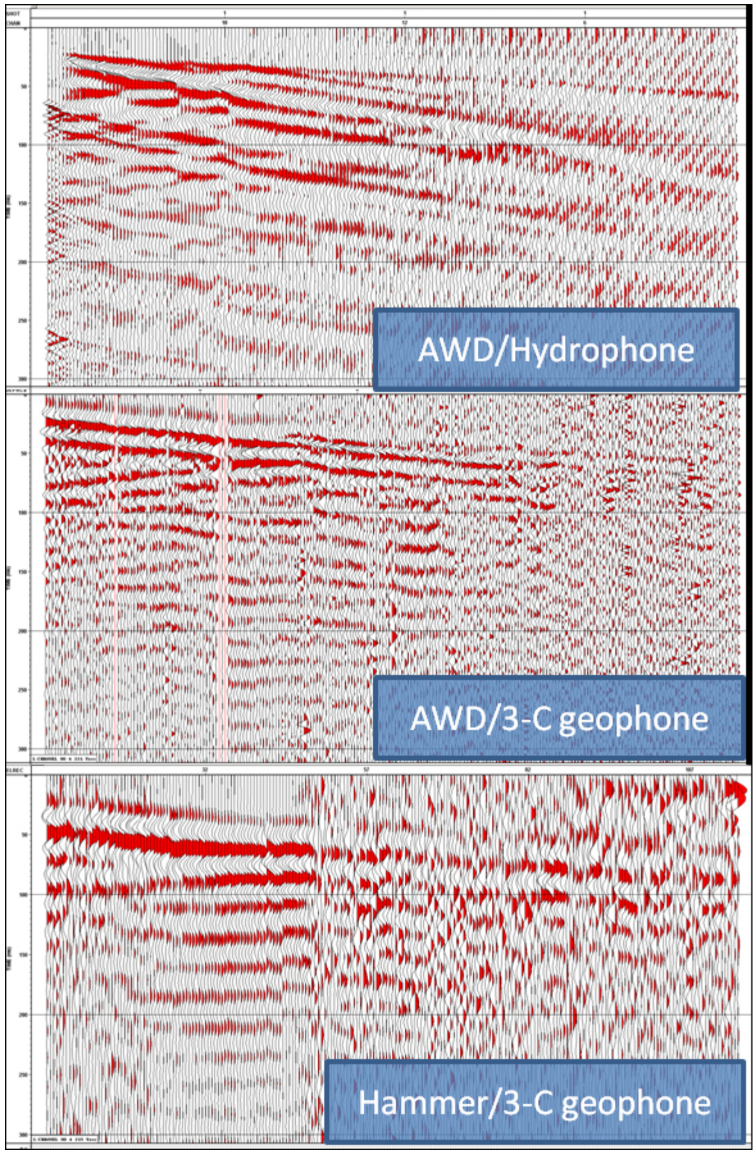

FIG. 10: AWD/Hydrophone VSP is 5.2m south of the GB-1 well head; AWD/3-C geophone is 3m east of the well head; Hammer/3-C geophone is 3m north of the well head (AWD is accelerated weight drop).

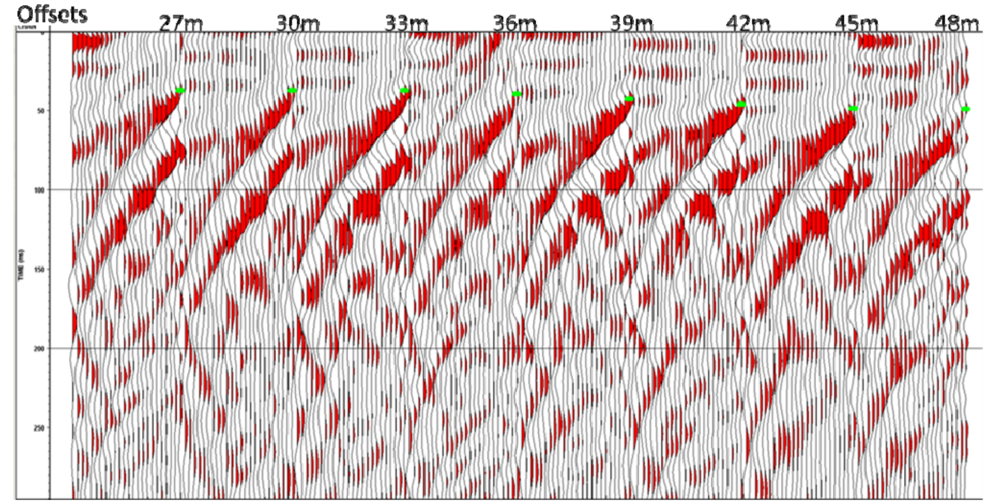

FIG. 11: AWD/Hydrophone Walk away VSP with 3m offset interval west of the GB-1 well head, hydrophone covers from 16m to 108m with 4m interval.

NEAR OFFSET VSP PROCESSING

VSP acquisition geometry and first break picking

The near-offset VSP (3m offset) with the AWD source used the 3C geophone placed at depths ranging from 4m to 114m with half-meter intervals. The sampling time was 0.5ms. The borehole receiver contains two horizontal components and one vertical component. The two horizontal components are named X and Y while the vertical component is named the Z component. The data acquired in the field contained all the shots in different files. The VISTA seismic processing package was employed for analyzing the data. In the VSP data files, channel numbers 1, 2, 3, correspond to X, Y, and Z components (lack of rotation control for the downhole geophone means that horizontal X and Y components have indeterminate azimuthal orientation). An essential step in VSP processing is the geometry input. This was done by sorting the data stacks according to Channel Number (primary sort) and Depth of Receiver (secondary sort) to create proper trace headers.

The reflected upgoing P-waves were much stronger and clearer on the Z component compared to those on the X and Y components. There was not enough upgoing energy in the X and Y components to be processed, so we focused only on the vertical Z component.

Well GB-1 was close to a local electric power line, and we have experimented with notch filters to attenuate the attendant 60Hz noise. An Ormsby band pass filter with corners at 30-60-150-300Hz and 500ms automatic gain control (AGC) were applied to the Z component for display. A principal use of VSPs is to determine the variation of seismic velocity with depth (Stewart, 1984). The first break times were picked on the raw vertical Z component as is shown on Figure 12. Interval velocities are calculated by dividing the straight-line distances from source to receiver by the picked first arrival times. The resulting interval velocities show that P-wave velocities are in the range from 2000 to 3500m/s. Figure 13 indicates that the VSP interval velocities follow the same trend as those on the sonic velocity log (sonic velocities ranged from 1500m/s in the very near surface to 3000m/s at 85m depth).

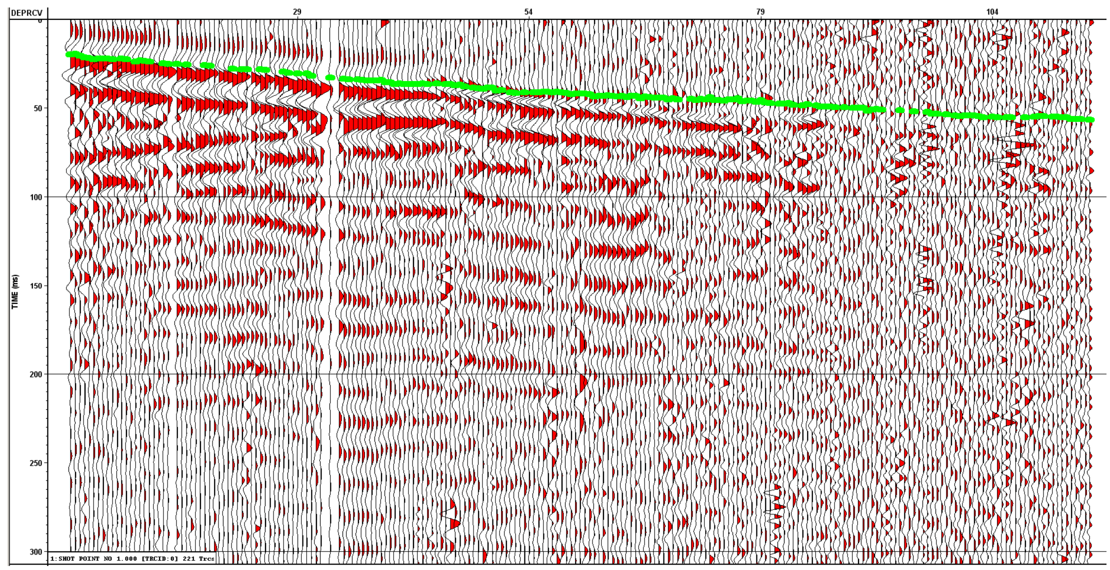

FIG. 12: First break picking from the GB-1 (display with Ormsby filter & 500ms AGC).

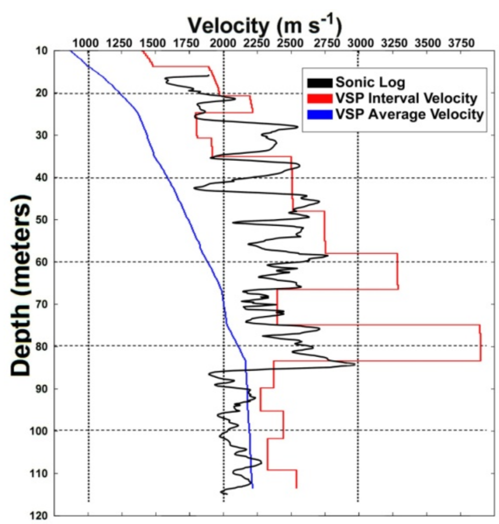

FIG. 13: Sonic log, VSP interval and VSP average velocity comparison from the GB-1.

Wavefield separation using median filtering

The next major processing step was to separate the downgoing from upgoing wavefields. The raw Z component was flattened to a 100 ms datum by subtracting the first break times from each trace (Hinds, 1996). Median filtering was chosen to separate the wavefields. We tested different lengths of 9, 11, 13, 19 and 21 points in the median filter. The traces of a selected window were organized in ascending amplitude, and the middle value of the sequence is picked as the filtered value (Stewart, 1985). After repeating many times, the median filter can separate the flattened downgoing wave from the total wavefield. By subtracting the downgoing wave from the total field, we obtained the upgoing wavefield. A 21-point median filter proved best at isolating the downgoing events and, after subtraction, produced the most continuous and coherent upgoing events (Fig. 14). Muting was then applied to the first 100ms of the resulting gather showing upgoing events.

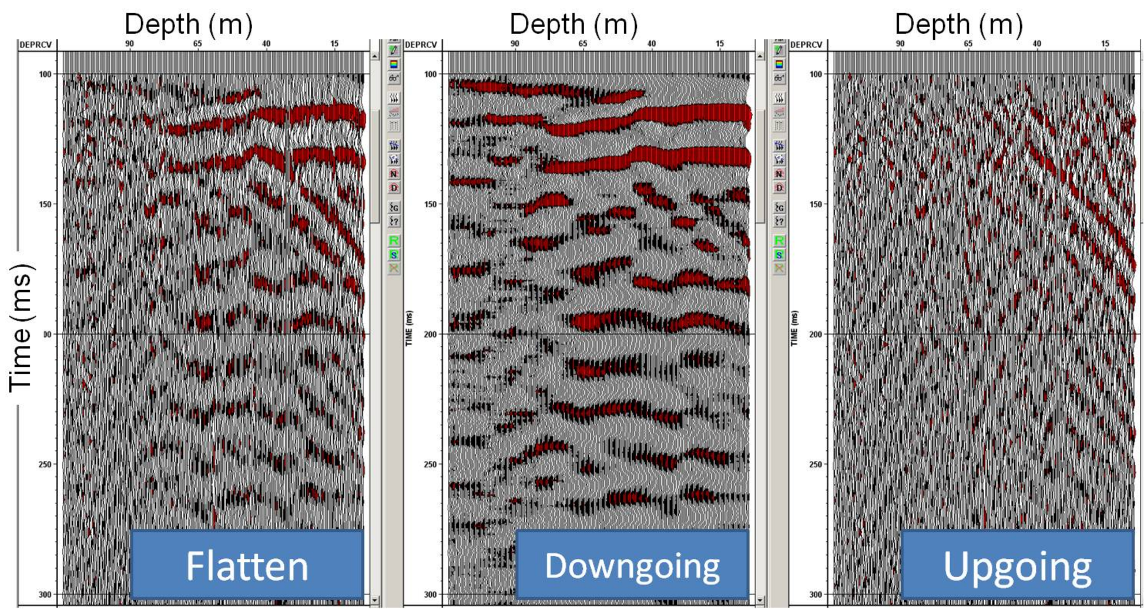

FIG. 14: Field separation (display with Ormsby filter & 500 ms AGC).

Deconvolution

The next step was to deconvolve the data using the downgoing direct wavefield to estimate the source signature. First, a deconvolution operator with optimized parameters was generated using the flattened downgoing traces. The deconvolution windows started at 0 ms and extended to 300 ms. This wide window was chosen because the data was found to not contain significant multiples within it. The deconvolution operator designed using the downgoing traces was then applied to the upgoing Z wavefield to get an estimated reflectivity series.

After deconvolution, both upgoing and downgoing events appear to be sharper and better defined. A 21-trace median filter was been applied to the deconvolved upgoing reflection events to further flatten and enhance them (Fig. 15).

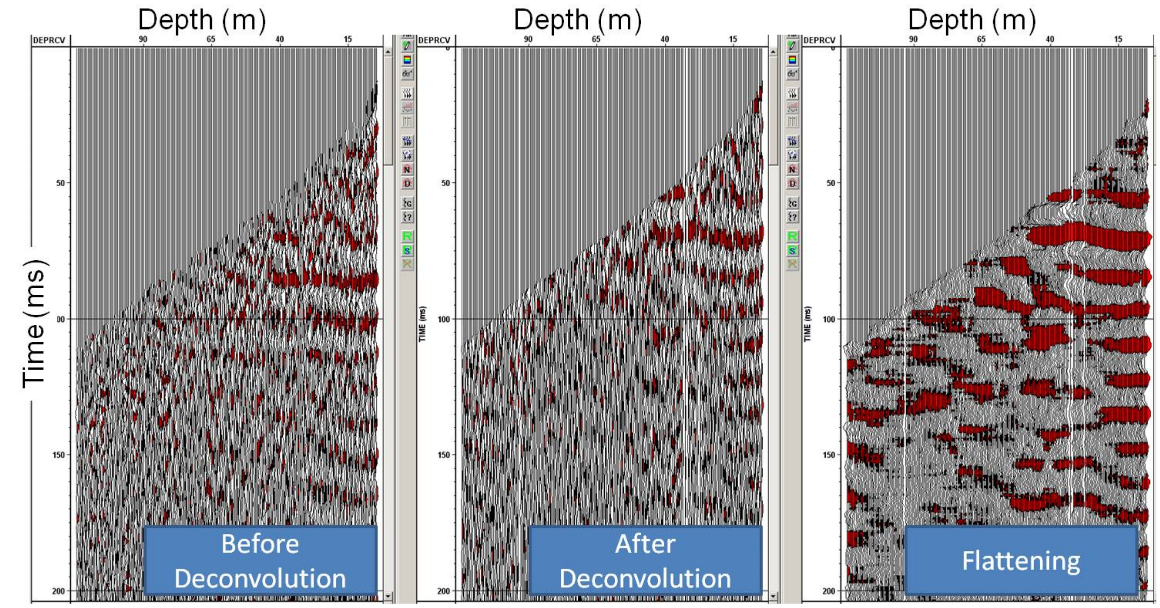

FIG. 15: Processing of upgoing wavefield (display with Ormsby filter and 500 ms AGC).

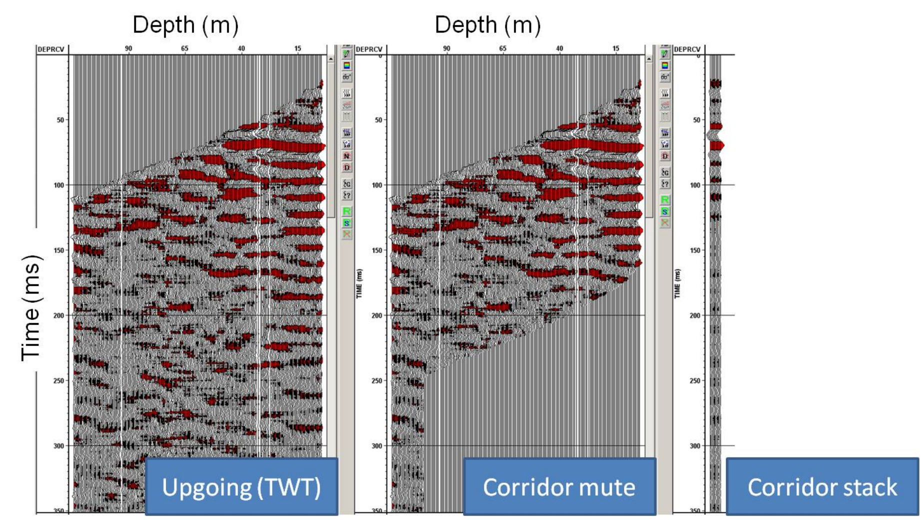

FIG.16: Corridor stacks (display with Ormsby filter & AGC).

Corridor stack

The upgoing P wavefield was converted into Two Way Time (TWT) by adding the first break time to every trace twice. This step produced the final estimate for the reflection coefficient series. In the field data, there is lots of noise in the pre-stack profile. The corridor is the window along the edge, to avoid noise from the whole data profile. A corridor mute of 150 ms is applied to the corridor muted data. Then the data were stacked across the corridor into one trace, and repeated 10 times for display (Fig. 16).

WIRELINE LOGS, 2D SEISMIC AND VSP COMPARISON

P-wave sonic velocity and gamma ray logs, acquired at depths of 4m to 115m, are shown together with the processed VSP on the L-plot of Figure 17. Also shown are the processed VSP and a gather of stacked seismograms from the 2D surface reflection survey.

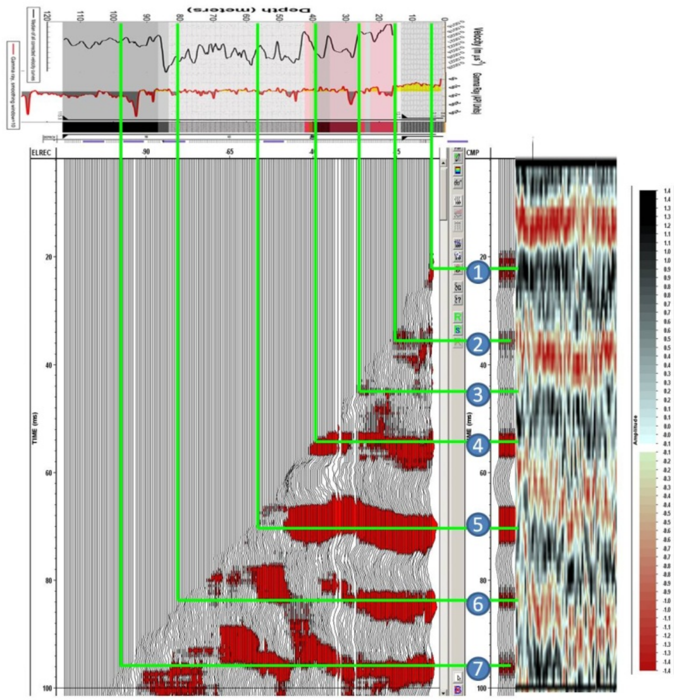

FIG. 17: L-plot of VSP and sonic & gamma logs, and VSP corridor stack correlated with surface 2D seismics (stacked with 2500m/s velocity).

The figure shows that prominent events on the VSP corridor stack correlate fairly well with the features on the geophysical logs. They also correlated with reflections on the 2D seismograms. Seven events can be identified on the L-plot. Event 2 and 3 are interpreted as two glacial deposits. Figure 3 indicated water-bearing zones next to the casing perforations at depths of 79-89m, 91-97m, and 104-110m; events 5, 6 and 7 on the corridor stack can be correlated to these water zones.

CONCLUSION

Near-surface geophysical logs and VSP were acquired on a glacial deposit near Red Lodge, Montana. Different data types correlated reasonably well with stratigraphy encountered in the borehole. The VSP survey, conducted with a locking 3C geophone an accelerated weight drop source, proved successful in providing some coherent data. The VSP was processed with a conventional workflow to produce a corridor stack that could be correlated with surface seismic.

ACKNOWLEDGEMENTS

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