

VSP and well logs from the U of C test well

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ABSTRACT

Shallow VSP and geophysical well logging surveys were conducted in a 127 m-deep well drilled at the Rothney Astrophysical Observatory site near Priddis, Alberta. The well was drilled through interbedded sands and shales of the Paskapoo formation. A contractor obtained a suite of well logs (including natural gamma-ray, single-point resistance, focused-beam resistivity, density, neutron-neutron, caliper, temperature and SP) in the open hole immediately after drilling. After PVC casing was inserted into the well and grouted to the formation rocks, we obtained natural gamma-ray and full-waveform sonic logs. For the VSP surveys, we used a 5.5 kg sledge hammer source with a downhole clamping 3C geophone and an eight-element hydrophone array. From the full-waveform sonic logs and VSP data, we determined P-wave velocities to lie between 1.7 to 3.0 km/s.

INTRODUCTION

The Paskapoo Formation in the Foothills region of Alberta is the groundwater source for over 100,000 water wells, and characterizing the formation hydrogeologically is a major undertaking by government and university institutions (Natural Resources Canada, 2007; Grasby et al., 2007). The Paskapoo Formation is comprised mainly of shales and sandstones of Tertiary age. We report here on the application of geophysical well-logging and vertical seismic profiling to investigate the geology and hydrogeology in the near-surface rocks of the Paskapoo Formation.

Recently, the University of Calgary Department of Geoscience had a test well drilled on Rothney Astrophysical Observatory property near Priddis, Alberta. The vertical well penetrated the Paskapoo Formation to a depth of 137 m. We retained a contractor to perform geophysical well logging in this well before PVC casing was installed. Soon after, the department held its 2007 geophysics field school at and near the Observatory over a period of two weeks in August and September. One activity carried out by students was the acquisition of VSP data and geophysical logs in the cased test well. In addition to introducing students to basic field procedures, the exercise resulted in interesting datasets useful for supporting groundwater studies of the Paskapoo formation.

THE UNIVERSITY OF CALGARY TEST WELL

Aaron Water Well Drilling Company of Dewinton, Alberta, drilled the test well on property attached to the University of Calgary Rothney Astrophysical Observatory near the Hamlet of Priddis, Alberta. Drilling of the well was done in mid-August, 2007, to a depth of 137 m with an open-hole diameter of 156 mm. The well was completed by inserting steel casing to a depth of 5.5 m with a stickup of 0.61 m above ground level. To prevent long-term collapse of the well, a quarter-inch-thick (6.35 mm) , 4.5-inch-ID (113

mm) PVC casing was inserted to a depth of 127 m. There was a one-day delay between the end of drilling and the insertion of the PVC casing, so that open-hole geophysical logging could be done. During this delay, rock detritus washed out of fracture zones fell to the well bottom and caused the loss of 10m of well depth. Because the well is not intended to produce water for domestic or commercial use, there is no well screen, and the PVC casing is closed off at the bottom and not perforated. Following standard procedure in Alberta for the completion of shallow water wells, the PVC casing is sealed to the rock with a combination of bentonite grout and bentonite pellets to prevent vertical groundwater flow.

Figure 1 shows details regarding the construction of the well and the geological materials it encountered. The geological log is an interpretation of cuttings described by the driller and the geophysical logs (resistivity and natural gamma-ray) on the figure.

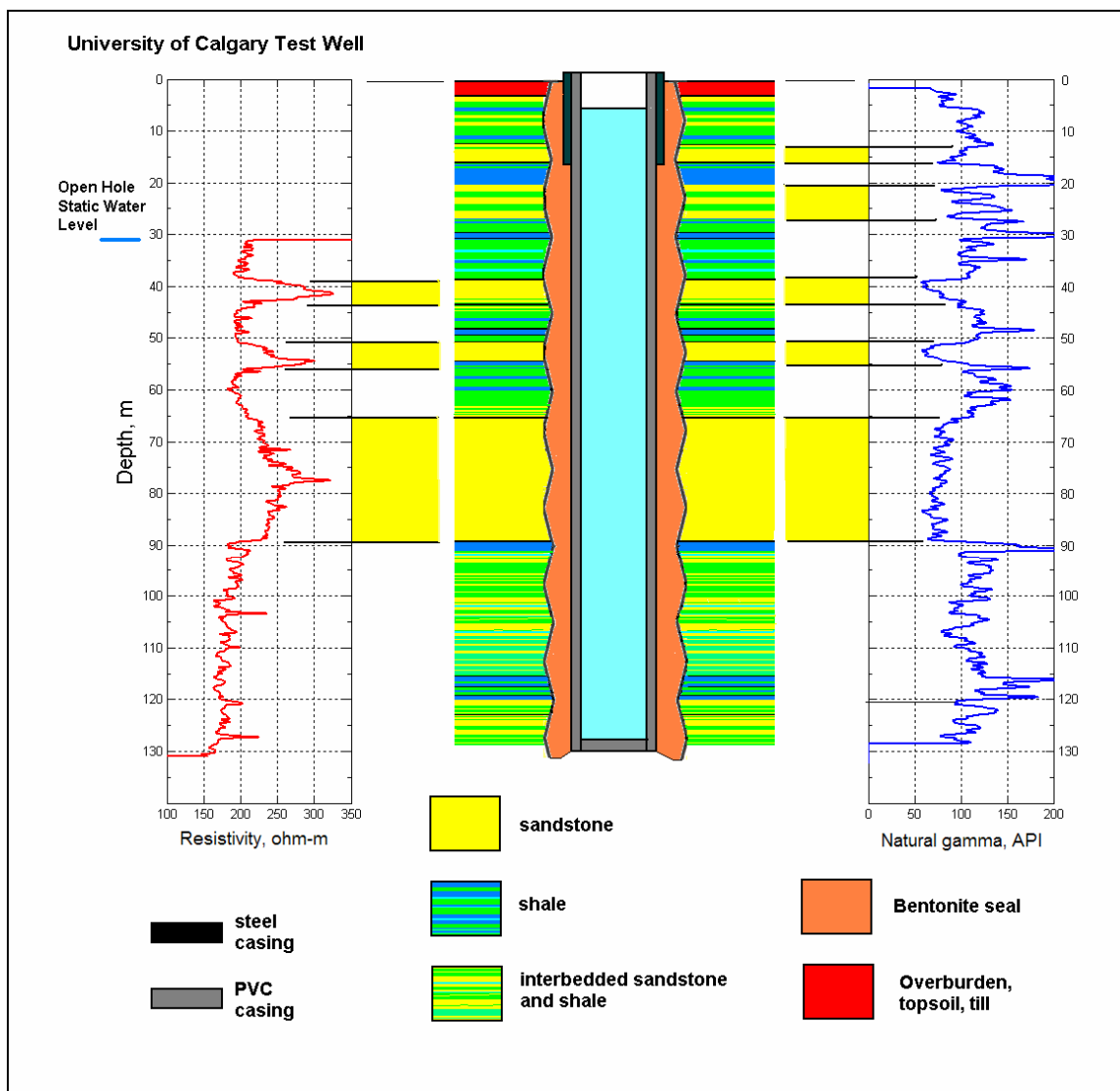


FIG. 1. The University of Calgary test well. The brown material around the casing is a bentonite seal used to prevent vertical groundwater flow.

According to the driller, water-bearing zones were encountered during drilling at depths of 24 to 28 m, 52 to 63 m, and 116 to 122 m. Examination of the geophysical logs reveals that these water-bearing zones occur at or near depths with low gamma-ray and high resistivity responses indicative of thin sandstone beds. The near-surface aquifer at 24 to 28 m flowed at a rate of 15 gallons/min. The driller measured the conductivity of this water to be about 350 $\mu\text{mho/cm}$, declaring it to be of excellent groundwater quality. In the open hole, the static water level was 30 m below ground surface after the drilling ended at the target depth of 137 m.

GEOPHYSICAL WELL LOGS

After the target depth of 137 m was reached, but before the well was cased, Roke Oil Enterprises Limited was retained to provide a suite of geophysical logs in the open hole (see Figures 1 and 2). In this report, we will not attempt to do quantitative interpretation of these logs, but we do make several interesting qualitative observations.

The 16-inch normal resistivity log and natural gamma-ray log are shown on Figure 1. Their variations follow closely the beds of the shales and sandstones within the Paskapoo formation. Shale layers coincide with low resistivity values and high gamma-ray activity; sandstone beds coincide with higher resistivities and lower gamma-ray activity. Other open-hole logs vary with lithology in similar fashion. For example, peaks on the neutron-neutron log (Figure 2a) and focused-beam resistivity log (Figure 2b) can be correlated with sandstone, while troughs can be correlated with shale.

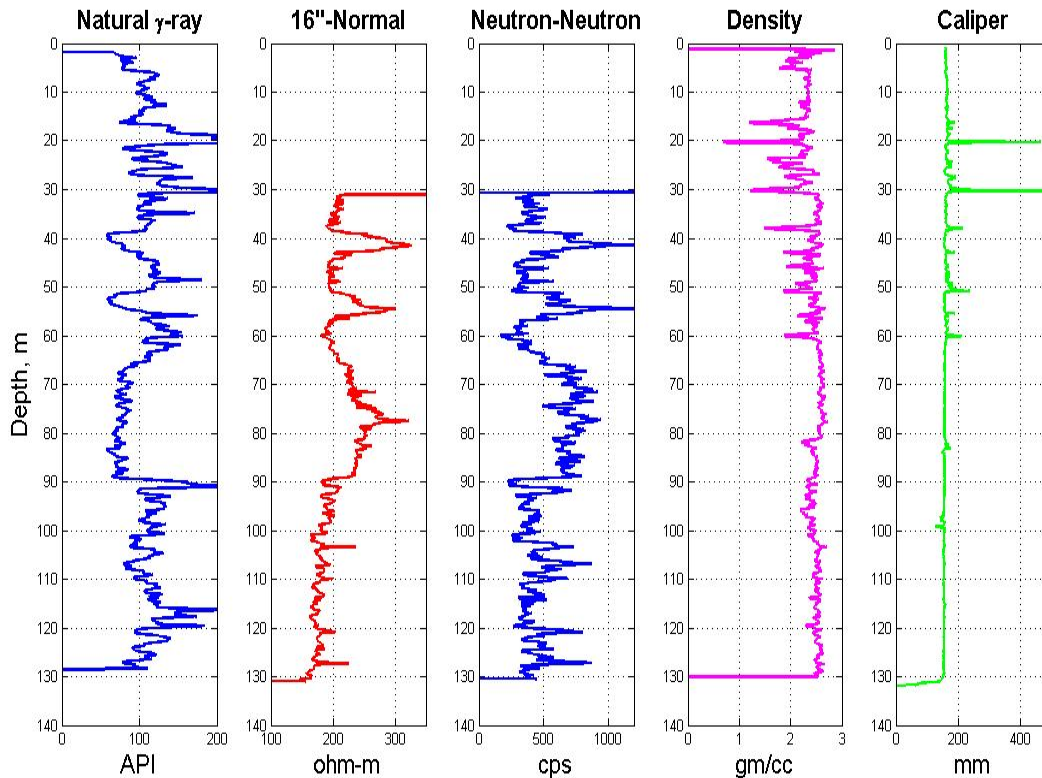


FIG. 2a. Open-hole geophysical logs in the U of C test well.

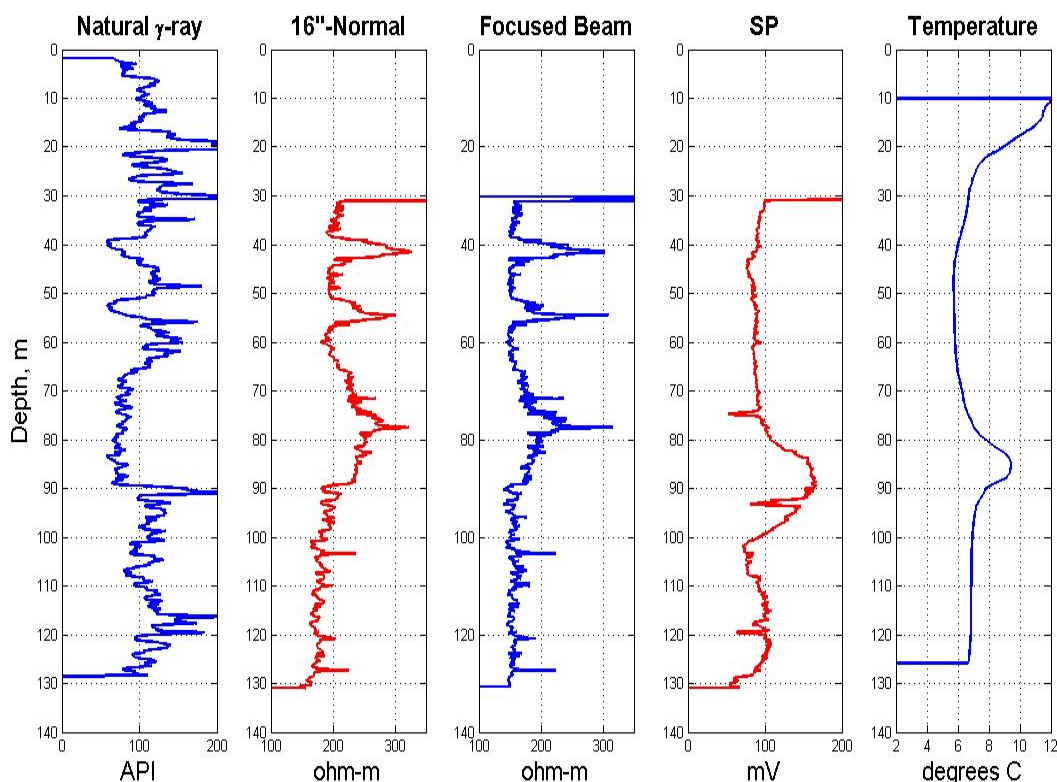


FIG. 2b. Open-hole geophysical logs from the U of C test well.

The density and caliper logs (Figure 2a) indicate significant fracturing in the upper 60 m of the well. The strongly-flowing aquifer noted by the driller to occur at depths between 24 and 28 m appears to coincide with thin sandstone beds whose low apparent density indicates that they are fractured. The open-hole static water level of 30 m coincides with a large fracture indicated by the caliper log. Listening to the well after drilling had been completed but before casing was installed, we could hear the sound of falling water. The static level and the sound of falling water suggest that the fractured sandstone above 30 m are a source of water, but the fracture at 30 m is a sink. That the fracture at 30 m is a large sink was confirmed during sealing of the well with bentonite grout. The grout is a slurry of water and bentonite which is pumped from the surface to fill the gap between the casing and the rock formation through a flexible plastic tube called a tremmie pipe. The slurry filled the gap effectively from the well bottom up to a depth of 30 m. But then a large volume was pumped into the gap without the grout level ever rising above 30 m. In the end, the driller poured solid bentonite pellets into the gap to complete sealing the top 30 m of the well.

The SP (spontaneous potential) and temperature logs on Figure 2b appear to behave oddly. Both logs are relatively flat with broad maximums occurring at depths between 80m and 90m. The sharp peaks on the SP log are probably measurement errors. Usually, SP logs follow variations in lithology, with SP lows associated with shales and SP highs associated with sandstones; however, high-salinity water can overwhelm the normal SP response. Steps and linear gradients on a temperature log usually indicate water inflow and outflow, and flow between permeable zones. The bumps on the present SP and temperature logs are unusual; they may indicate a zone in the sandstone layer with locally high-salinity, high-temperature groundwater but little inflow or outflow. The SP and temperature logs were taken within hours after drilling was completed, so that thermal equilibrium had not been reached.

U OF C FIELD SCHOOL WELL LOGS

Recently, the University of Calgary Department of Geoscience and the CREWES Project jointly purchased a Matrix II Geophysical Logging System from Mount Sopris Instruments. This system will support the teaching of geophysical well-logging courses by the department and research activities conducted by CREWES. At present, the system hardware includes natural gamma ray, single-point resistance, spontaneous potential, and full-waveform sonic tools.

The 2007 Geophysical School was held at the Geophysical Test Site at the Rothney Observatory, and one of the activities was well-logging using the Matrix II system in the test well. Because the well was cased with PVC, students used only the natural gamma-ray tool and the full-waveform sonic (FWS) tool. To provide coupling to the rock for hydrophone VSP and full-waveform sonic logging, the cased well was filled from the surface with water. The PVC casing is made up of 20 ft (6.1 m) sections threaded together, and slow leakage takes place through the threads. At the time of the field school, the water level inside the well was about 6 m below ground level.

The full-waveform sonic (FWS) tool consists of a small piezoelectric transmitter near the bottom of the tool; three piezoelectric receivers (Rx-1, Rx-2, and Rx-3) are located 0.914 m, 1.22 m, and 1.52 m above the transmitter. In recording full waveforms, the transmitter was driven by a pulse with dominant frequency of 15 kHz. For each of the three receivers, 512 digital points were acquired with 4 μ sec sampling. On Figure 3, we have plotted the gamma ray log and the Rx-1 FWS log from the U of C test well. The gamma ray log matches almost exactly with the gamma ray log recorded by Roke Oil Enterprises Limited.

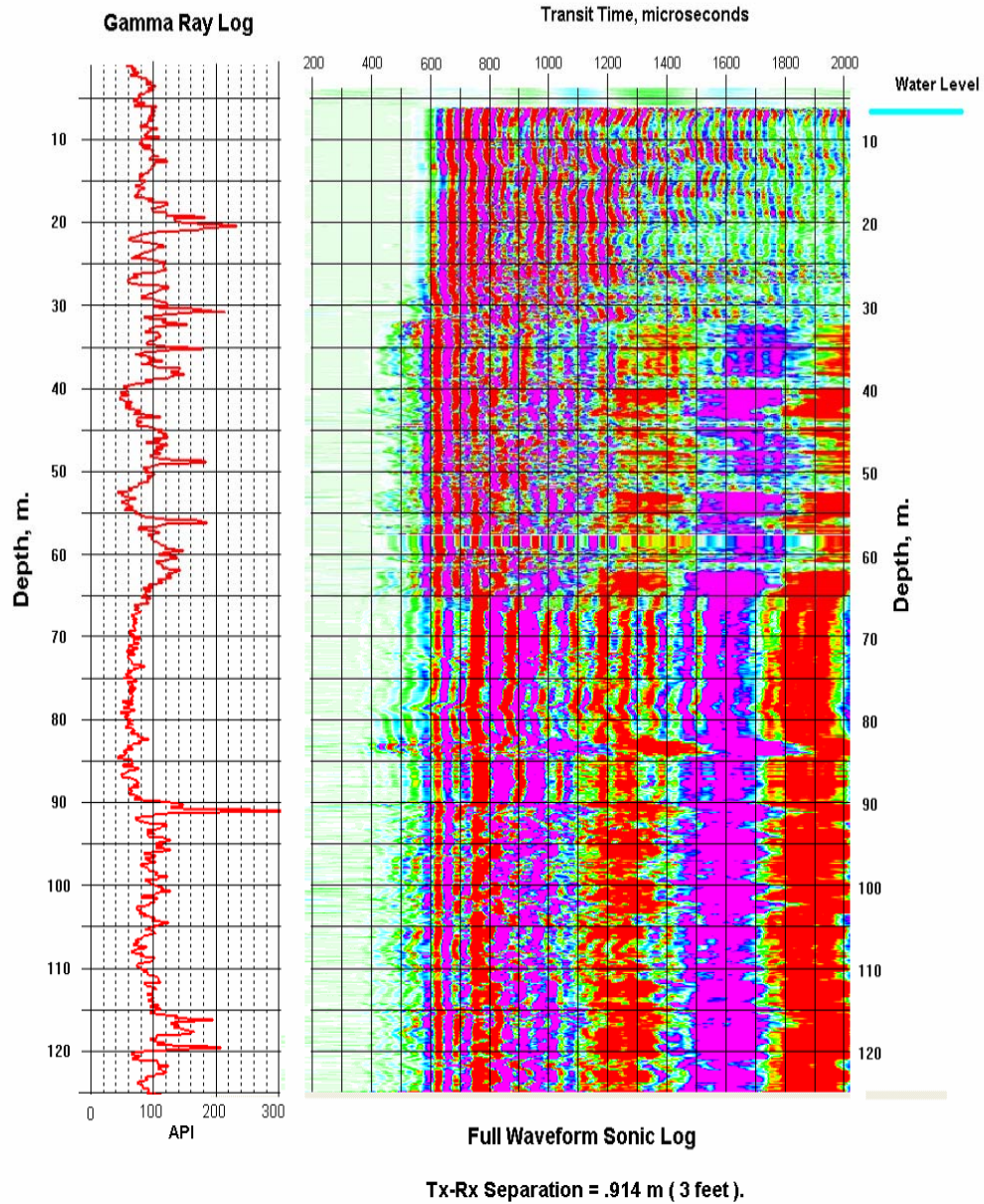


FIG. 3. Cased-hole natural gamma-ray log and FWS log for the Rx-1 receiver recorded by field school attendees in the U of C test well.

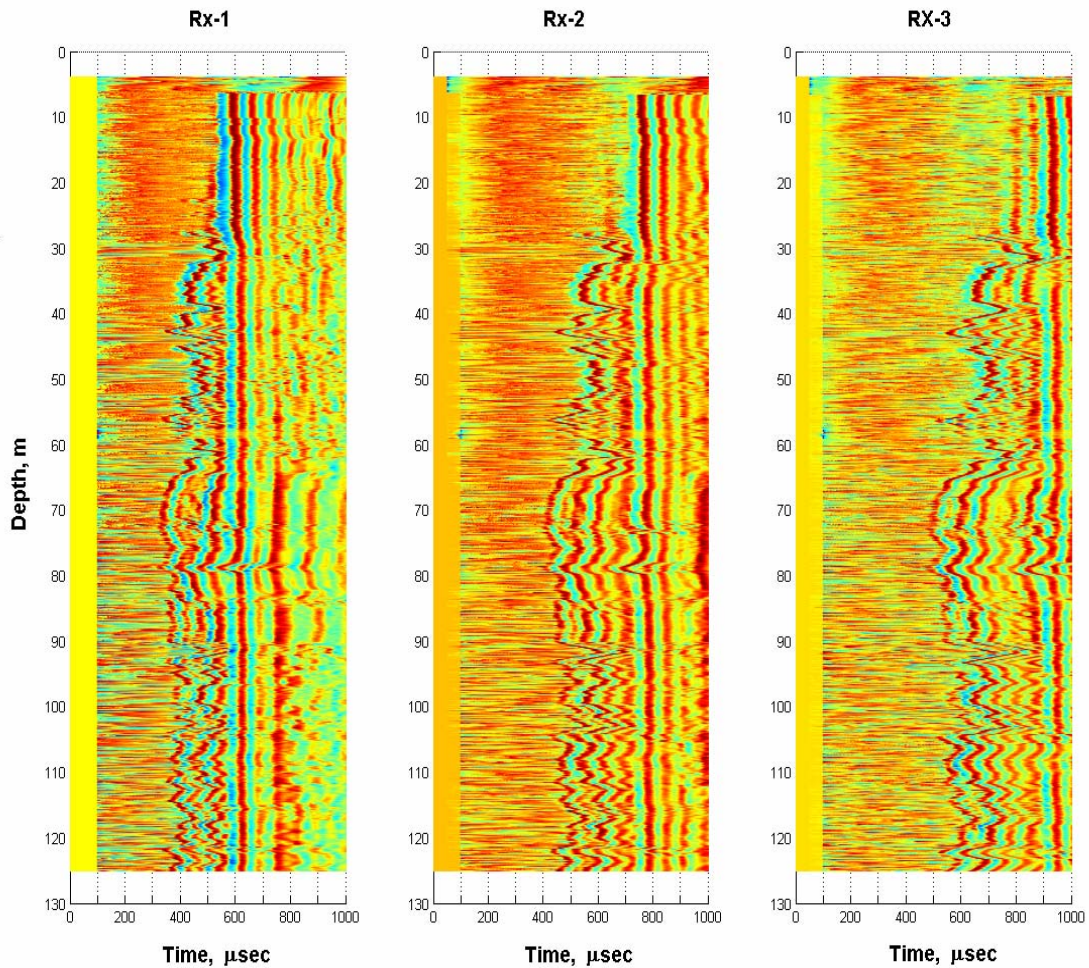


FIG. 4. FWS logs for receivers RX-1, Rx-2, and Rx-3 after AGC to enhance the clarity of the first breaks. The AGC facilitates interactive and automatic time picking.

The first arrivals on the FWS log of Figure 3 have small amplitudes, and picking reliable first-break times on the raw field seismograms is difficult. To improve the clarity of the first arrivals, we apply automatic gain control (AGC) to the traces before displaying them. This is done on Figure 4 for all three receivers. After AGC, interactive or automatic picking of first-break times is accomplished with greater reliability. At depths above 20 m, first arrivals through the rock formation appear to be lost in noise even with AGC. The poor signal amplitudes at these shallow depths indicate poor coupling between the formation rocks and the well casing. Coupling likely is poor because no water exists in the unsaturated geological materials above the static water level at 30 m to aid acoustic contact to the casing.

Figure 5 shows the first-break times picked interactively for the three FWS receivers at depths below 20 m. Also shown are logs of P-wave slowness and P-wave velocity calculated from these picks. The blue profiles are calculated from the Rx-1 picks and a source-detector distance of .914 m, while the green profiles are calculated from the Rx-2 picks and a source-detector distance of 1.22 m. The red profiles are the averages of the Rx-1 and Rx-2 values. Comparing the velocity profiles with the natural gamma-ray log on the left-hand side of the figure, we see that the lower velocities (2.0 to 2.2 km/sec) coincide with high gamma-ray values associated with shales. Higher velocities (2.5 to 3.0 km/sec) coincide with low gamma-ray values associated with sandstones.

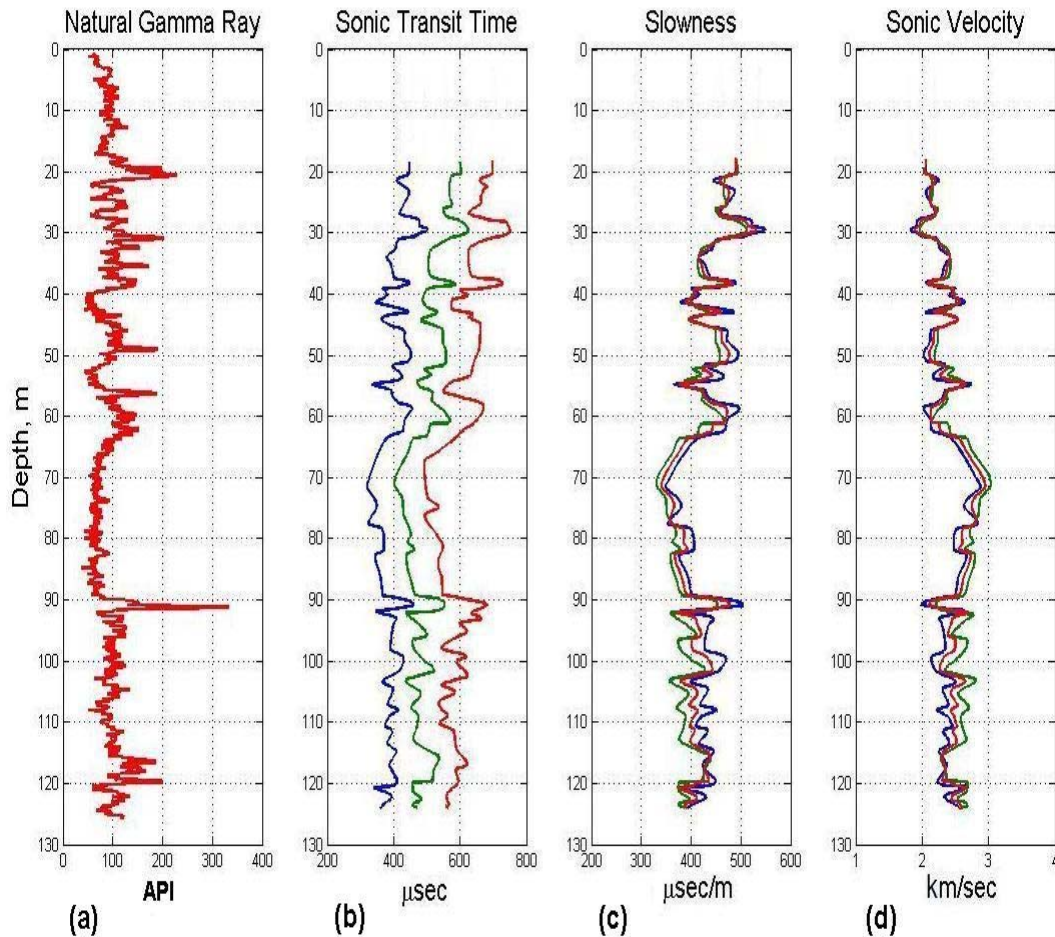


FIG. 5. (a) Natural gamma-ray log; (b) FWS transit times for receivers Rx-1 (blue), Rx-2 (green), and Rx-3 (red); (c) calculated slowness for Rx-1 (blue), Rx-2 (green), and their average (red); (d) P-wave velocity for Rx-1 (blue); Rx-2 (green), and their average (red).

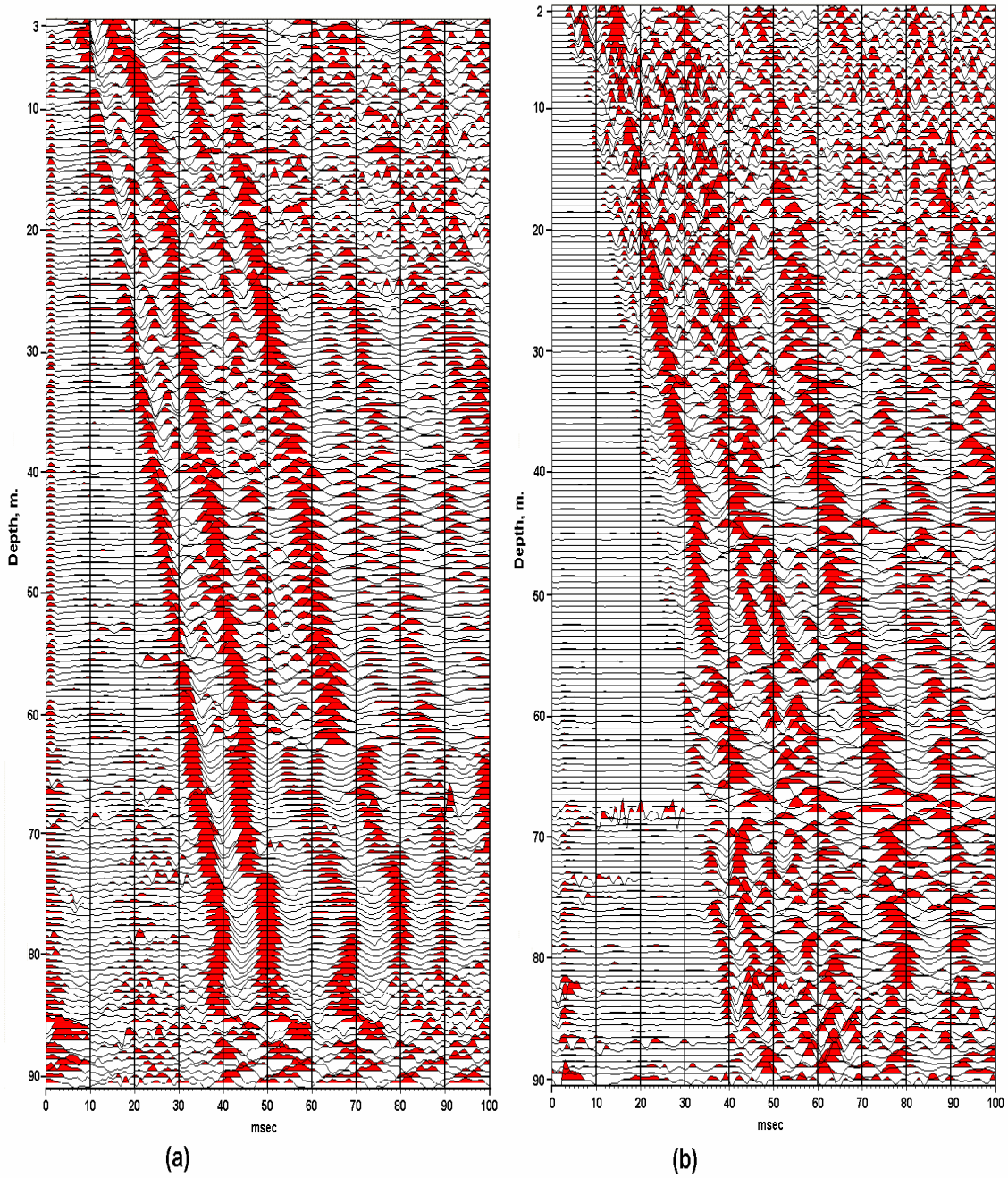


FIG. 6. Clamped geophone VSP (a) with 1.5m source offset; (b) with 0m source offset. The maximum depths were limited by the length of the cable used.

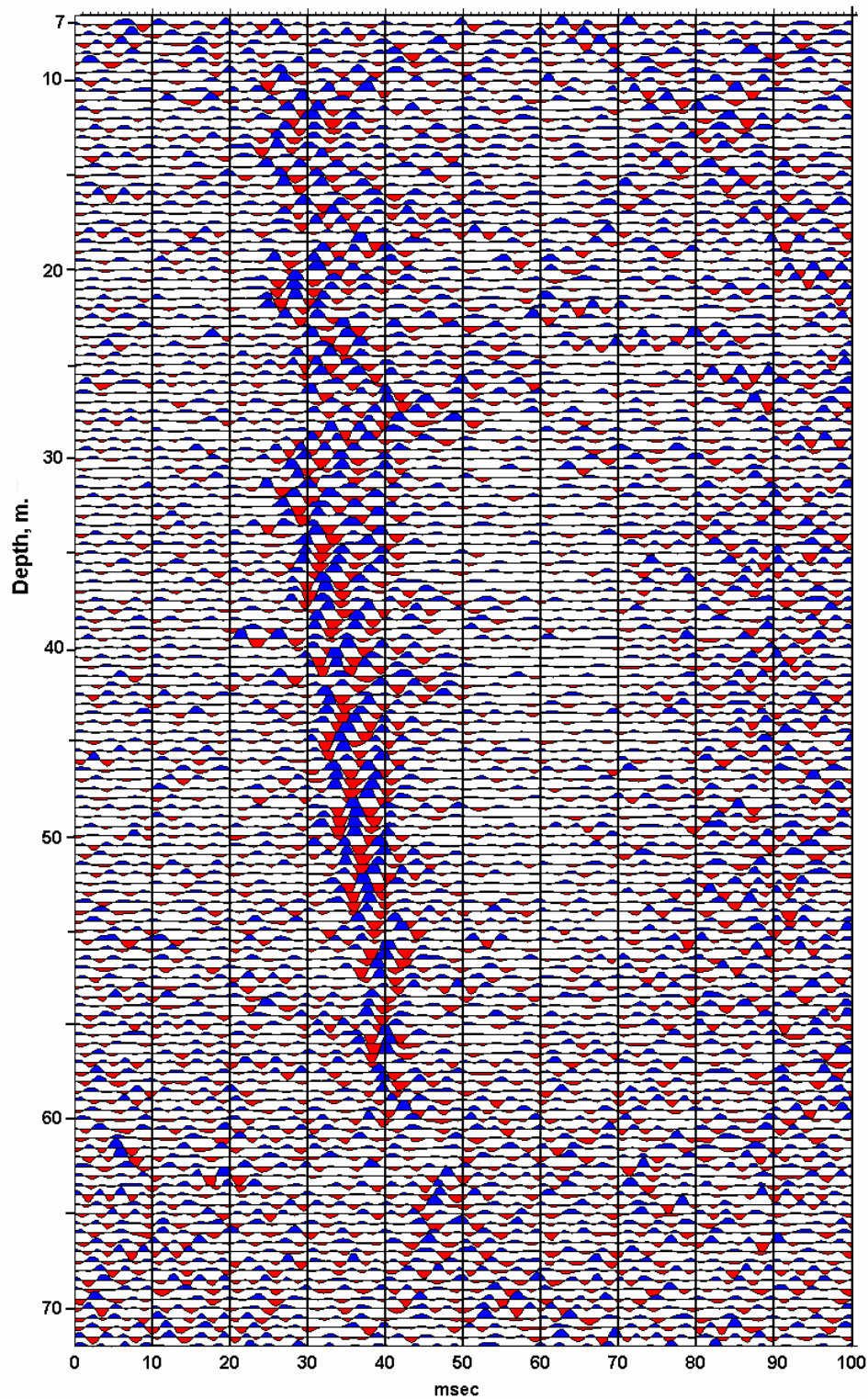


FIG. 7. Hydrophone VSP with source offset of 15m.

VERTICAL SEISMIC PROFILING

Vertical seismic profiles were recorded in the U of C test well using a 5.5 kg sledge hammer as a source on the ground surface. The downhole receivers were a Geostuff BHG-2 clamping 3C geophone and an array of eight hydrophones. Recording was done with a 24-channel Geometrics Geode acquisition module controlled by a Panasonic CF-30 Toughbook portable computer. Separate ends of conducting wires were attached to the metal head of the sledge hammer and the aluminum strike cylinder. The metal head striking the aluminum cylinder closed the triggering circuit of the seismograph, initiating digital sampling of the detector outputs. This arrangement provided a reliable zero time.

The downhole geophone and the hydrophone array were lowered down into the well by guiding the attaching cable over a sheave wheel mounted over the wellhead. The top of the sheave wheel was 1.1 m above ground level. Geophone and hydrophone have been corrected for the sheave wheel elevation, and so are referenced to ground level. The downhole geophone occupied depths ranging from 2 m to 92 m at half-metre intervals. Hydrophones were placed below water level at half-metre increments from 7 m to 72 m. We recorded the VSP seismograms with a sampling rate of 0.5 ms, a record length of 1000 ms, and a high cut filter of 500 Hz.

Downhole 3C geophone VSPs

Figure 6 shows the vertical component of two VSPs recorded using the BHG-2 geophone. For the data in Figure 6a, the source was located 1.5m away from the wellhead. For the data in Figure 6b, the source was striking through a piece of wood right on the steel casing. We applied an Ormsby filter with corners at 60-80-200-300 Hz and AGC before displaying the data. Frequencies as high as 150 to 200 Hz are present near the first breaks.

Hydrophone recorded VSP

The VSP recorded with hydrophone receivers is shown on Figure 7. The hydrophones contain an integral high-pass filter with a low-cut frequency of about 200 Hz. An Ormsby filter with corners at 60-80-400-600 Hz and AGC has been applied before display. The dominant frequency on the hydrophone traces is about 200 Hz. The signal-to-noise ratios for the hydrophone VSP are rather low. Seismic arrivals are not clearly visible below 60m. Stacking of three or four hammer blows per trace may improve the signal amplitudes, but only if the hammer blows are consistent.

SUMMARY AND DISCUSSION

The geophysical well logs and VSPs presented in this report give useful information regarding the near-surface geological and hydrogeological characteristics of the Paskapoo Formation at the Rothney Observatory site.

Natural gamma-ray, resistivity, and neutron-neutron logs delineate the shale/sandstone bedding with good precision. The density and caliper logs clearly indicate fracturing in the top 55 m of the well. Thin sandstone beds (identified by the gamma log) that are coincident with fractures (identified by the density log) appear to be closely associated with the fast-flowing aquifer at depths of 24 m to 28 m. We acquired full-waveform sonic (FWS) logs that closely mimic the natural gamma-ray log. The first-arrival times picked interactively from the FWS logs give P-wave velocities that are in the range 2.0 to 2.2 km/s for shale, and in the range 2.6 to 3.0 km/s for sandstone.

We acquired excellent zero-offset and 1.5-m-offset VSPs with a sledge hammer source and a downhole clamping geophone down to depths of 92 m. From the first arrivals on vertical component data, we find that the P-wave velocities are about 2.0 km/sec. A hydrophone-recorded VSP down to depths of 60 to 70 m with a source offset of 15 m gives somewhat lower estimates of 1.7 to 1.8 km/s. The signal-to-noise ratios on the hydrophone VSP was only fair. Stacking more hammer blows may improve the signal level, but only if hammer blows are precisely repeatable. In practice, this condition is seldom met, especially when measuring high frequency seismic arrivals. A better solution is to use a controlled vibrator transmitting a linear sweep or a pseudorandom sequence.

In this report, we have limited our discussion to the data acquisition and qualitative observations about how the data relate to the geology and groundwater conditions in the well. Future interpretation of the well logs will include quantitative analysis, while the VSPs will be subjected to velocity modeling and reflectivity mapping.

ACKNOWLEDGMENT

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