VSP and Well Logs from a Shallow Test Well

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Introduction

The Paskapoo Formation in the Foothills region of Alberta is the groundwater source for over 100,000 water wells, and hydrogeological characterization of the formation is a major undertaking by government and university institutions (Grasby et al., 2006; Natural Resources Canada, 2007). The University of Calgary had a 127-m-deep test well drilled into the Tertiary sandstones and shales of this formation at the Rothney Astrophysical Observatory site near Priddis, Alberta. Geophysical well logs (natural gamma-ray, 16”-normal and focused-beam resistivity, SP, temperature, density, and caliper) were acquired in the open hole immediately after drilling. To prevent long-term collapse of the well, a quarter-inch-thick (6.35 mm), 4.0-inch-ID (102 mm) PVC casing was then inserted and grouted to the formation rocks. Natural gamma-ray and full-waveform sonic logs were obtained in the cased well. The geophysical logs were useful for delineating the sandstone and shale beds, and for providing hydrogeological information at the well site. VSP surveying also was done in the cased hole using a hammer source with a downhole clamping 3C geophone. First-arrival times on the sonic logs and VSP seismograms gave P-wave velocities in the range 2.0 to 3.0 km/s. Standard VSP processing resulted in a corridor stack of up-going reflections that correlated fairly well with a 1-D synthetic seismogram constructed from the density and P-wave velocity logs.

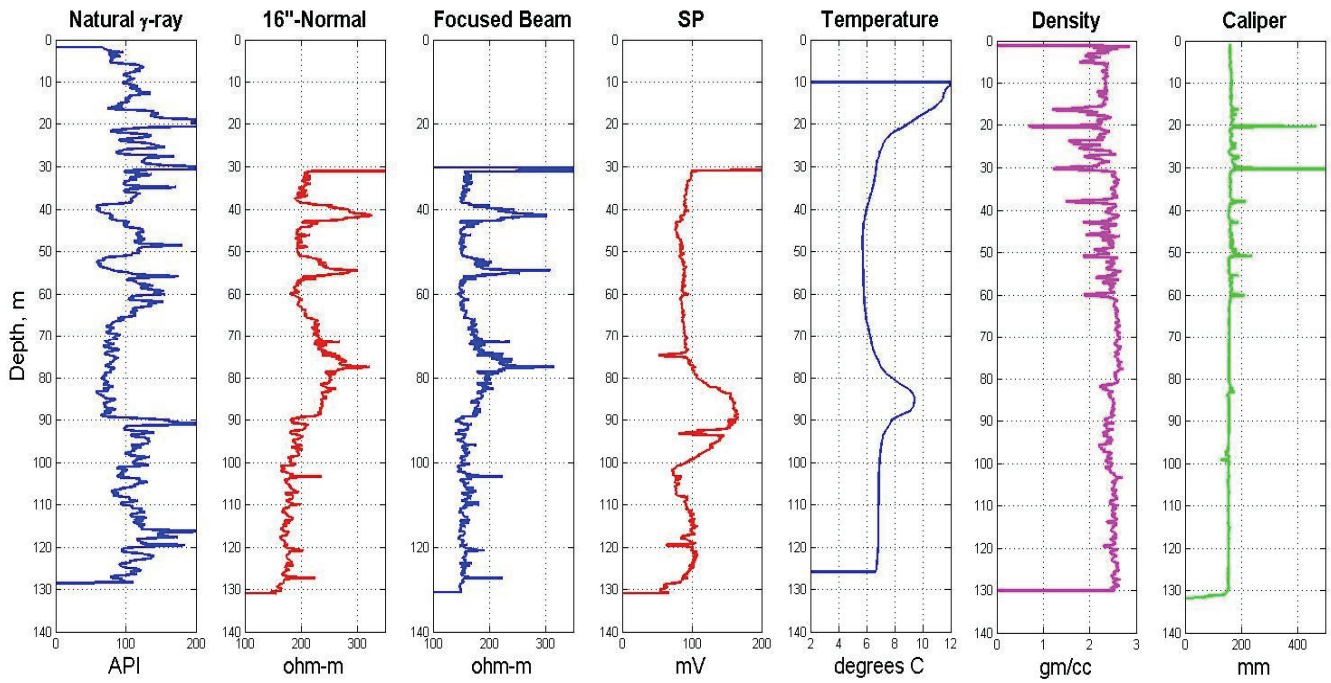

Figure1: Open-hole geophysical well logs.

Open-Hole Geophysical Well Logs

The suite of open-hole geophysical logs is shown Figure 1. The lithology encountered in the well (interpreted from cuttings and the natural gamma-ray log) is shown on Figure 2. Shale layers coincide with high gamma-ray activity, while sandstone beds coincide with lower gamma-ray activity. Other open-hole logs vary with lithology in similar fashion. For example, peaks on the 16”-normal and focused-beam resistivity logs correlate with sandstone, while troughs correlate with shale. Resistivities and SP could not be measured above the static water level at 30 m.

The local peaks on the SP and temperature logs at approximately 85 m depth are consistent with a zone of weak groundwater inflow near the base of the large sandstone unit that extends from about 63 m to 90 m in depth. The temperature log was taken within hours after drilling was completed, so that thermal equilibrium in the well had not been reached. The density and caliper logs are evidence of significant fracturing in the upper 60 m of the well.

Figure 2 shows the water-bearing zones reported by the driller at depths of 24 to 28 m, 52 to 63 m, and 116 to 122 m. These aquifers appear to be located just below major sandstone/shale interfaces indicated by the natural gamma-ray log, or else near fractured sandstone beds indicated by the caliper and density logs. The near-surface aquifer at 24 to 28 m flowed at a rate of 15 gallons/min. The likely source for this fast-flowing water is the large fracture at 20 m, and/or smaller fractures in the alternating thin beds of sandstone and shale at depths between 22 m and 29 m.

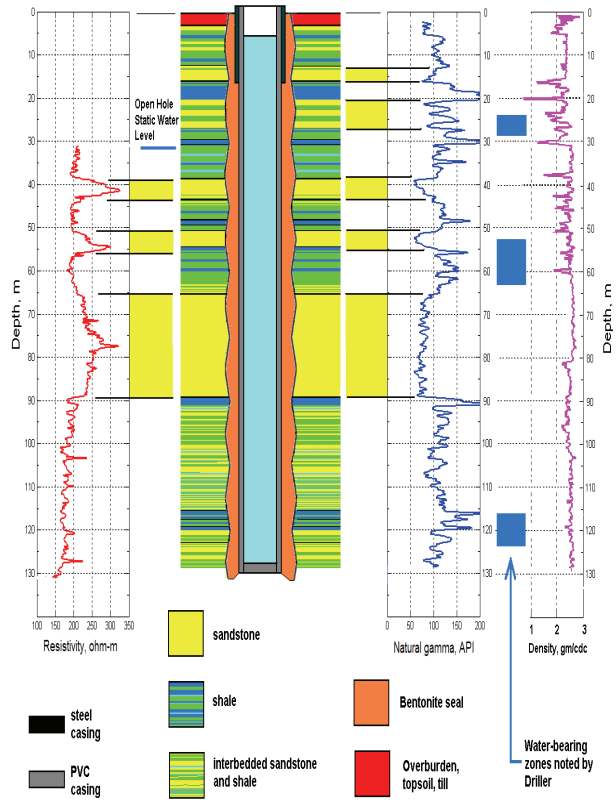

Figure 2: Lithology interpreted from gamma-ray log and drill cuttings. The 16”-normal resistivity and density logs are also shown.

Cased-Hole Geophysical Well Logs

Full-waveform sonic (FWS) and natural gamma-ray logs were acquired in the cased well, and are plotted on Figure 3 The FWS tool consists of a small piezoelectric transmitter near the bottom of the tool, and three piezoelectric receivers, Rx-1, Rx-2, and Rx-3, 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 about 15 kHz. For each of the three receivers, we acquired seismograms 525 digital points long with 4 μsec sampling at depth intervals of 10 cm. On the left side of Figure 3, we see the FWS seismograms displayed with automatic gain control (AGC).

Figure 3(a) is a plot of the cased-hole gamma-ray log. Shown on Figure 3(b) are the first-break times picked interactively for the three FWS receivers at depths below 20 m. On Figures 3(c) and 3(d), we see logs of P-wave slowness and P-wave velocity calculated from the Rx-1 and Rx-2 time picks. The picks from the Rx-3 receiver were not considered because they are less reliable. The blue profiles were calculated from the Rx-1 picks and a source-detector distance of .914 m, while the green profiles were 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. Comparison of the velocity logs with the gamma-ray log shows that lower velocities (2.0 to 2.2 km/sec) coincide with high gamma-ray activity associated with shales, while higher velocities (2.5 to 3.0 km/sec) coincide with low gamma-ray activity associated with sandstones

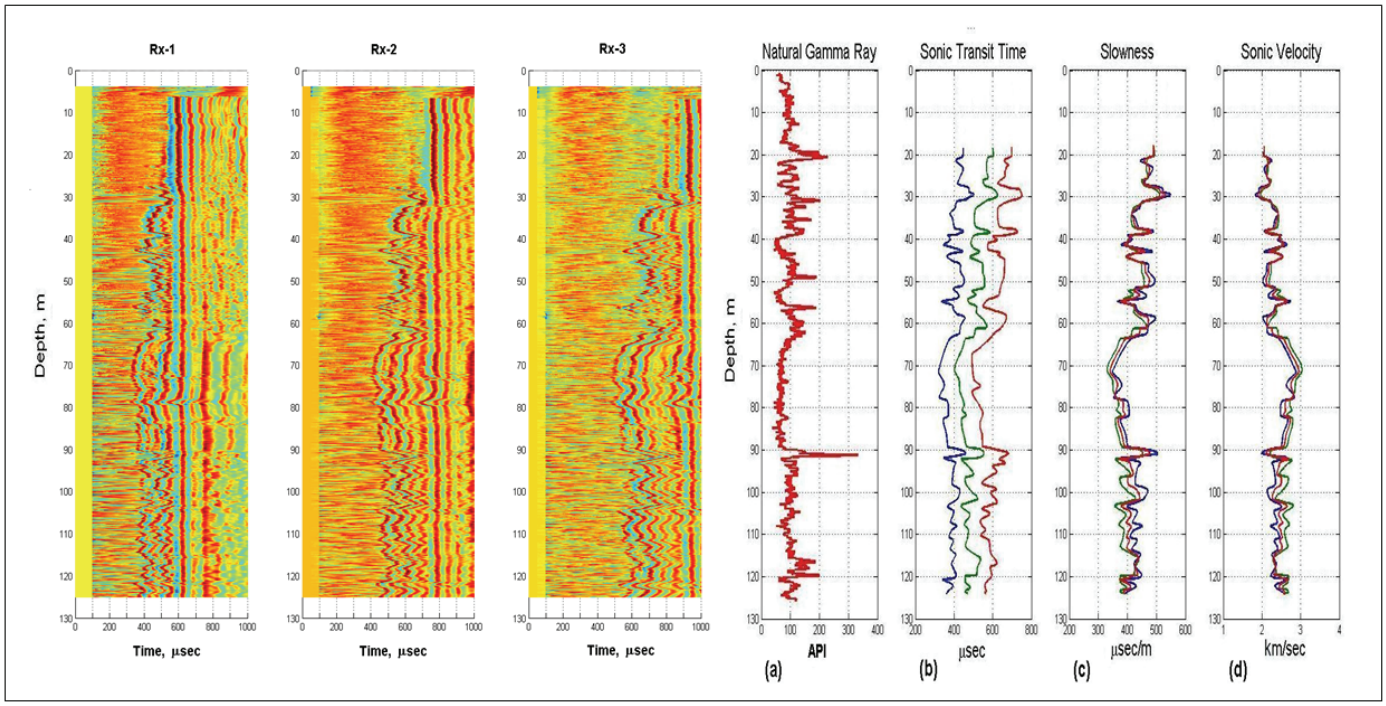

Figure 3: Full-wavform sonic seismogramss for three receivers are plotted with AGC on the left. The cased-hole natural gamma-ry log is plotted on (a). First arrrival time picks for the Rx-1, Rx-2, and Rx-3 receivers are shown on (b). On (c) and (d) are the slowness and velocity profiles for Rx-1 (in blue) and Rx-2 (in green), with their averages plotted in red.

Vertical Seismic Profiles

We acquired zero-offset VSP seismograms with a 5.5 kg sledge hammer source and a downhole clamping 3C geophone down to a depth of 92 m. The vertical component traces are shown on Figure 4(a). From the first-arrival times, P-wave velocities were estimated to be about 1.5 km/s in the overburden, and up to 3.0 km/s in the sandstones. The dataset was analyzed with standard zero-offset VSP processing (Hinds and Kuzmiski, 2006) to obtain a corridor stack of up-going reflections. Figures 4(b, c) show that prominent events on the VSP corridor stack correlate somewhat with a synthetic 1-D seismogram generated from the density and P-wave velocity logs, and with boundaries between sandstone and shale beds indicated by the gamma-ray (GR) log.

Conclusions

The geophysical well logs and VSP presented in this study gave useful information regarding the near-surface geological and hydrogeological characteristics of the Paskapoo Formation at a site near Priddis, Alberta. Natural gamma-ray and resistivity logs delineated the shale/sandstone bedding with good precision. Open-hole density and caliper logs clearly indicated fracturing in the top 60 m of the well. A large fracture at 20 m depth and fractured thin sandstone beds between 20 and 30 m were identified by the gamma-ray, density, and caliper logs. These appeared to be the source of fast-flowing groundwater that the driller estimated came from depths of 24 m to 28 m. The temperature and SP logs indicated that, at a depth of about 85 m within a thick sandstone unit, there is a zone of warmer water inflow not identified by the driller. A driller-identified water-bearing zone, extending from 116 m to 122 m, did not have an apparent geophysical log signature. However, it might be associated with the sandstone just above the sandstone/shale interface indicated by gamma-ray logs to occur at 116 m. Logs of full-waveform sonic (FWS) first-arrival times closely mimicked the natural gamma-ray log. P-wave velocities determined from first-arrival

times on FWS logs and VSP seismograms fell 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.

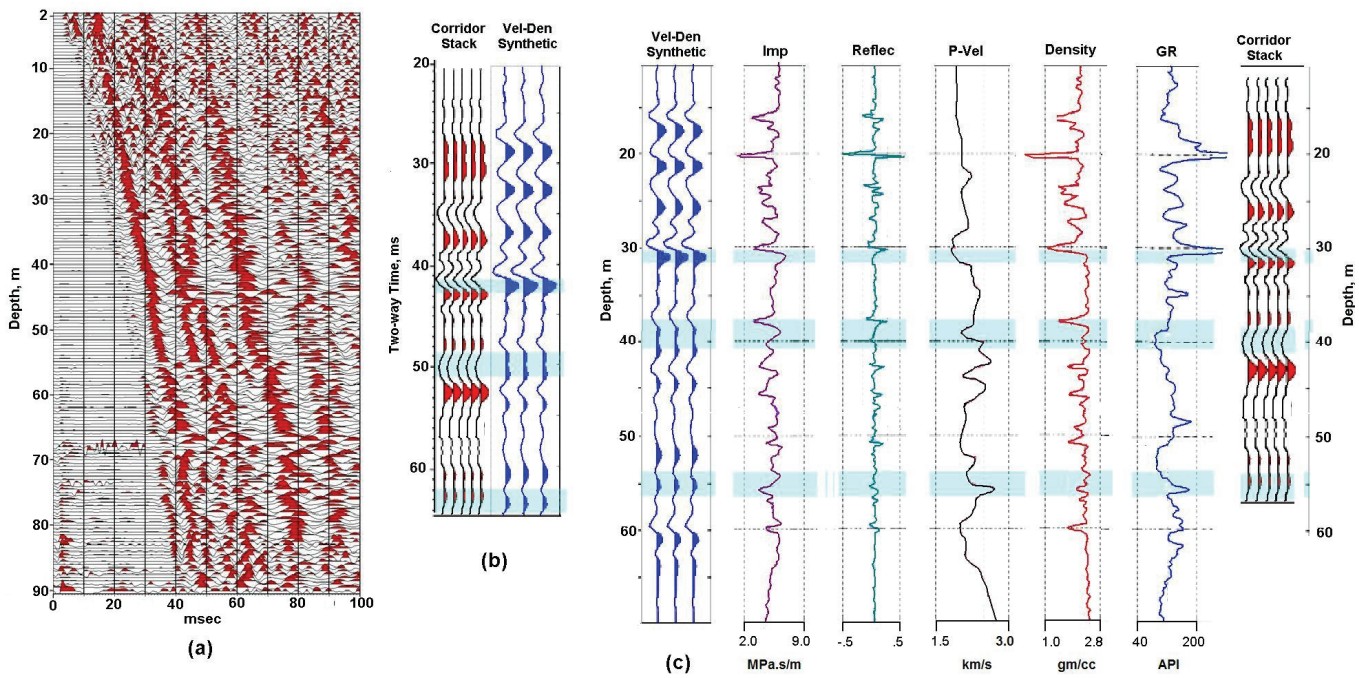

Figure 4: (a) Vertical component VSP seismograms. (b) Corridor stack of processed up-going reflections from the VSP gather, compared with a synthetic seismogram repeated three times. (c) Synthetic seismogram and corridor stack mapped to depth, compared with logs of seismic parameters and natural gamma-ray activity.

Acknowledgements

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