Contribution of 2-component VSP measurements to the characterization of a geothermal site

Introduction

As part of a deep geothermal project, in southern Luxembourg, a reconnaissance borehole of about 400 m depth was drilled to determine the geothermal parameters of the geological formations crossed. To validate the geological hypotheses and to position optimally a potential exploration borehole, several seismic reflection profiles were recorded in the area. In the reconnaissance borehole, enhanced geothermal response tests were conducted, and a VSP was recorded. The national borehole reference is FR-216-200, and the location is approximately 1.1 km south of the centre of the city of Dudelange. We show the contribution of VSP measurements to the characterization of the geothermal site.

VSP acquisition and processing

The VSP was recorded with a depth sampling interval of 5 m in the 20 - 330 m depth interval. The source is a vibrating source emitting a sweep in the 20 - 120 Hz frequency band. The offset of the source from the borehole head is 8 m. The time sampling interval is 0.5 ms. The receiver is a 4-component borehole sensor, including a 3-component geophone and a hydrophone. Figure 1 shows the VSP sections, after amplitude compensation, observed on the vertical geophone and on the hydrophone. On the vertical geophone section, we observe a downgoing P-wave, strongly attenuated in the 150 – 200 m depth interval. We note the presence of both a downgoing Stoneley wave attenuated from 150 m and a fluid wave (with a propagation velocity of 1540 m/s) in the 150 - 200 m depth interval. On the hydrophone section, we observe the downgoing P-wave with a conversion to a Stoneley wave at a depth of about 200 m. We also observe a strong downgoing Stoneley wave with a set of reflected upgoing Stoneley waves, the strongest of which occurs at the depth where the converted downgoing Stoneley wave is created. The two VSP sections are processed independently. The processing sequence includes amplitude recovery, picking of the arrival times of downgoing wave fields, wave separation using both f-k filters and SVD (singular value decomposition) filters, deconvolution of upgoing wave fields by the associated downgoing wave fields, design of stacking corridor on flattened deconvolved upgoing wave section and computation of corridor stacked traces both in time and in depth. Picking of the arrival times of the downgoing wave fields (P-wave and Stoneley wave) is used to compute time -versus-depth laws, interval velocity logs, and attenuation logs after flattening of the downgoing wave fields. The time -versus- depth laws are used to convert in depth the corridor stacked traces computed in time. Figure 2 shows the processing of the P-waves observed on the VSP geophone section.

VSP and lithology

Figure 3 shows the comparison between VSP measurements and lithology. VSP measurements include corridor stacked traces in depth and interval velocity logs for both P-wave and Stoneley wave. The shear velocity VS-St (figure 3) of the formation is derived from a simplified version of the Stoneley wave dispersion equation (White, 1983). Corridor stack obtained from deconvolved reflected P-waves represents the distribution of acoustic impedance contrasts in the VSP depth interval and below the terminal depth of the borehole. Figure 2 shows the prediction of seismic reflectors up to 1100 m. Stoneley waves are sensitive to lithological changes but also to the state of continuity of the borehole wall. In the VSP depth interval, corridor stack obtained from deconvolved reflected Stoneley-waves represents the distribution of shear velocity contrasts and the lack of continuity of the borehole wall (figure 3)

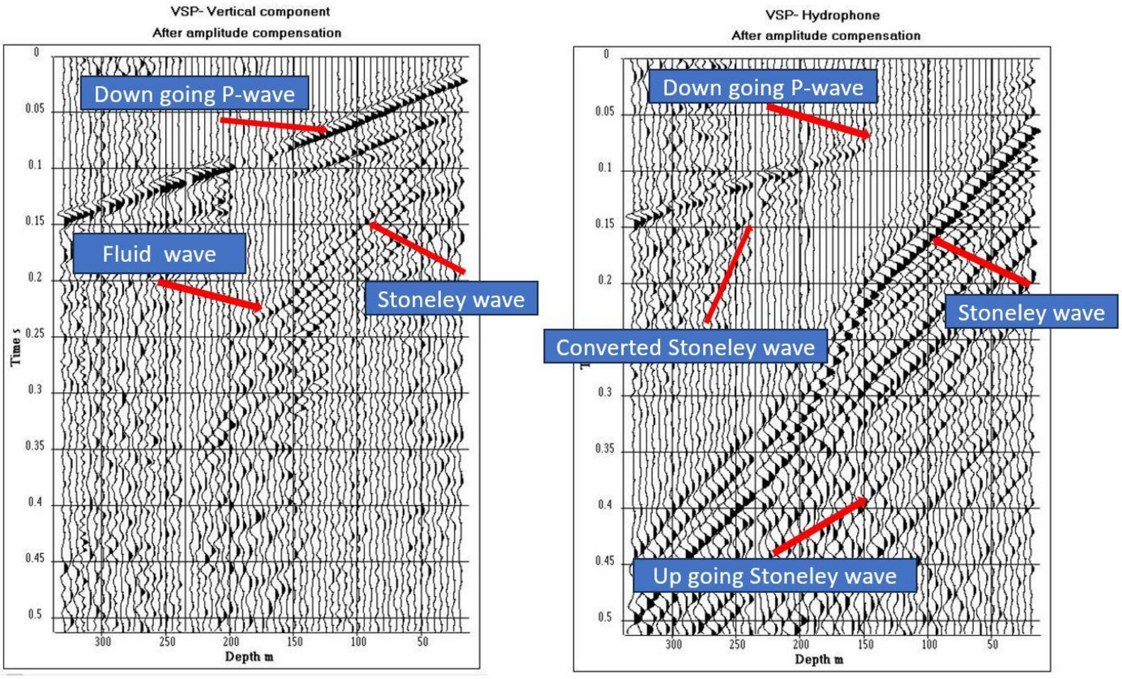

Figure 1 VSP sections and wave identification..

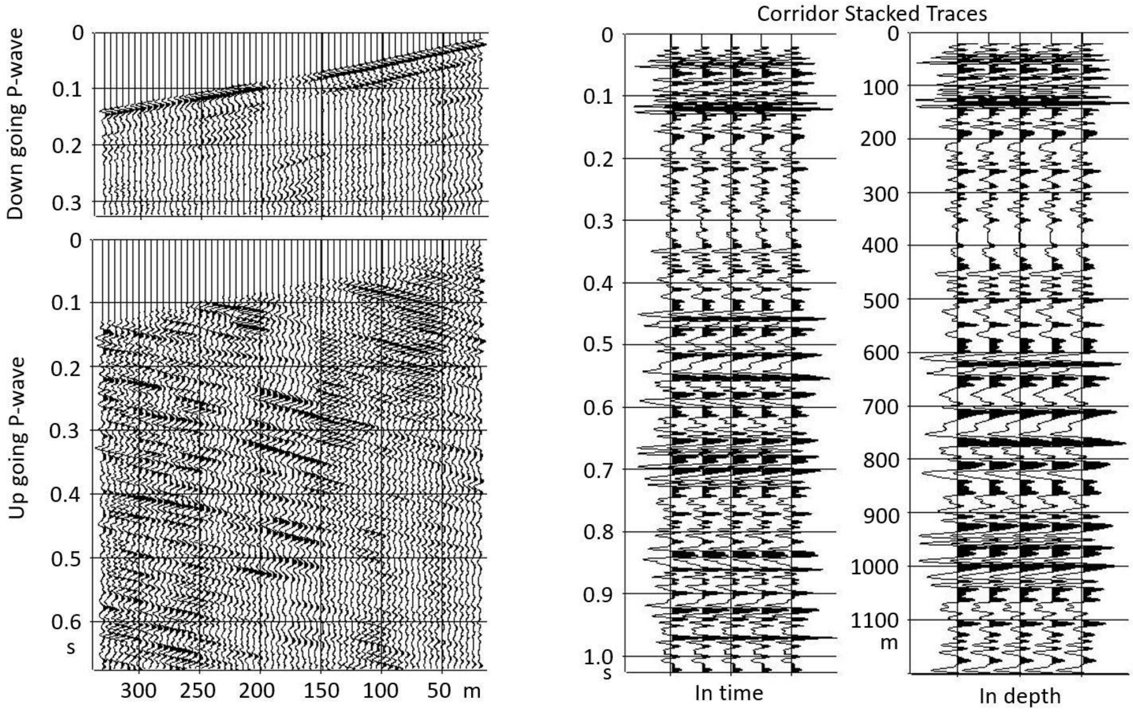

Figure 2 *VSP geophone section processing: P-wave separation (left) and corridor stacked trace computation both in time and in depth (right).*

The reconnaissance borehole crosses, after a few meters of landfill and alluvium, that is unconformably underlain by rather similar mainly marly formations dating from the Upper and Middle Liassic, showing slight facies changes towards more silty and sandy or more calcareous facies (units lo4 to lo1a and lm3 to lm1; Toarcian to Pliensbachian, Lower Jurassic).

In detail, the lithology record by the Geological Survey shows, after the 2 rather homogeneously marly units lo4 and lo3, a gradually increasing content in organic matter, observed in the lo2 and lo1 units (70 - 126 m), also showing a thin lamination, culminating in the lo1a unit below (126 - 139 m), which is more silty, sandy and contains bituminous horizons. Below, the lm3 unit appears to have an even higher sand/silt content but is also richer in limestone nodules and beds (140 - 210 m). The following lm2 unit, the sand and silt content gradually decreases again until the depth of 230 m and the basis of this unit (at 340 m) is homogeneously marly. We note a significant decrease in shear velocity in the 140 - 200 m depth interval corresponding to the lo1a and lm3 units, richer in sand/silt and organic matter (lo1a) or limestone (lm3). Figure 4 (on the left) shows the attenuation logs computed from the downgoing P and Stoneley waves. The results obtained (decrease of both energy and velocity of the Stoneley wave) are consistent with the results which could be obtained by a Biot-Rosenbaum model (1974) used to access to permeability from the evolution of Stoneley's phase velocity and attenuation (Mari, 1989). The velocity and attenuation VSP logs and the corridor stacked traces in depth associated with both P-wave and Stoneley wave show a very good correspondence with respect to the lithological variations observed in the borehole.

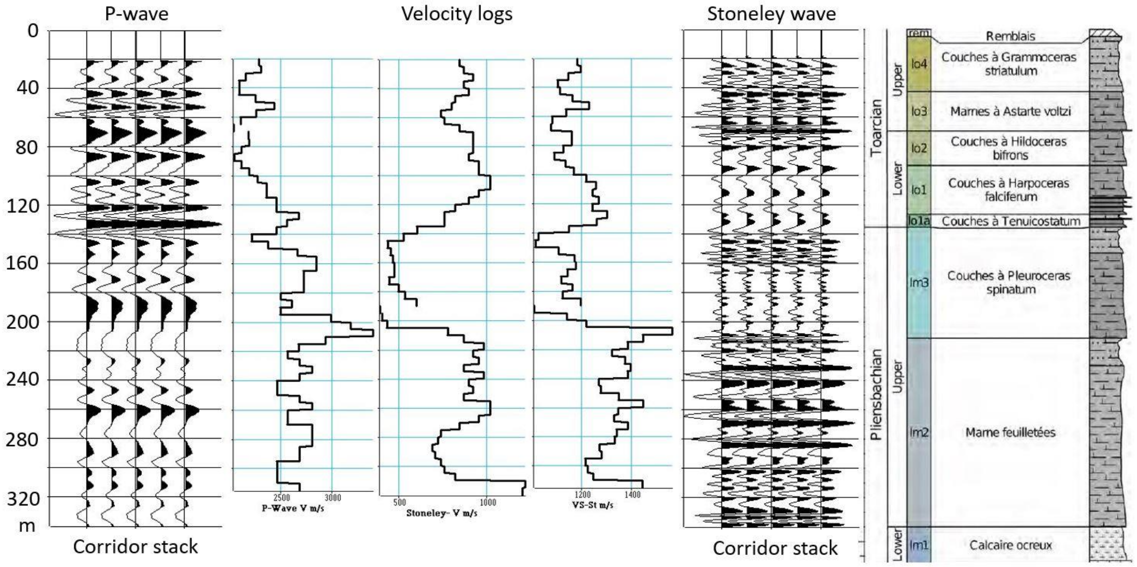

Figure 3 *VSP measurements and lithology. From left to right: P-wave corridor stack in depth, velocity logs (P-wave velocity, Stoneley velocity, Shear velocity), Stoneley wave corridor stack in depth, lithological column..*

VSP and geothermal tests

The well was equipped with a hybrid cable, comprising 2 optical fibers and 2 electrical conductors, suitable for geothermal applications. Fiber optic temperature measurement enables optimal monitoring of temperature distribution and thermal conductivity in the subsurface as a function of depth. Temperature measurements are made before and after heat injection phases, which are carried out by sending an electric current through the electrical conductors of the hybrid cable. Before heat injection, the temperature increases linearly from 12oC at 20 m to 23oC at 320 m. Once the heat injection phase has begun, temperature profiles, recorded after different heating time intervals, show the evolution of the subsurface temperature after respectively 1 h (cyan curve), 3 h (yellow curve) and 108 h (red curve) of thermal dissipation (figure 4). Different variations, similar on each of the curves, can be identified during the heat injection phase. The main anomaly, located between 160 and 180 m deep, results in a smaller increase in temperature compared to the surrounding depths. Based on the lithologic description the occurrence of a higher sand/silt, organic matter or limestone content observed in the units lo1a and lm3 can be identified at the depths corresponding to these anomalies with lower temperature increases. These can therefore be interpreted as a due to a higher groundwater flow rate in the facies having a slightly higher permeability, causing a leaching of the thermal plume. The heat supplied is more efficiently dissipated thanks to this flow, resulting in a smaller rise in temperature.

The presence of flows is confirmed by Stoneley wave velocity decrease (figure 3), Stoneley wave and P-wave attenuation increase (figure 4) and the presence of a fluid wave (figure 1) in the 140 – 180 m depth interval. We also note a good correspondence between the thermal conductivity profile and the attenuation VSP logs.

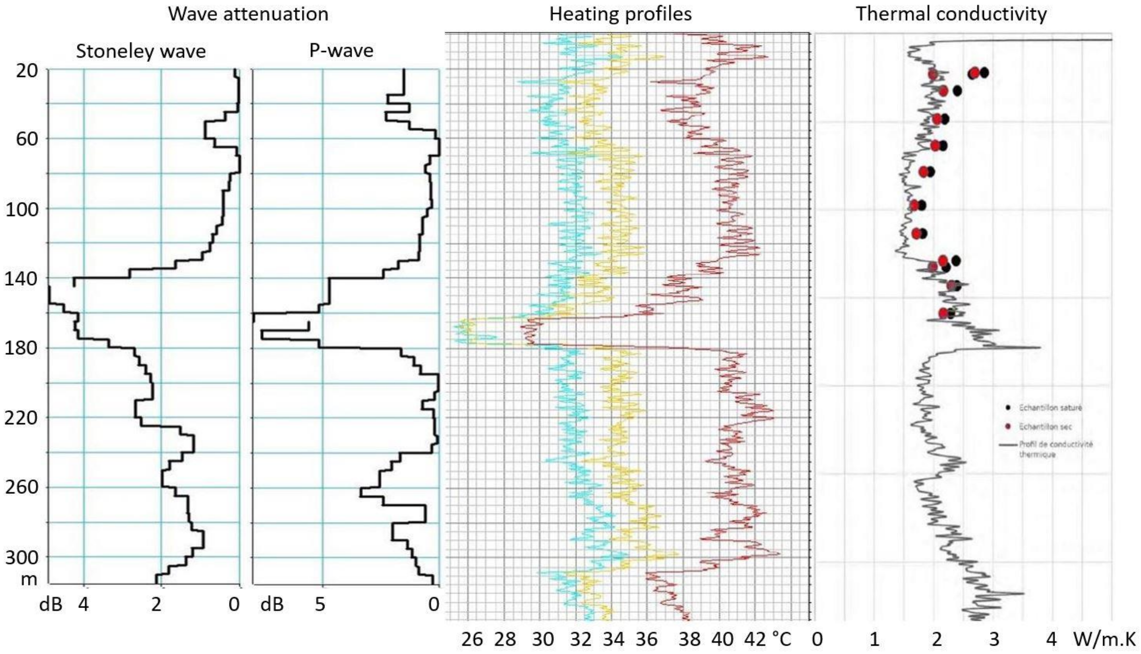

Figure 4 *VSP measurements and geothermal tests. From left to right: Stoneley and P-wave attenuation, heating profiles and thermal conductivity.*

Conclusions and Outlook

A detailed VSP interpretation enabled us to confirm small and barely visible changes in lithology and to confirm their hydrogeological and geothermal importance. The seismic reflection profiles and a planned exploration borehole will allow the characterization of geological formation up to a depth of 1000 m as well as the realization of hydraulic and geothermal tests and the comparison with VSP measurements such as P and Stoneley wave attenuation.

Acknowledgements

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References

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