Drill-bit SWD and seismic interferometry for imaging around geothermal wells

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Summary

In this work we present the results of a seismic while drilling (SWD) application using the drill-bit as a seismic source in geothermal wells. The survey was performed in a well drilled in the Nevada desert with the aim of providing geophysical information while drilling and images of the geological structures around the well. We present a summary description of the drill-bit seismic technology adapted for geothermal purposes, and the SWD results obtained along 2D profiles passing through the well. The good-quality seismic-while-drilling results have been subsequently used to obtain images of the well area in the direction normal to the main fault system, with SWD reverse vertical seismic profiling (RVSP) data migration, using seismic interferometry to extend laterally the coverage of the SWD RVSP images. The migrated seismic interferometry results confirm the main trends of the 2D geological model in the geothermal area.

Introduction

Drill-bit seismic while drilling is a known methodology (Rector and Marion, 1991; Poletto and Miranda, 2004) used in oil wells to predict the formation and structures ahead of the bit and support drilling geophysically. The drill-bit SWD technology is a tool useful also in geothermal wells, where drilling vertical wells in hard rocks with roller-cone bits makes the application favorable for obtaining good-quality data and imaging around the well purposes. In this context the drill-bit SWD technology has the advantage with respect to conventional wireline borehole seismic methods of providing multioffset information around the well without the need of recording tools in the well, where high temperature may be a critical condition for the recording equipment.

In this paper we describe a SWD application performed in Nevada (US), where the standard SWD technology and processing flow used for oil wells was adapted to provide while-drilling and after-drilling imaging results. The survey area is located in a regional trans-tensional system characterized by the presence of major NW-SE trending strike-slip faults leading to very complex fault patterns and structures on the small scale (Faulds et al., 2005). The well was drilled close to a NE-SW striking normal fault, possibly intersecting two of these right-lateral strike-slip faults. The fault zone dips NW and is associated with several synthetic, antithetic and Riedel faults on both its hanging wall and footwall. Hydrothermal fluids upflow occurs at locations associated with fractures and fault intersections and results, in this case, in the presence of silica caps due to hydrothermal alteration of quaternary sediments.

A significant difference with respect to conventional SWD survey preparation was that surface reflection seismic lines are not available in this area. This makes the additional seismic information from SWD even more important for the reconstruction of the structural and geological characteristics of the complex subsurface around the well. At the same time, this makes more crucial the task of estimating the preliminary seismic parameters using the existing information, i.e., geological and that obtained by gravity and magneto-telluric surface profiles, for survey design purposes and interpretation of the final results in zones where the SWD coverage is lower.

The main results consist of conventional-SWD (Poletto and Miranda, 2004) and new products, which include check shot, velocity profile and while-drilling prediction ahead by single and multioffset VSP, while-drilling diffraction analysis, while- and after-drilling tomography and data migration, drill-bit seismic interferometry (Poletto et al., 2009), and fault model tuning by waveform analysis. In this work we present while drilling prediction, migration and interferometry results.

SWD survey description

The survey was performed using a cross of two seismic lines of surface geophones, with a layout designed on the basis of the geophysical and geological information.

The main surface acquisition line was deployed in the NW-SE direction, passing through the well and perpendicular to the normal fault system. A second and shorter surface receiver line crossing the main line in the well position, was deployed approximately in the perpendicular SW-NE direction to monitor possible lateral effects due to the strike-slip fault systems. The length of the main line was set to cover the expected zone of reflections from the dipping fault/silicified zone by one line branch (negative offsets), and to cover the diffraction bodies interpreted in the subsurface geological model derived from gravity profiles by the opposite-side branch of the line (positive offsets). The offset of the main line ranges approximately from -750 to 870 m, and that of the secondary line from -700 to 300 m from wellhead. The distance between receiver groups is 30 m, with the nearest offset from the well in each line branch is 60 m.

Drill-bit seismic data have been recorded using a Seisbit^R system hosted in the mudlogging cabin, during near-vertical drilling between 180 m to 750 m depth with roller cone bits. Acquisition was performed in automated mode driven by drilling parameters, and average depth-level acquisition interval of 5 m. The SWD survey was obtained using surface pilot signals measured at the top of the drill string. Acquisition was assisted by data quality control (QC) in field, and real-time remote support and QC from OGS headquarters (OGS, Italy) via satellite connection. Acquisition duration was approximately one month. During this period all the data collected while drilling were preprocessed with pilot correlation and deconvolution, and used for seismic processing and diagnostics while drilling. In general, the quality of the data is good, with relevant waveform variations in relation to the complex geological area. Figure 1 shows an example of SWD signals recorded at bit depth 290 m. Figure 2 shows the layout of the main recording line on the gravity map.

Geothermal SWD survey results

While-drilling results

Seismic-while-drilling results included conventional products, such as the calculation of the interval velocity profile and the prediction ahead of the bit using two-way-time upgoing reflections of single-offset and multioffset reverse VSPs (Fig. 3). The main seismic events detected and predicted while drilling, corresponding to transitions between sandy alluvium, intrusive volcanic, quartzite, silicified and tuff formations, were confirmed by the drilling results. Due to the structural complexity of the subsurface in this faulted area, the single-offset vertical seismic profiles along different lines show significant differences.

The while-drilling signal analysis was extended to the interpretation of diffraction-shaped events as markers and indicators of expected faults near the well location. This was done by interpreting selected events detectable in the field shots of the main line. Images of reflectors and faults at well location were obtained while drilling by 2D depth migration of upgoing wavefields, compared to the the reverse VSP prediction results, and again confirmed by the borehole geological and dip results.

SWD data migration and imaging

The 2D seismic-velocity model used for data migration and imaging was built and refined by stripped depth-interval analysis, minimizing the differences between measured-picked direct arrivals and the calculated traveltimes of the updated velocity model in selected depth intervals. Figure 4 shows the picked direct traveltimes (blue lines) compared to the model-calculated traveltimes (green lines), and the time errors for the traces of the main lines with the drill-bit source in the depth interval 340-520 m.

Based on the general good-quality of the SWD roller cone data, further imaging was calculated by 2D migration of upgoing reflection wavefields, and traveltime tomography inversion (Böhm et al., 2005) using the picking of the direct arrivals and of selected reflections at positive offsets.

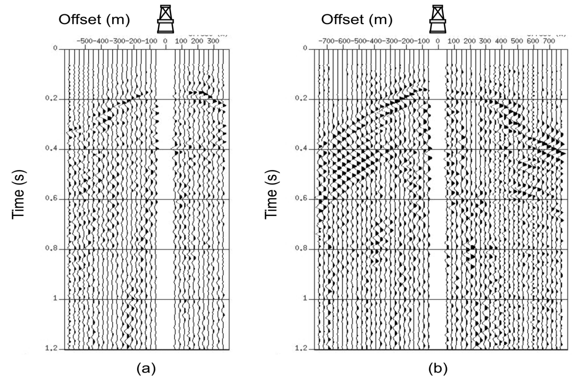

Fig. 1: SWD signals along the seismic lines recorded at drill-bit depth 290 m. b) Main line perpendicular to the principal fault system, and a) secondary line for control of possible lateral effects.

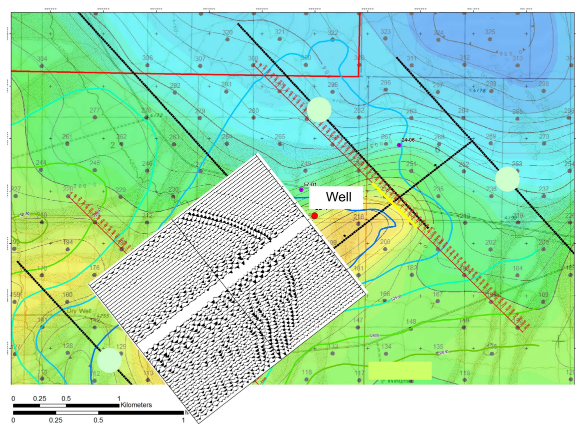

Fig. 2: SWD shot record of the main line perpendicular to the principal fault system, plotted on the gravity map used to plan the survey.

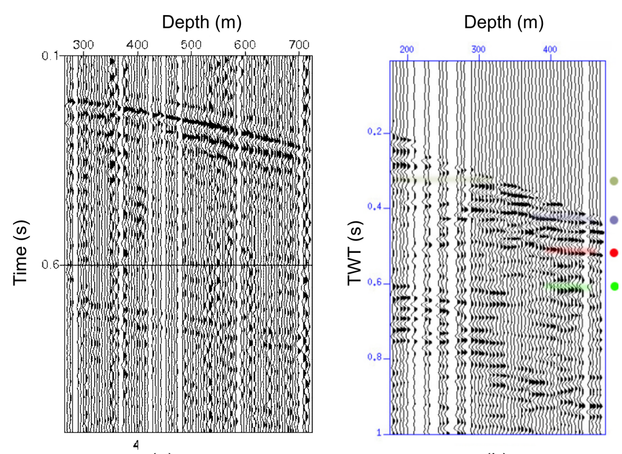

Fig. 3: Example of a) SWD single offset VSP total field, and b) two-way-time (TWT) prediction ahead of the bit.

Taking into account the aperture limitations for the tomographic inversion in the well-surface SWD geometry, we used the approach to design the velocity model based on the interpretation of the geological setting, driven by the residual error traveltime analysis and by the tomographic inversion results in the central-upper part of the model, above the maximum drilling depth of 750 m (Fig. 5). In this region, the tomographic inversion of the direct arrivals provides important and detailed information on the local velocity variations, corresponding to geothermal silicified zones in the proximity of the faults. This result is in good agreement with the while-drilling results, SWD migration and existing geological information.

To analyze the model shallower variations in offset we compared also the synthetic model results and the wavefields of the SWD real shots.

Deeper velocity model was obtained by common-image-gather (CIG) velocity analysis, and by migration result interpretation. Figure 6 shows the geological model and Fig. 7 shows the migration results plotted approximately between the minimum (-800 m) and maximum (+900 m) offset of the main seismic line perpendicular to the strike of the main fault system. In this wide region, the SWD RVSP migration provides images with lower coverage and lateral effects for signals at large offsets, say, those higher than 500 m or lower than -500 m, and without primary upgoing reflections in the shallower region above the 180 m starting depth of the drill-bit SWD survey.

With the purpose to extend the seismic information below the surface recording line, and provide more structural details in the shallower part, we redatumed the seismic-while-drilling data by seismic-interferometry approach. This task is even more important for the definition of the structural subsurface settings in the absence of surface reflection seismic lines in the investigated area.

Drill-bit seismic interferometry

One of the potentials of seismic interferometry is to create new wavefields with sources redatumed at receiver points to increase seismic coverage. One of the application scenario is redatuming data from VSP to surface (Schuster, 2009). Figure 8 shows the interferometry concept applied to SWD. The real drill-bit source is used to illuminate the surface receivers to reconstruct redatumed source signals at the surface. The interferometry signals are then migrated using the same velocity model, and the results combined with those of the SWD RVSP migration of Fig. 7. An advantage of the method is that we do not need subsurface information to recover the redatumed functions, and we only need the model below the new sources where the new data are migrated. In this way we extend the investigation area with the interferometry Green's function synthesized in the shallower layers, where we do not have SWD primary-reflection information, and at large offsets.

To obtain the interferometry signals by the drill-bit source we use the crosscorrelation approach discussed by Poletto et al. (2010). For this purpose, we crosscorrelate the pilot-correlated signals after pilot signal deconvolution, using the wavefields of the same drill-bit VSPs used for migration purposes. The crosscorrelation and stacking of the data was extended to all the drill-bit source depths between 180 m and 750 m drilling depth. The interferometry data were calculated separately for positive and negative offsets. Taking into account possible limitations for stationary conditions by the available geometry, the depth migration of the interferometry signals was calculated with aperture adapted to include the external shot traces with respect to the interferometry sources obtained at closer position with respect to the well.

The migration interferometry results of the positive-offset and negative-offset line branches are muted to preserve the upper and lateral side of the seismic migrated section. The muted interferometry migration signals are plotted together with the SWD migrated results of Fig. 7, which are muted before combination to preserve the central bell-shaped RVSP migration zone. The combined result is shown in Fig. 9. We can observe and appreciate the matching and the continuity of the reflection events, which confirm the structural features and dipping layer trends interpreted in the drill-bit seismic section. The results are in agreement with the model of Fig. 6 obtained also with the support of wavefield's interpretation.

Conclusions

A SWD survey was performed obtaining good-quality seismic signals used for monitoring while drilling, fault detection and interpretation, and subsequent imaging of the well area. In the absence of the surface reflection seismic, the SWD survey was designed starting from existing geological models derived from gravity and magneto-telluric profiles.

Due to the particular geological setting and to the targets of the geothermal exploration, the typical SWD work flow used for oil exploration applications was adapted and the geophysical products tuned paying particular attention to: the detection of anomalies possibly related to nearby faults, the analysis of diffractions, the while-drilling inversion of traveltimes and imaging. In this process, a key point is that the method provides extended multioffset information while drilling.

The analysis shows that the integrated interferometry and migration results are in good agreement with the SWD results and with the shallow geological and magneto-telluric geophysical information used to map the geothermal field. This provides detailed information in the drilled area and new structural seismic information to define and characterize the geothermal reservoir around the well.

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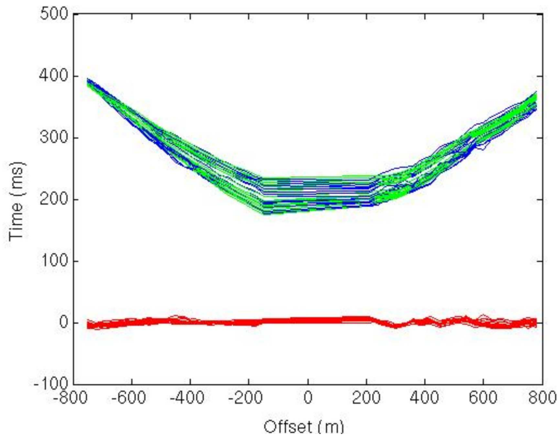

Fig. 4: Comparison of SWD direct arrivals (blue line) and model calculated traveltimes (green line) in the depth interval 340-520 m. The traveltime differences are plotted in red.

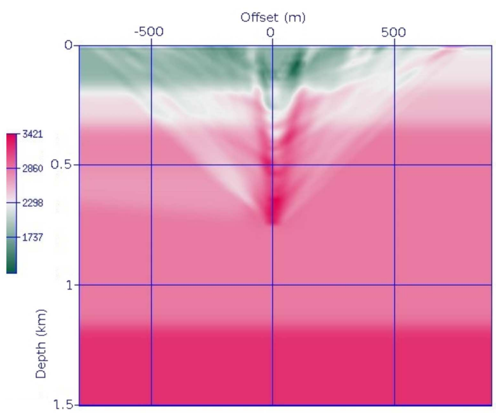

Fig. 5: Tomographic inversion of SWD traveltimes. Velocity scale is in m/s.

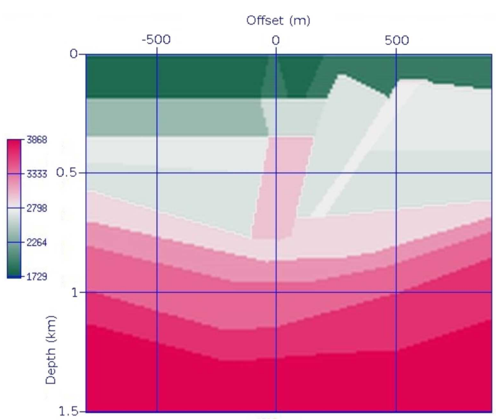

Fig. 6: Velocity model below the main SWD seismic line. Velocity scale is in m/s.

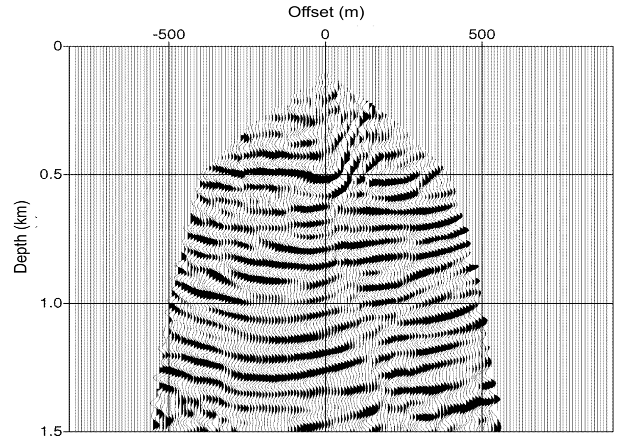

Fig. 7: SWD depth migration results.

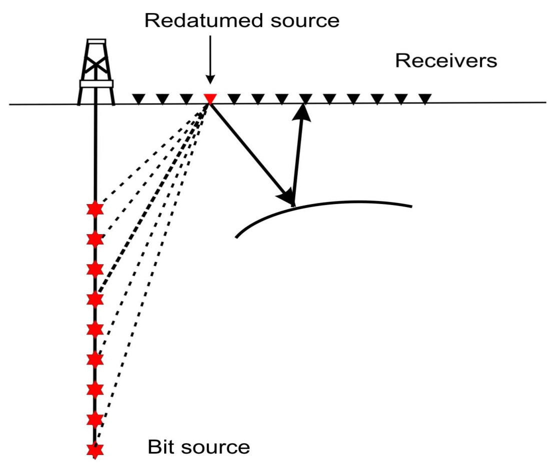

Fig. 8: Concept of seismic interferometry application for drill-bit SWD purposes.

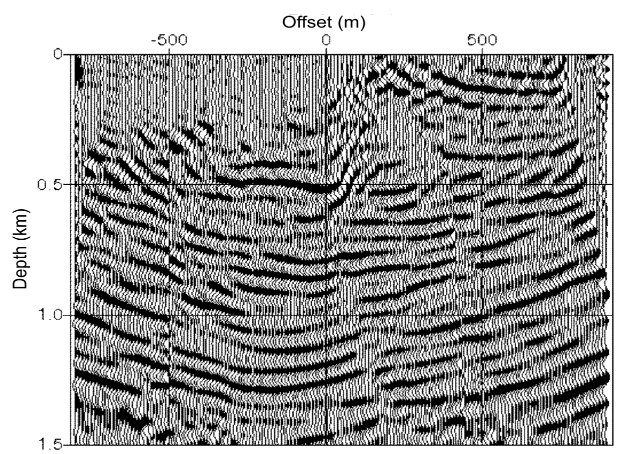

Fig. 9: Combination of RVSP SWD migration and SWD interferometry migration.

EDITED REFERENCES

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