A Model of the Subsurface Structure at the Rye Patch Geothermal Reservoir Based on Surface-to-Borehole Seismic Data

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ABSTRACT

In 1998, a three-dimensional surface seismic survey was conducted to explore the structure of the Rye Patch geothermal reservoir (Nevada) to determine if modern seismic techniques could be successfully applied in geothermal environments. Furthermore, it was intended to map the structural features which may control geothermal fluid production. The results suggested the presence of at least one dominant fault responsible for the migration of fluids in the reservoir. In addition to the surface receivers, a three-component seismometer was deployed in a borehole at a depth of 3900 ft, within the basement below the reservoir, which recorded the waves generated by all surface sources. The purpose of the study was to use the collected data set to determine the subsurface structure as a function of azimuth. A total of 2005 first-arrival travel times were determined out of 2134 possible traces. 2-D ray tracing was performed to simulate wave propagation from the surface sources to the receiver at depth. The ray tracing was based on a 2-D laterally homogeneous velocity model derived from a velocity profile calculated from a previous vertical seismic profile (VSP) recorded in the same well. It was assumed that differences in travel time between the observed and modeled data are caused by structural deviations from a homogeneously layered model as determined by the VSP, and thus were mapped into topographic changes at depth. The results suggest an east-west-trending structure (possibly a horst) with boundaries that match the location of faults found based on the analysis of the 3-D seismic surface data.

Introduction

Lawrence Berkeley National Laboratory (LBNL) has cooperated with The Industrial Corporation (TIC) and Transpacific Geothermal Inc. (TGI) in studies to evaluate and apply modern seismic imaging methods for geothermal reservoir definition under the U.S. Department of Energy's (DOE) Geothermal Program. As part of this cooperation a vertical seismic profile (VSP) was acquired in 1997, at the Rye Patch Geothermal field in Nevada, to determine the structure of the reservoir. The VSP survey was conducted to determine the seismic reflectivity of the reservoir horizons and to obtain reservoir velocity information. Because the results of the initial VSP indicated apparent reflections at depth (Feighner *et. al.*, 1998), it was decided to proceed with a 3-D seismic surface survey which was completed in 1998.

In addition, an experiment was conducted during which a three-component geophone was installed at 3900 ft depth. This geophone recorded all seismic waves generated by the surface sources, creating a second dataset in addition to the seismic reflection data. The analysis of the second dataset is the content of this paper.

The location of the surface survey and the location of borehole 46-28 where the geophone was installed at depth are indicated in Figure 1 (overleaf). The Rye Patch temperature anomaly is bounded by the Humbold City Thrust in the East and the Rye Patch reservoir in the West. Feighner *et. al.* (1999) suggested possible faulting at depth based on results derived from surface reflection seismic studies and surface-to-surface tomographic travel time investigations. This study is intended to determine whether the dataset, which was recorded with minimal extra effort at depth, can provide additional valuable information and if so, whether it can support the results of the previous studies.

Data Acquisition and Processing

The Rye Patch seismic surface survey covered an area of 3.03 square miles and had 12 north-south receiver lines and 25 east-west source lines. The source interval was 100 feet while the source line spacing was 400 feet. Four Litton 311 vibrators were used in a squared array with the source point at the center of the array. The source signal was a sweep with a frequency bandwidth between 8 Hz and 60 Hz. A detailed description of the data collection can be found in the contractor's report (SECO, 1998).

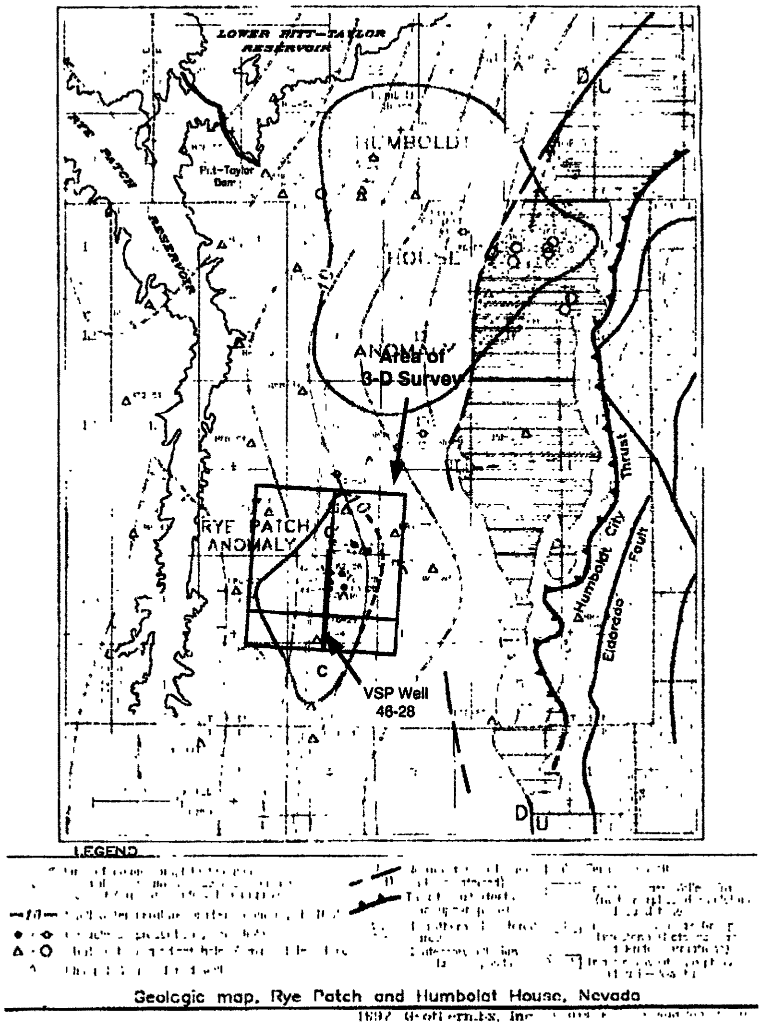

Figure 1. Rye Patch Geothermal Field. Location map showing 3-D survey area and VSP Well 46-28.

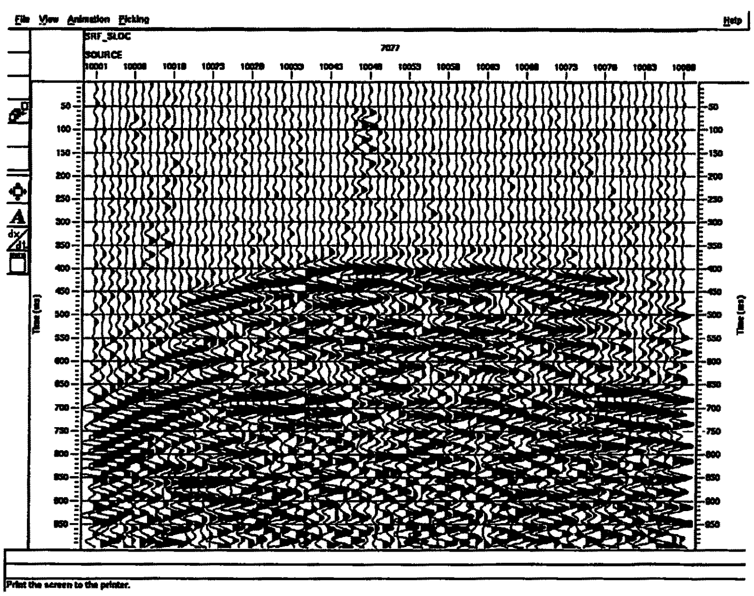

Figure 2. Common receiver gather for all sources along source line 10 running north of well 42-28.

A high temperature, wall-locking, three-component geophone was installed in well 46-28 at 3900 ft depth. The borehole geophone recorded all shots throughout the survey area, amounting to a total of 2134 traces. The data quality is good with a frequency content of about 25 Hz for the first arriving waves. Figure 2 shows a representative receiver gather of source line north of well 46-28. It is evident, as a first-order effect, that the amplitudes and the moveout of the first arriving waves vary with distance to the well. Additionally, local and smaller variations in arrival time can be seen between source positions 10048 and 10063. These local variations in travel time will be mapped into topographic changes of the reservoir horizons at depth.

A total of 2005 first arrival travel times were determined out of 2134 possible traces. Most of the picks were reliable because the well sampled spatial moveout across the source lines facilitated the picking.

Ray Tracing

In 1997, a VSP was recorded in well 46-28 (Feighner *et. al.*, 1998). The resulting P-wave velocity profile between 400 ft and 4150 ft depth represents the best estimate for the distribution of velocities in the subsurface around the well, and is the only in situ velocity measurement available. Based on these results, a velocity function was derived that represents a smoothed average of the VSP velocity profile and is shown in Figure 3. The

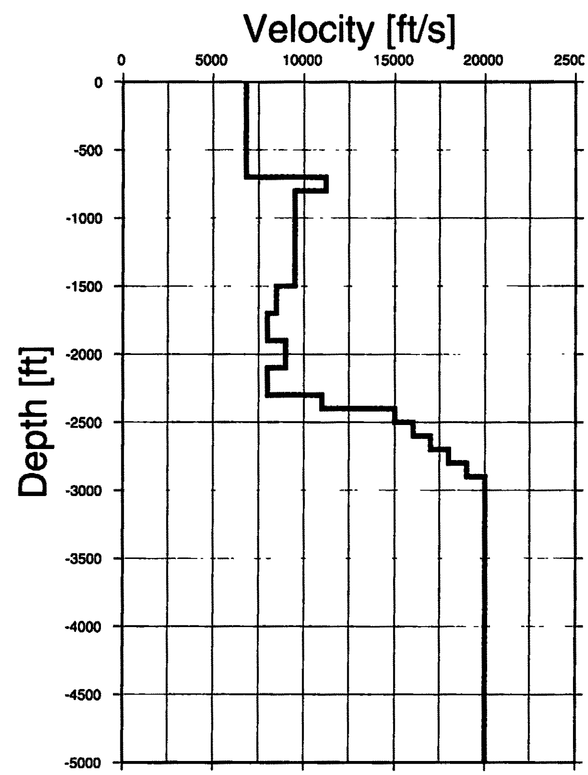

Figure 3. Velocity profile from the VSP survey in Well 46-28.

prominent features of this velocity function are the high velocity layer of 11,500 ft/s between 700 and 800 ft depth, followed by a velocity inversion to approximately 9000 ft/s over a depth range of 1500 ft, and a gradual increase to 20,000 ft/s representing the basement at a depth of 2900 ft.

This velocity profile was subsequently extended to a 2-D velocity model with homogeneous layers extending throughout the survey area. Based on this velocity model, a 2-D ray tracer was used to simulate wave propagation from surface sources to the receiver at depth. Figure 4 shows representative results of the ray tracing. The velocity model is the 2-D representation of the function in Figure 3. Sources are denoted by stars while the receiver is indicated by an inverted triangle at 3900 ft depth. The 2-D ray tracing produced a total of 2134 rays, connecting the sources to the receiver at depth, and their associated travel times. None of the 2134 rays crossed path with other rays which prevented the application of a tomographic inversion approach. Therefore, we cannot simultaneously find lateral velocity variations within the layers. However, under the assumption that the homogeneous velocity model is a good representation of the subsurface structure (i.e. velocities can be extrapolated away from the borehole) the observed and modeled travel times can be compared for each source-receiver combination, and differences can be attributed to changes in elevation of the subsurface horizons.

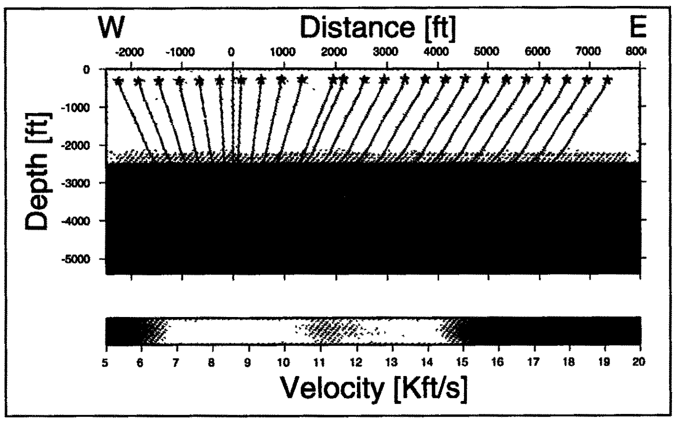

Figure 4. Velocity model and ray paths from the sources in source line 20 (running east-west across well 46-28) to the receiver in well 46-28.

Mapping Travel Time Deviations to Elevation Changes at Depth

Methodology

Mapping travel time deviations to elevation changes is a technique that has been used in seismic refraction studies in the past. The method is an approximation that can be applied in environments where a low-velocity layer is located above a high-velocity layer or basement. Under the assumption that the ray path from source to receiver is known, any difference between the calculated and observed travel times is converted into a distance using the velocity model and applied as a deviation in the boundary between the basement and the overlaying layer. We employ the same principle in our approach assuming that the top layer can be approximated by an average velocity of 9000 ft/s and that the basement is represented by a halfspace with a velocity of 20,000 ft/s (refer to Figure 3). The travel time deviations are computed for each ray path and the differences converted to elevation changes. In our case, we apply the total travel time difference for each ray to the whole geologic model, thus assuming that any possible faulting affected the whole geologic sequence above the basement. However, this is only one possible interpretation of the data and other scenarios may be as likely. It is feasible that a fault cuts only through the basement and a fraction of the layers above, while in another case it may cut through the basement only. These latter cases would represent events where sedimentation continued after the fault stopped being active. This might be the case at Rye Patch, where there is no surface evidence of the SE fault. However, as it is not possible to determine where the fault stops, we choose to interpret the whole sequence above the basement as being affected by faulting.

Interpretation

Figure 5 shows a South-West view of the survey area (refer to the black square in Figure 1). It displays the elevation changes of the basement and the geologic sequences above. The location of borehole 46-28 is shown for reference (circle in foreground). Positive deviations denote source positions from which the actual waves travel faster to the receiver than in the ray-tracing simulations. The assumed explanation in this case is that the high-velocity basement is uplifted relative to the homogeneously layered velocity model used in the simulations. Similarly, negative deviations denote slower wave propagation than assumed in the simulations, indicating a thicker low-velocity layer on top of the basement (e.g., the basement is shifted downwards).

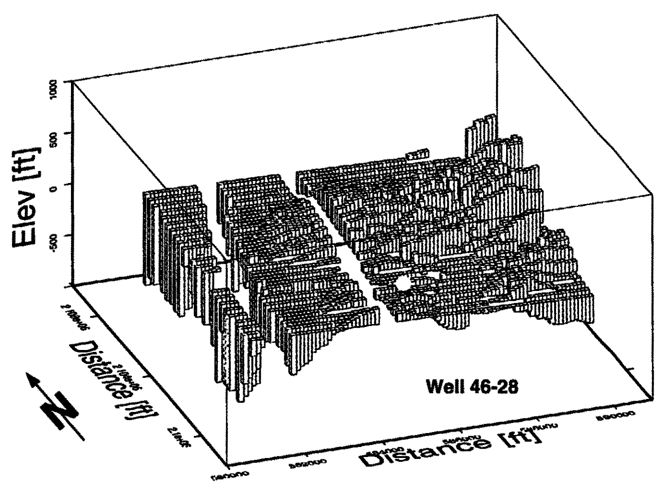

Figure 5. Variations in basement interface elevation. VSP well 46-28 is indicated by the circle in the foreground. View from Southwest.

The main feature in Figure 5 is an elevation high in the central eastern region of the survey area bound by lower elevations towards the North and South. However, contrary to the eastern region, the western half of the survey area reveals a pronounced trend to negative travel time deviations. The reason for that may be an artifact due to very low sedimentary velocities West of Interstate 80 that were reported in a previous 2-D tomographic study (Feighner *et. al.*, 1999). These velocities estimates were as low as 5000 ft/s for the shallow layers down to 200 ft depth. Because these velocities (if correctly estimated) are lower than the one assumed in the current homogeneous model (6800 ft/s down to 700 ft depth; see Figure 3), the resulting travel time difference and thus elevation changes would be negative throughout this region.

The actual elevation changes of the basement horizon are probably smaller than the ones shown in the present mapping, since all deviations from the assumed horizontally layered velocity model are mapped into elevation changes. Additionally, this model may not be a good representation at great distances from the borehole. It is also feasible that a deviation in travel time is caused by a local velocity unconformity rather than a change in a boundary of the layered velocity model. However, it is not possible to estimate those local velocity changes from the available data, as this would constitute a solution to a complex inversion problem for which data coverage with numerous crossing rays is needed. The current data set, however, does not contain any crossing rays in the subsurface. Thus, the estimated changes in elevation represent upper bounds for the actual values.

A mapview of the basement horizon elevation is provided in Figure 6. The three boreholes 46-28, 44-28, and 42-28 are shown for reference. It can be seen that the 0 ft elevation contour line runs through well 46-28, which is expected since the velocity model is based on the VSP data acquired in that well and only a small deviation between the modeled and measured data is expected at this location. The map shows the contours of the elevated structure extending from East to West across the survey area while cutting through the steep descent on the western flank. The north-south extent of this rise reaches roughly from 2107000 (north of well 42-28) to 2102000 (between wells 46-28 and 44-28), while the east-west extension seems to reach beyond the boundaries of the survey area (refer to Figure 6). The elevation in the reservoir could be described by a horst or a ridge structure that is bound by two east-west trending faults to the North and South.

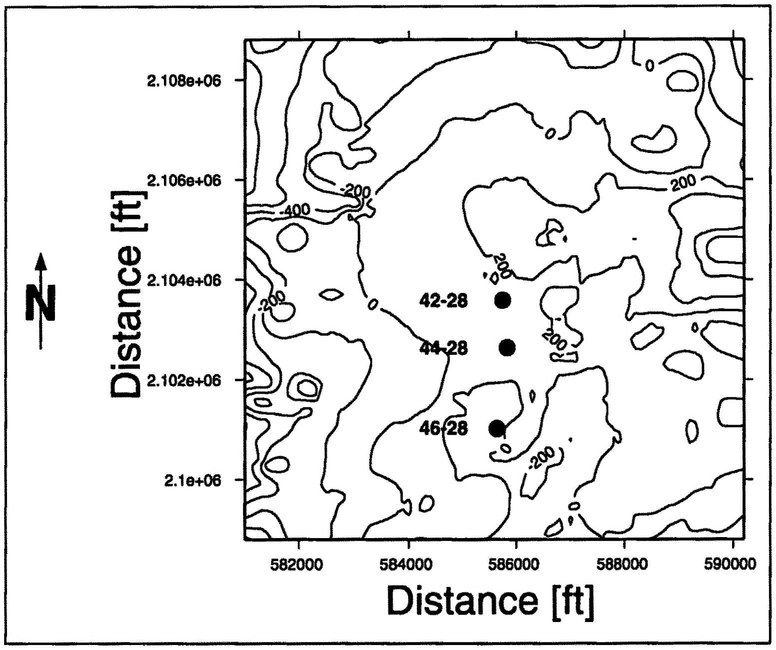

Figure 6. Contour map of the variations in basement interface elevation. The three boreholes are indicated for reference.

Conclusion

The geophysical experiments conducted at Rye Patch geothermal field, provided various datasets which help to interpret the subsurface structure of the reservoir. The addition of a depth geophone to record surface generated seismic waves during the 3-D reflection survey provided an additional independent dataset at low cost and with minimum technical and labor requirements. Because most geothermal areas provide access to open boreholes during the developing stages of the reservoir, it is recommended that a VSP survey is conducted first, to obtain information about the velocity structure and the reflectivity of the subsurface. These in situ measurements are the only direct methods to determine seismic velocities at depth, and are imperative for the planing of any future surface seismic reflection surveys.

VSP results are normally extrapolated from the vicinity of the borehole into the surrounding area to provide a 3-D velocity model. However, because of the heterogeneous nature of geothermal reservoirs, the error in extrapolating the VSP information can be minimized by conducting VSP surveys in several boreholes in the field. A suite of VSP surveys is highly recommended for any reservoir exploration, since all following seismic experiments rely on the velocity information derived from these surveys. If it is determined that a surface seismic reflection survey may provide more detailed information on the reservoir structure, it is recommended to add geophones in any available borehole within the survey area. These datasets collected at depth provide an independent, low-cost alternative to the surface data, and can help in characterizing the subsurface structure.

In the latest study, the data recorded in borehole 46-28 provided information that supports results from previous experiments. The interpretation of an elevated basement with an east-west trend, bounded by linear features towards the northern and southern extension is in agreement with 2-D tomographic results (Feighner *et. al.*, 1999) and possibly with geophysical investigations undertaken in a previous study (Teplow, 1999). However, it should be recalled that the interpretation of an elevated basement is just one of several structural models that can explain the data. Furthermore, the uplift that is indicated in Figures 5 and 6, should be seen as an upper bound on the actual lift, as the difference between observed and modeled travel times is converted to elevation changes, rather than viewed as horizontal velocity variations, which are undoubtedly present in the reservoir. In order to estimate these variations, a dataset is needed that contains multiple crossing raypaths which have yet to be collected at the Rye Patch geothermal field.

Acknowledgments

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References

Feighner, M.A., Daley, T.M., Majer, E.L., 1998. Results of the Vertical Seismic Profiling at Well 46-28, Rye Patch Geothermal Field, Pershing County, Nevada, Lawrence Berkeley National Laboratory Report LBNL-41800.

Feighner, M., Gritto, R., Daley, T.M., Keers, H., Majer, E.L., 1999, Three-Dimensional Seismic Imaging of the Ryepatch Geothermal Reservoir, Lawrence Berkeley National Laboratory Report LBNL-44119.

SECO, 1998, 3-D Seismic Survey, Rye Patch Geothermal Field, Pershing County, Nevada, June-August 1998, Report to The Industrial Company, Subsurface Exploration Company, Pasadena, CA.

Teplow, B., 1999. Integrated Geophysical Exploration Program at the Rye Patch Geothermal Field, Pershing County, Nevada, Final Report to Mount Wheeler Power.