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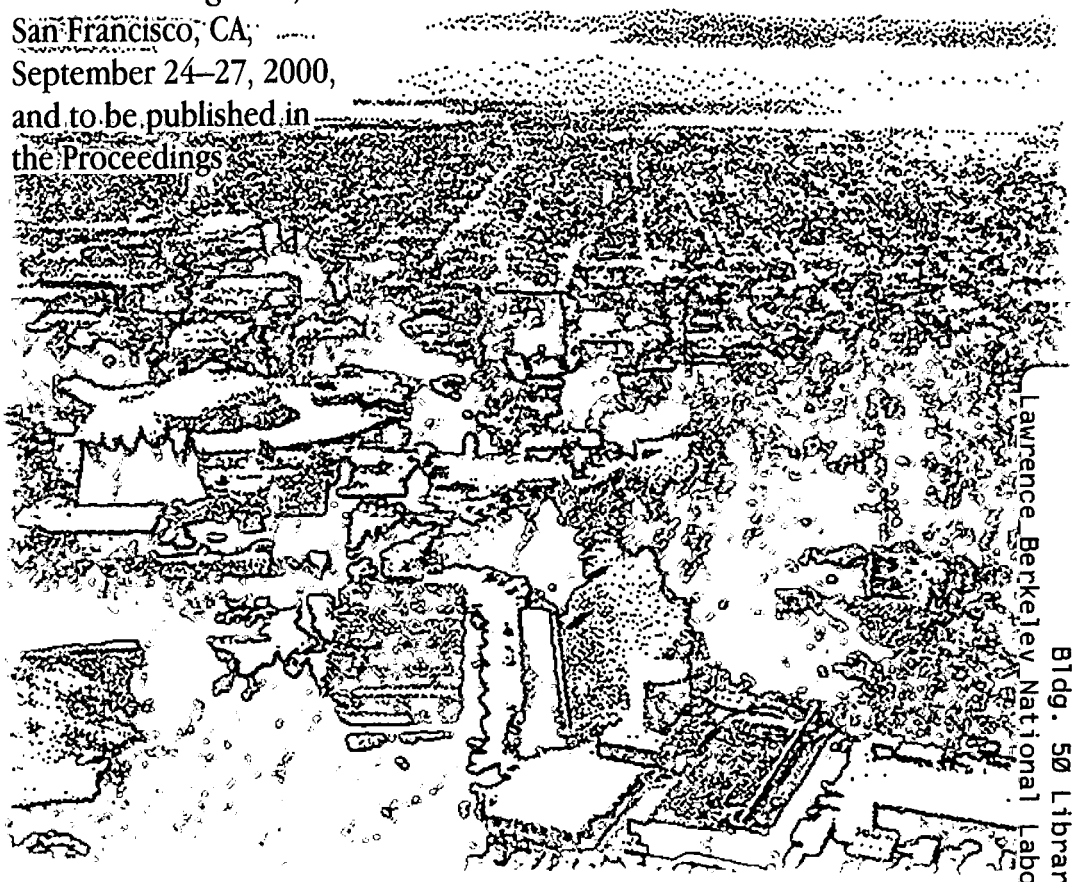

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# Development and Application of 3-D Seismic Imaging Methods for Geothermal Environments

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**Keywords:** 3-D Seismic Imaging, Seismic Reflection, Seismic Tomography, Rye Patch

## Abstract

A 3-D surface seismic survey was conducted to better define the structure of the Rye Patch geothermal reservoir (Nevada) and to determine if modern seismic techniques could be successfully applied to geothermal environments. Furthermore, it was intended to map the structural features which may control geothermal reservoir production. The seismic survey covered an area of 3.03 square miles and was designed with 12 north-south receiver lines and 25 east-west source lines. Seismic processing involved, among other steps, the picking of phases to determine first arrival travel times, normal moveout correction, 3-D stack, deconvolution, time migration, and depth conversion. The final data set represents a 3-D cube of the subsurface structure in the reservoir. Additionally, the travel times were used to perform tomographic inversions for velocity estimates to support the findings of the surface seismic imaging. The results suggest the presence of at least one dominant fault controlling the migration of fluids in the subsurface. Furthermore, it is suggested that this feature might be part of a fault system that bounds a graben structure.

## Introduction

As part of the U.S. Department of Energy's (DOE) program in geothermal research, Lawrence Berkeley National Laboratory (LBNL) has been cooperating with The Industrial Corporation (TIC) and Transpacific Geothermal Inc. (TGI) to evaluate and apply state-of-the-art seismic imaging methods for geothermal reservoir definition.

The overall objective of the work is to determine if modern techniques in 3-D surface seismic profiling could be successfully applied to geothermal environments directly. If not, could they be modified to derive useful information on reservoir structure. Past efforts using 2-D seismic reflection have proved marginally successful in some cases. However, due to extreme heterogeneity in many geothermal areas, 2-D seismic surveys have not been cost effective.

Initial exploration efforts at the Rye Patch, Nevada geothermal field in the late 1980s and early 1990s resulted in one successful well (44-28), while other wells were either too cold

or were not productive. In 1997, TGI proposed a 3-D seismic survey to determine the geologic structure on the (hypothesized) fault-controlled reservoir.

A 3-D surface seismic survey was conducted to explore the geologic structure of the Rye Patch reservoir (Nevada), and to map the structural features which may control geothermal fluid flow. This was possibly the first application of the 3-D seismic method to a geothermal field and therefore of interest to the entire geothermal community.

Although 3-D seismic methods are an integral part of modern oil and gas exploration efforts, the heterogeneous and hydrothermally altered nature of geothermal reservoirs makes all seismic imaging more difficult. It is not known how well the methods used in petroleum exploration can be transferred to the geothermal industry. Before conducting a full-scale 3-D survey, however, DOE contracted LBNL to investigate the reflectivity of the target zone in order to assess the viability of seismic imaging in the Rye Patch field.

In December 1997, LBNL conducted a vertical seismic profile (VSP) in well 46-28 to determine the seismic reflectivity in the area and to obtain velocity information for the design and potential processing of the proposed 3-D seismic survey (Feighner et al., 1998). Because the results of the VSP indicated apparent reflections, TGI proceeded with the collection of three square miles of 3-D surface seismic data over the Rye Patch reservoir. In addition, Mt. Wheeler Energy Corporation is drilling a well to increase the production of the reservoir. At this time (May 2000) the drilling is still in progress but it is hoped that the results will soon be known in order to correlate them with the seismic data.

## Progress to Date

The seismic survey covered an area of 3.03 square miles and was designed with 12 north-south receiver lines and 25 east-west source lines. The receiver group interval was 100 feet and the receiver line spacing was 800 feet. The source interval was 100 feet, while the source-line spacing was 400 feet. The sources were comprised of four vibrator trucks arranged in a squared array. In addition to the surface receivers a three-component geophone was installed in a well near the center of the surveyed area at the assumed reservoir depth. The geophone recorded data while the surface 3-D seismic survey was being performed. Figure 1 shows the location of the seismic survey area within the Rye Patch geothermal field.

Seismic processing involved, among other steps, the picking of over 700,000 of the possible one million traces to determine first-arrival travel time, normal moveout correction, 3-D stack, deconvolution, time migration, and depth conversion. Additionally, the travel times were used to perform tomographic inversions for velocity estimates to support the findings of the surface seismic imaging. Data from the borehole geophone were used to determine seismic anisotropy that may be indicative of fracture and fault orientation.

The results suggest the presence of at least one dominant fault controlling the subsurface flow of geothermal fluids. Furthermore, it is suggested that this feature might be part of a fault system that includes a graben structure.

Seismic Processing

The seismic processing included field statics to smooth sudden changes in elevation, followed by a bandpass filter and automatic gain control. Stacking velocities were picked for several horizons. Refraction static processing was unsuccessful because near offset first-break arrivals were weak and could not be determined for most shot locations, whereas the target horizon for reflection statics (the clastic unit at depth) revealed incoherent reflections throughout the receivers lines, likely caused by faulting throughout the reservoir area. After normal moveout correction and 3-D stacking a coherency filter was applied to the stacked data to enhanced the strength of the weak reflectors. This was followed by a time migration using smoothed stacking velocities that were shifted to the final datum at 4735 feet above sea level. The time data was finally converted to depth using 103 % of the VSP velocities. These VSP velocities provided a match between the top of the clastic unit identified by the VSP and the center of the wavelet in the reflection data. Figure 2 shows a depth migrated CDP section with two independent interpretations of the possible location of the fault at depth.

The use of VSP velocities to convert from time to depth was appropriate at the well. However, the velocities certainly change with distance away from the well. Therefore, the calculated depths away from the well are only approximate and the uncertainty could easily approach several hundreds of feet. The only other alternative would have been to use a percentage of the stacking velocities. However, these velocities would have been unreliable for depth conversion, and it is believed that the resulting errors in depth would have been much greater than using the extrapolated VSP velocities. VSP data from other wells would have been useful in adding control to the depth conversion process. We would recommend this for future 3-D seismic surveys in geothermal areas.

Travel Time Tomography

From the beginning of the project it was believed that 3-D heterogeneity in the system due to tectonic activity and hydrothermal alteration would combine to reduce the effectiveness of standard 3-D seismic processing. The goal to understand the near-surface heterogeneity led us to attempt tomographic analysis using first-arrival times. These times represent a 3-D experiment independent of the common-depth-point (CDP) reflection processing, one which probes the shallow region of the reservoir.

Before analysis could begin, the first-arrival travel time data set had to be constructed. Since standard industry automatic time picking algorithms could not be applied, it was decided to hand pick the first arrivals in the seismic data. The original idea of a 3-D data volume of estimated P-wave velocities throughout the survey area had to be abandoned because of the nature of the survey geometry and the data acquisition process. While all 12 receiver lines had 87 or more receivers in north-south direction, there were only 12

receiver in east-west direction. This geometry prevents any reasonable resolution of inversion estimates in the east-west direction. Furthermore, only the four nearest receiver lines in the immediate vicinity of the source locations recorded these shots. Therefore, only the lines in the north-south direction were processed, and 2-D ray tracing and travel time inversions were performed along these lines.

An initial velocity model which resembled the estimated velocity profile of the VSP survey was created. The 2-D ray tracing algorithm is based on the shooting method, while the inversion uses a back-projection algorithm. Although inversions were done for all 12 receiver lines, reliable results were only obtained for few of them. Clear first-arrival energy for intermediate distances was missing in the data of most lines. This lack of first-arrival time picks transforms into poor ray coverage at intermediate depth. Since the ray coverage was always poor for depths below 1500 ft, the missing time picks limited reliable velocity estimates to the upper 500 ft. The tomographic results concentrate on the receiver line crossing the VSP well where a possible fault was interpreted in the seismic reflection data and are only interpreted to a depth of 1500 ft. The result of the velocity inversion below receiver line 7 is shown in Figure 3.

## Conclusions

The 3-D seismic reflection data provided interpretable results for a depth range below 500 ft, whereas the tomographic travel-time inversion produced reliable results down to 500 ft only. The first notable result of the 3-D seismic processing is that neither refraction nor reflection static corrections helped to increase the data quality. Refraction static processing was unsuccessful because near offset first-break arrivals were weak and could not be determined for most shots locations, whereas the target horizon for reflection statics revealed incoherent reflections, likely caused by faulting throughout the reservoir area. However, estimating correct surface statics could improve the CDP image.

The depth mapping of the time migrated data was based on velocity values equal to 103 % of the VSP velocities. This approach lined up the reflection of the clastic unit in the VSP and reflection data at depth. However, these velocities are only valid in the vicinity of the VSP well, and have to be extrapolated at greater distance from the well. We still feel that this method is more precise than using stacking velocities, which are questionable due to the lack of horizontal continuity of the reflectors at depth.

The travel time tomography results indicate a possible graben structure in the area, bound by two faults to the south and north. This interpretation is partially supported by the reflection seismic results, which indicate the presence of the southern fault of the inferred graben structure. The lack of first-arrival energy from the far offset shots in the shadow of the graben supports the tomographic results as the faults bounding the graben may inhibit the waves on their propagation across this structure

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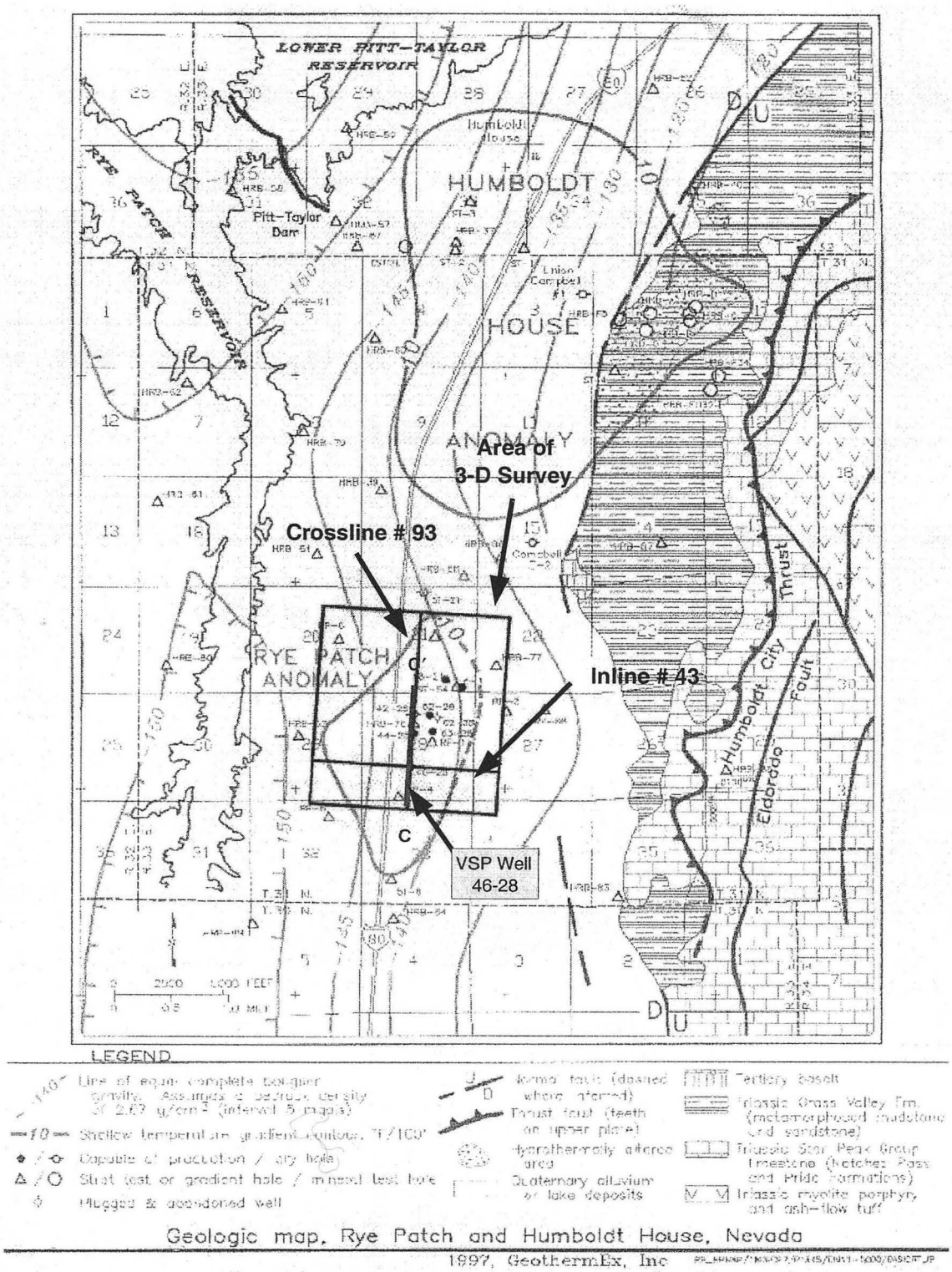


**Figure 1:** Rye Patch geothermal area. Location map with the area of the 3-D seismic survey. Also shown are the cross-section profiles of C-C', Inline 43, and Crossline 93. Figures 2 and 3 show results along Crossline 93.

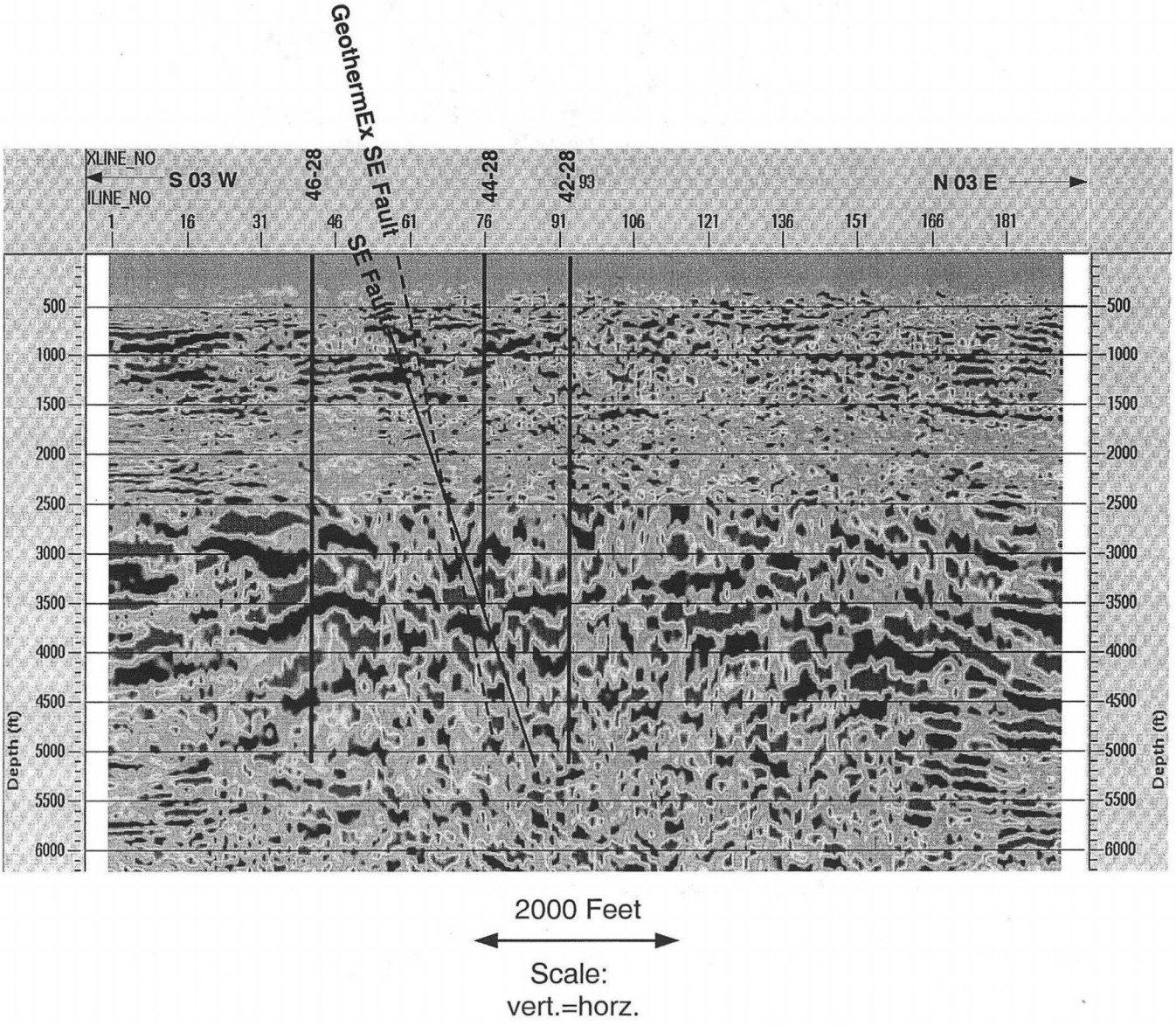


**Figure 2:** Two dimensional depth migrated CDP section along Crossline 93 (see Figure1). This image represents a slice out of a 3-D depth migrated data volume. Two interpretations of the possible location of one of the producing faults are indicated. "SE Fault" (solid line) denotes the interpretation by Teplow (1999), while the location of "GeothermEx Fault" (dashed line) is based on previous interpretation by GeothermEx (1997).

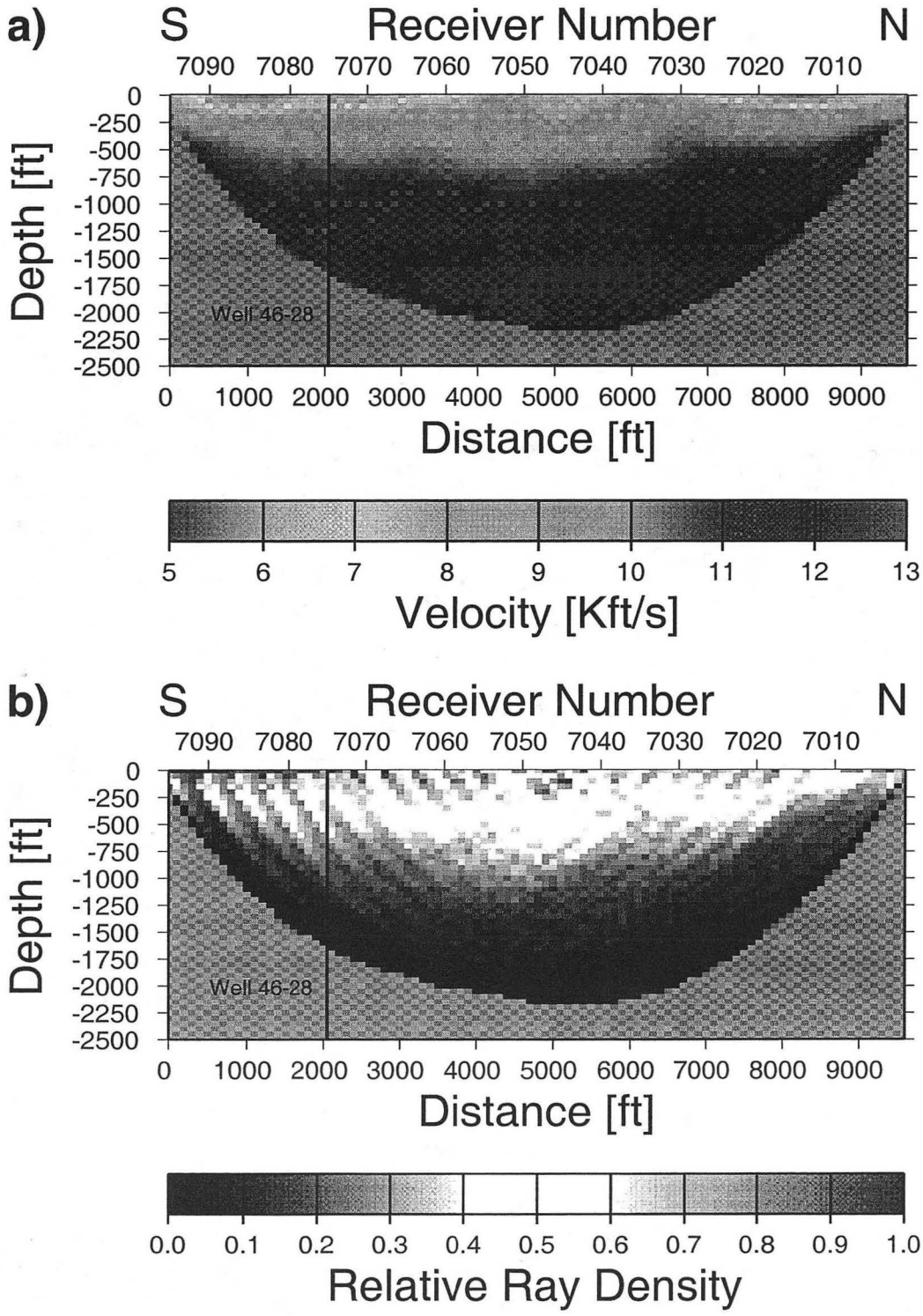


**Figure 3**: Travel time inversion results for crossline 93. Gray areas represent no ray coverage. The VSP well 46-28 is projected onto the image for reference. a) Velocity estimates. b) Ray coverage (maximum number of rays per cell is 99)

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