Three-Dimensional Kirchhoff Migration Analysis of VSP Data From a Geothermal Field

Richard L. Gibson, Jr., Jung Mo Lee*, M. Nafi Toksöz*, Ivano Dini†, and Gian Mauro Cameli†*

* *Earth Resources Laboratory, MIT, Cambridge, Massachusetts 02139, USA*
†*ENEL SpA/DPT/VDT-G, Via A. Pisano 120, 5612%Pisa Italy*

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ABSTRACT

We investigate the application of 3 D Kirchhoff migration methods to the analysis of vertical seismic profile (VSI') data collected in the Colla 2 well of the Larderello geothernial field in the 'I'uscany region of Italy. The shallow geological structures of this field, which have been mapped using surface seismic. data. are strongly **3-D,** leading to complicated seismic wave propagation and suggesting that the 1-D or 2-D methods may be of limited applicability. Modeling experiments show that even with the limited source distribution of the Colla 2 experiment, 3-D resolution of a hypothetical point scatterer is theoretically possible. However, application of the migration to the observed VSP data is difficult due primarily to noisy data and varying source site conditions. Thr images are improved by performing a *weakly* 3-D migration allowing limited lateral propagation in a 3-D model.

1. INTRODUCTION

An extensive geophysical investigation of the Larderello gcothermal field has been carricd out for a number of years to characterize and evaluate especially the deeper. port ions of the reservoir (e.g., Batini *et al.,* 1983; Batini *et al.*, 1991; Block, 1991). This project, has included several seismic surveys, utilizing both conventional surface methods and vertical seismic profiling. One of the principle objectives of this research effort has been to identify and locate fracture zones which may be controlling the flow of subsurface fluids, since the permeability associated with such fractures will havc an important influence on the movements of steam in the geothermal system. Gibson *et al.* (1993) performed a modeling study with this specific objective. A vertical seismic profile (VSP) experiment had bccn conducted in the Larderello field, in the Badia 1A well, in ordcr to evaluate the deeper portions of the reservoir. Reflections originating from below the depth of the well were identified in the data, and it was suggested that they were caused by a fractured region at a depth of approximately 3.3 km. Beginning with the hypothesis that these reflections came from such a fracture zone distributed over a depth range of approximately 0.2 km, the ray-Born method was successfully applied to niodel the waveforms using a 3-D simulation (Gibson *et al.*, 1993). This method uses 3-D ray tracing to synthesize wave propagation in a smoothly varying background medium and the Born approximation to estimate the amplitudes of waves scattered by the small, localized fracture zone.

When additional VSP data were recently obtained in the Colla 2 well, located very close to the Badia 1A wcll. we began with a ray-Born modeling similar to that used to explain the reflections observed in the Badia 1A VSP data (Cameli *et al.*, 1994). While the modeling was able to explain some of the larger reflections, it can be a fairly subjective analysis. anti wc chose to explore the application of migration to infer the locations of subsurface reflectors. Because of the extensive seismic exploration in this geothermal field, maps of the shallow geological structures are available, and these maps show that the interfaces are strongly 3-D. There are two principal layers in the upper portion of the geologic section, and these laycrs are underlain by a rather thick metamorphic formation which has relatively constant seismic velocity (Figure 1). Because the of this highly heterogeneous structure, application of typical 1-D or 2-D migration or modeling algorithms will not likely give completely satisfactory estimates of tlie locations of subsurface features. In this area, the shallow interfaces can cause ray paths to deviate strongly from the trajectories that would be followed in a simpler medium (Gibson et *al.*, 1993). The strong deviation of the well exaggerates the three-dimensionality of the problem, since the wave propagation can never be accurately considered to take place in any given source/receiver plane (Figure 1).

Hence the major motivation for the work in this paper is to investigate the application of 3-D migration methods to the Colla 2 VSP data, and, as with the modeling, tlie major objective is to infer the locations of the subsurface reflectors that rnay bc associated with fracturing. We first briefly describe the implementation the Kirchhoff migration algorithm arid the data set collected in the Colla 2 VSP. Prior to presenting the migration of tlie data, we show some results froni a modeling study where we compute synthetic data for the known structure using a liypothctical point scatterer. These *tests* confirm that a multioffset analysis of the data should be possible, given high quality data from all four offsets. Since, however, the data is not of uniform quality, the combination of migration results in a direct application of 3-D migration is not extremely successful. Instead, we apply a "weakly" 3-D migration where the imaging volume is relatively narrow in the direction perpendicular to tlie source/well plane. The data from each source are separately imaged. When the resulting images are displayed together in 3-D visualizations. they yield useful information on the distribution of reflective features below the well.

2. MIGRATION METHOD

We apply a migration based on the Kirchhoff integral, an approach frequently applied to VSP data in 2-D settings (e.g., Keho, 1986; Keho and Beydoun. 1988; Dillon, 1988, 1990; Payne *et al.*, 1994). The basic idea of the migration is fairly simple. The travel times from tlie source and the receiver to a point in the subsurface are computed, and then the seismic datum corresponding to this travel tinie for the given receiver is added to the image. The Kirchhoff integral is used to provide a rigorous application of this intuitively

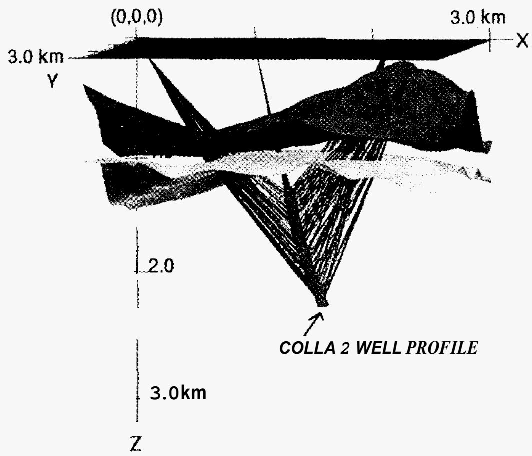

Figure 1: Three-dimensional display of the interfaces defining the two shallow sedimentary layers in the area of the Colla 2 well. Also shown are the 1'-wave ray paths from each of the four source positions to the receivers. There were 41 receivers used in the experiment, and they were evenly distributed (every *25* m) along the portion of the well profile indicated by the thick tube in the figure. This section of the Colla 2 well extends from 1.16 km to 2.16 km in drpth. The model is 3 km in each horizontal dimension, and no vertical exaggeration is applied in this figure.

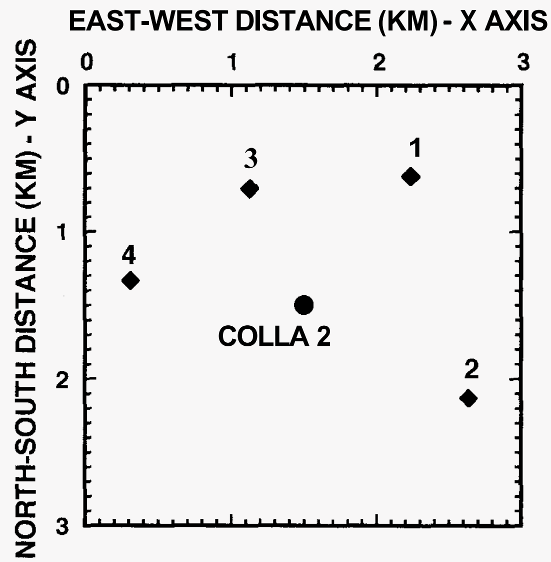

Figure 2: Locations of the four source offsets (the diamond symbols) used in the Colla 2 VSP experiment. These source positions can be seen relative to the 3-D map of the shallow geologic structures and the receiver locations in Figure 1.

reasonable approach, as it provides weight factors based on the displacement fields at the imaging point. In extended these methods to 3-D applications, we follow Keho and Beydoun (1986) (see also Keho, 1986), utilizing the elastic wave Kirchhoff integral to perform the migration and employing paraxial ray tracing the compute the Green's tensors for the background model used to perform the migration. Since 3-component geophones were nsed in the Colla 2 experiment, the elastic wave formulation of the migration allows us to take full advantage of the polarization information in the data. By taking the amplitude of the migrated wavefield relative to that of the incident wavefield generated by the source, we compute a pseudo-reflectivity distribution that is the final result of the migration.

The paraxial ray tracing algorithm allows a relatively quick and efficient means of computing the arrival time, polarization and amplitude for rays propagating from a given source point to a general location in a specified earth model (Červený, *1985).* This is because the paraxial approach computes the wavefront curvature as well as ray path location and travel time. 'This extra effort allows not only a computation of the ray amplitude, the geometrical spreading, but it also can be used to extrapolate known travel time and amplitude information from the ray to nearby locations. Since the migration requires that this information be available for waves propagating from the source to a large, 3-D volume of subsurface points (i.e., the imaging volume), this is a particularly valuable feature. For **a** given ray passing through the image volume, the time and polarization can be extrapolated from the ray to a comparatively large number of points in the vicinity of the ray, greatly reducing the amount of computation required.

Our implementation of the migration computes the amplitude and travel time information for all image points prior to applying the data to the image in order for computational efficiently and simplicity. **A** ray is traced through the model until it either reaches one of the boundaries or it reaches some upper time limit based on the time window of interest in the data. Since there is a limit on the distance over which paraxial approximations can be applied (Beydoun and Keho, 1987), the distance from the ray to each lattice point for which the Green's tensor information has not yet been computed must be computed. The paraxial estimates can then he generated only for points sufficiently close to the ray. In a 3-D volume, the number of points to be checked is very large, and this one of the most time consuming stages in the migration. Therefore, we gain additional improvements in computation time by computing the ray tracing quantities on a comparatively sparse 3-D lattice of image points in the model, then interpolating the time and amplitude at these points during the migration step. Using a bilinear interpolation (Press *et al.,* 1988), we have found that the ray tracing lattice can be accurately interpolated by a factor of up to approximately 4 in each of the *3* coordinate directions.

3. DATA

Two Vibroseis sources were used in four source offsets to collect the data (Figures 1, *2).* These offsets were located at distances ranging from 880 m to 1300 m from the well head. The source sweep had a duration of 12 seconds and ranged from 10 to 74 Bz. **A** total of 41 receiver positions were occupied at increments of *25* m in the highly deviated well.

In order to apply the Kirchhoff migration to these data, the upgoing wavefield had to be estimated. We compared median and $f-k$ filtering and found that the two methods yielded similar results, with neither method giving consistently better filtering. Most of the results presented here used the $f-k$ filtered data. **An** example of the upgoing wavefields we obtained is presented in Figure **3,** which displays the vertical component from source offset 4. These data show the best signal to noise ratio out of the four source positions, especially compared to source *2.* Shot point *2* was located in a river valley, and was apparently situated on alluvial sediments which severely attenuated the source energy and reduced the overall frequency content. The spectra from the data of sources 1, *3* and 4 each centered around **30** Hz,

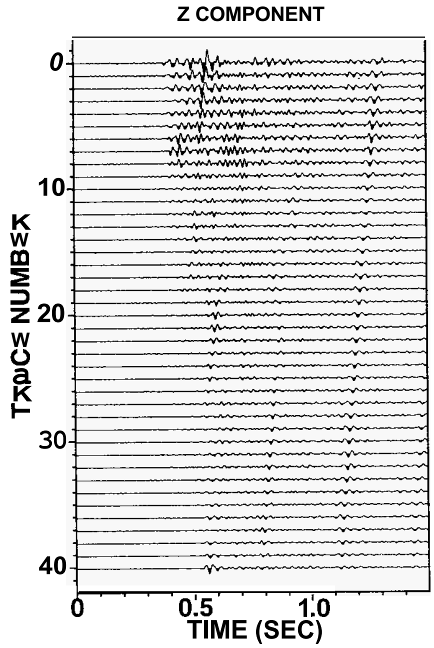

Figure *3:* Vertical component of the upgoing wavefield from source location 4 (Figure 2).

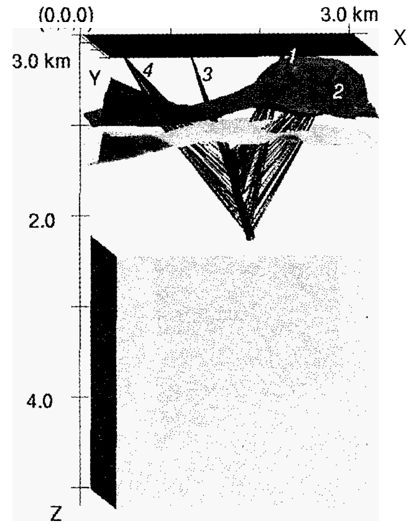

Figure 4: Imaging volume (the rectangular prism) for the migration tests of the point scatterer response.

but the dominant frequency of the data from source 2 was almost half that value. While there is a considerable amount of upgoing energy in the seismograms in Figure *3,* the event seen on lracc 40 at about 1.1 sec is of particular interest, since it is not observed from any other source position. It, is strong enough to be seen on the raw, unprocessed data, whereas each of the other datasets must be filtered bcforc any significant upgoing energy can be detected. Hence, one of the major motivations for detailed analysis of these data is to attempt to explain the origin of this very strong reflection.

We based our velocity models used for the migration of these data on regional velocity information and on modeling the strong downgoing P-waves. Regional investigations have shown that the velocities of the three layers in our model (Figure 1) increase with depth. In modeling the P-waves, we found that it was impossible to adequately reproduce the first arrival travel times with the same model for each source point. This is most likely caused by the strong lateral variations known to occur in the most shallow layer, so in migrating the data, we varied the velocity of this shallow layer to match the arrival times of the downgoing P-waves. This velocity varied around 4 km/s. In contrast, the velocities of the middle layer and the lower metamorphic layer were held fixed at 5.0 km/s and 5.6 km/s, respectively.

4. 3-D MIGRATION TEST: A POINT SCATTERER

In order to test whether **3-D** migration analysis would be feasible given the source configuration in the Colla 2 VSP experiment, we performed some tests using synthetic data for a point scatter located below the well. The scatterer was located within the imaging volume shown in Figure 4, which ranges from 0.1 to 2.9 km in the x and y directions (Figure 2). and from 2.9 to 5.0 km in depth. The coordinates of the point scatterer were x = 1.22 km, y = 1.49 km, and z =3.1 km. Synthetic seismograms were computed using the source and receiver configuration utilized in the experiment, and the 3-D background model in Figure 1. **A** source wavelet with a frequency of 20 Hz was applied. This wavelet corresponds to a wavelength of 0.28 km in the metamorphic formation. The four resulting synthetic data sets were migrated separately and the images were stacked **lo** produce the total image. The reflectivity was computed at a spacing of 0.056 km in the x, y and z directions. yielding a total of 132651 points. This imaging analysis was therefore a highly three-dimensional application of the Kirchhoff migration. Figure **5** shows a vertical and horizontal slice through the final pseudo-reflectivity image, demonstrating that. in principle a **3-D** migration can successfully image relatively small features in the subsurface, although there are some artifacts visible.

Another test that we performed considered the possibility of approximating the **3-D** structure with a 1-D model. Examining the ray paths from any one ol the sources in Figure 1, it appears that the ray paths intersect the two upper interfaces in a region of fairly small lateral extent. This suggests that it might be possible to approximate the model with planar interfaces at the depths where the rays intersect the actual structures. However, when we applied such a 1-D approximation, the migration results for the synthetic point scatterer were noticeably mislocatcd. While it might be possible to achieve a better 1-D or 2-D approximation with enough effort in estimating the approximate model, this comparison demonstrated that when 3-D effects are as strong as they are in the Larderello field, appreciable error can arise in attempting to make such approximations. In addition, it would be fairly tedious *to* derive a useful equivalent model for each of the source locations since they would have to be quite different.

5. MIGRATION OF FIELD DATA

Not surprisingly, the applicaliori of the Kirchhoff migration to the field data yielded less satisfactory results than the point scatterer, largely due to the strong variations in data quality from offset to offset. When the signal to noise ratio decreases, a combination (stackingj of images from different source locations does not produce a very satisfactory result. This problem was exacerbated for the Colla 2 data by the extremely low frequency content of the data from source 2. In practice, therefore, using the migration to obtain a composite image requires either a very consistent quality of data in order to have the images combine to yield a useful

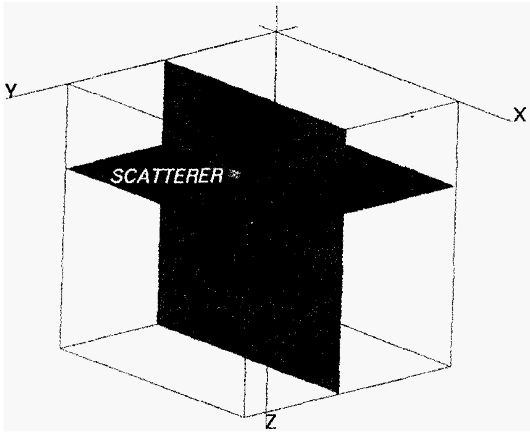

Figure 5: A vertical arid horizontal slice through the imaging volume for the point scatterer test. This grey scale image displays the reflectivity estimate in the imaging volume shown in Figure 4. By combining the data from the four source locations, we are able to obtain a fairly good estimate of the scatterer location (the bright area just, to the right, of the word "scatterer") though some migration artifacts are visible.

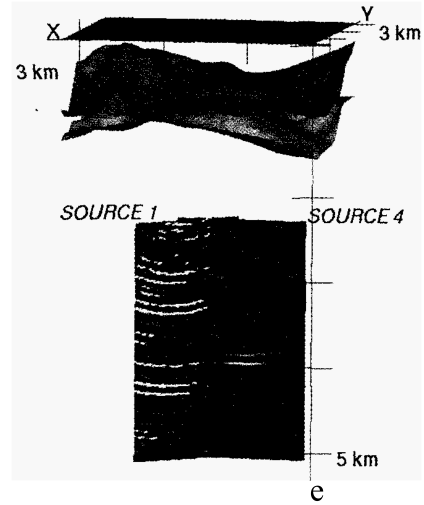

Figure 6: Migration results from source locations 4 arid I. The migration images are displayed in vertical planes containing the source and the Colla 2 well head. The two migration images intersect. along a vertical line directly underneath the well head. Note that the viewpoint, of this figure is on the opposite side of the model from that of Figure 1, so that the relative positions of sources 4 arid 1 are reversed. The energy corresponding to the strongest reflection in the data from source 4 (Figure 3) is imaged at about 3.85 km in depth.

combined result, or else a larger number of source positions must, he utilized to achieve higher data redundancy.

In order to effectively apply a 3-D migration analysis. arid to avoid having to estimate many equivalent 1-D or 2-D background models, we assumed that the wave propagation from any one of the sources down to the receivers took placr in a volume that, though 3-D. was still relatively narrow in the direction perpendicular to the plane containing source and the well head. Kay tracing experiments with hypothetical interfaces showed that this assumption of nearly 2-D wave propagation is fairly good, because the reflection points from model interfaces near the depth of interest: though not by any means contained in a source/receiver plane, were still not too widely distributed. Therefore, the imaging volume was restricted to be fairly narrow in the direction perpendicular to the source/well head plane, thereby defining a weakly three-dimensional migration. This procedure is in essence an extension of 2.5-D migration allowing for slightly 3-D propagation and bending of the rays in the earth model overlying the imaging volume.

Results of this migration procedure for shot points 1 and 4 are depicted in Figure 6. The migration was performed for imaging volumes that extended from the source to just beyond the Colla 2 well head and ranged from 2.2 to 5.0 km in drpth. The width in the direction perpendicular to the source/well head plane varied somewhat from source to source. Image point spacing in the volume was 0.020 km. The migration lattices as shown here are stacked along the narrow dimension of the volume in order to produce this display. A careful interactive analysis using 3-D visualization technologies is able to show the lateral positions within the imaging volumes of the reflection points estimated by the migration analysis. From these results we see that the strong reflection in the data from source 4 (Figure 3) is well imaged, though it is more difficult to see this individual event **in** the source 1 image. It does appear, however, that the event may be present in both images. Since all of the reflections in the data collected from shot point 1 were much weaker than observed from location 4, the migrated image of the source 1 data is plotted with a higher gain, giving it the appearance of containing more reflections. If the gain on the image from shot point 4 were increased, it also would show more events. It should also be pointed out that a color display allows a much better resolution of subtle featnres in these images.

The depth of the major reflector in the source 4 data is estimated to he between 3.8 and 3.85 km from this migration analysis, which is slightly more shallow than our initial estimates usirig modeling (Cameli *et al.*, 1994). Since this analysis uses the waveforms recorded in the experiment and the modeling used a synthetic waveform, a slight miscomparison is not surprising, and the more accurate estimate is probably obtained with the migration. The depth of the K horizon, a major regional seismic reflector (Batini *et al.*, 1983; Block; 1991), is estimated from reflection seismic to be about 4 km in depth at this locality, so it is possible that the reflected energy is generated from this feature.

Migration results from source 3 were very similar to those of source 1. In contrast, the image obtained from shot point 2 was quite poor in comparison to all of the others. This is mainly because of the inferior data quality and could only bc improved by repeating the experiment with a source location outside of the valley that attenuates the source energy.

6. CONCLUSIONS

We have implemented a 3-D Kirchhoff migration algorithm for VSP data analysis in areas such as the Larderello geothermal field, which has a strongly 3-D structure in its upper sedimentary layers. Tests of the migration on synthetic data computed for. a point scatterer show that with good quality data, the method is capable of resolving fairly small features with the experimental configuration used to collect data from the Colla 2 well. These tests also demonstrated that the failure to account for the 3-11 wave propagation can distort images obtained by migration. Given the relatively poor signal to noise ratio of some the field data collected from the four source positions in the Colla 2 experiment, we restricted the application of the migration to imaging volumes that were narrow compared to the source/receiver distance, allowing for weakly three-dimensional wave propagation. The results were best for source 4, and we estimate the **depth** of the major reflecting feature to be ahout 3.85 km. Because we have applied a careful 3-D analysis, this estimate is more reliable than could have been obtained using an estimated approximate 1-D or 2-D model. We anticipate that 3-D migration methods can find useful application in future VSP experiments, especially if the experiments are designed to take advantage of the 3-D processing technologies.

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