Seismic depth imaging of normal faulting in the southern Death Valley Basin

Sergio Chávez-Pérez*, John N. Louie†, and Sathish K. Pullammanappallil**

ABSTRACT

Motivated by the need to image faults to test Cenozoic extension models for the Death Valley region of the western basin and range province, an area of strong lateral velocity variations, we examine the geometry of normal faulting in southern Death Valley by seismic depth imaging. We analyze COCORP Death Valley Line 9 to attain an enhanced image of shallow fault structure to 2.5 km depth. Previous work used standard seismic processing to infer normal faults from bed truncations, displacement of horizontal reflectors, and diffractions. We obtain a detailed velocity model by nonlinear optimization of first-arrival times picked from shot gathers, examine the unprocessed data for fault reflections, and use a Kirchhoff prestack depth imaging procedure to handle lateral velocity variations and arbitrary dips properly. Fault-plane reflections reveal the listric true-depth geometry of the normal fault at the Black Mountains range front in southern Death Valley. This is consistent with the concept of low-angle extension in this region and strengthens its association with crustal-scale magmatic plumbing.

INTRODUCTION

Death Valley is a region of active extension and Quaternary volcanism. It is located in eastern California between the Panamint Mountains on the west and the Black Mountains on the east, within the southwestern portion of the basin and range province (Figure 1). Death Valley is a pull-apart basin developed in a releasing bend of a dextral strike-slip fault system. The northeastern boundary of the basin is controlled by the northern Death Valley-Furnace Creek fault zone and the southwestern boundary is controlled by the southern Death Valley fault zone. The central part of the basin is characterized by normal faulting. The western slopes of the Black Mountains are essentially an exhumed west-dipping normal fault that transfers motion between the two strike-slip faults (e.g., Topping, 1993). Death Valley is therefore an asymmetric half-graben basin.

The data collected by Consortium for Continental Reflection Profiling (COCORP) in this region may have imaged, perhaps for the first time, crustal-scale plumbing associated with a deep magma chamber beneath a pull-apart basin (de Voogd et al., 1986; 1988). Line 9 traverses roughly east-west, subparallel to the direction of extension, while Line 11 runs almost perpendicular to the dominant extensional direction (Figure 1). A dipping event in the time sections of both lines extends from above a prominent midcrustal reflection [identified by de Voogd et al. (1986) as the "Death Valley bright spot"; Figure 1] at about 6 s two-way time to near the surface, at a faulted cinder cone of Quaternary age. de Voogd et al. (1986) suggested this event is a reflection from a magma conduit or feeder dike that has now solidified. Shallow-dipping events to 2 s on Line 9 define a half-graben that appears to be bounded by a listric fault (Serpa et al., 1988).

Interest in fault reflections spans several decades (e.g., Swartz and Lindsey, 1942; Deacon, 1943; Robinson, 1945; Bortfeld and Hurtgen, 1960; A llenby, 1962; Hole et al., 1996). Fault reflections are of fundamental value for the correct positioning in space of the fault planes and optimum stacking of depth migrated shot gathers. There have been very few attempts, however, to image steeply-dipping faults in deep crustal data directly (Louie et al., 1988; Louie and Qin, 1991; Pullammanappallil and Louie, 1993). This is mostly because of the strong lateral velocity variations and the lack of reliable velocity models.

Current debates about the listric (concave upwards) versus planar geometry of normal faults in extensional terranes are
partly caused by the lack of reliable depth images from seismic reflection data. A recent example of this controversy has arisen concerning the geometry and nature of the Sevier Desert normal fault in west-central Utah (Von Tish et al., 1985; Anders and Christie-Blick, 1994). The presence of shallow-dipping normal faults is one of the most important criteria for recognizing extensional regimes (e.g., Shelton, 1984). In fact, substantial extension can only be accomplished by initially shallow faults or by faults that rapidly rotate toward shallower dips as extension proceeds (Wernicke and Burchfiel, 1982).

There has been controversy on the accommodation of crustal extension in the southern Death Valley Basin (e.g., Wright and Troxel, 1973; Wernicke, 1981; King and Ellis, 1990). Faults on seismic sections collected in this region have been inferred from sedimentary bed truncations (Serpa et al., 1988), and not directly imaged; thus, a depth-imaged view of this fault zone is needed. The geometry of the fault plane can only be obtained by depth imaging of the fault reflections.

The bulk of the research using seismic reflection data to investigate basement-involved extensional tectonics is based on time imaging, where lateral velocity variations are not considered. This occurs because depth imaging requires reliable velocity models to migrate reflected refractions and straddle reflections (de Bazelaire and Vialliix, 1994) from steep fault planes into their true position. Motivation for this study comes from the need to directly image fault geometries that cannot be constrained using conventional time sections, and to help lessen the ongoing controversy of how crustal extension is accommodated at depth. Standard time imaging techniques, like the one used by Serpa et al. (1988), provide a good starting point for subsequent depth imaging processing. However, defining fault plane geometries demands a reliable velocity model and detailed prestack imaging including nonhyperbolic fault reflections exhibiting reverse moveout on record sections.

DEPTH IMAGING METHOD

New approaches to prestack depth imaging of land data with complex topography (e.g., Rajasekaran and McMechan, 1995a,b) require only preprocessing, velocity analysis, and
We analyze the COCORP data by following an equivalent processing scheme. We use minimum pre-processing (editing, muting, and trace balancing), a well-constrained velocity model for shallow depths, and Kirchhoff-sum prestack depth migration to image fault-plane reflections. Traveltime computation for the imaging process can thus rely on a very accurate velocity structure to enhance the final migrated product.

**Velocity model**

We modify the velocity profile of Line 9 developed by Pullammanappallil and Louie (1994) by using a simulated-annealing optimization scheme for inversion of first-arrival times. The scheme employs a fast finite-difference solution to the eikonal equation (Vidale, 1988) to compute traveltimes, and it produces a suite of final models with comparable least-square error. This enables us to select and average together the models most likely to represent the geology of the region. This scheme is independent of the starting model and it has the ability to find the global minimum, unlike commonly used linearized inversion techniques.

Pullammanappallil and Louie (1994) analyzed ray coverage through their velocity model and used the standard deviation of a suite of final models having similar error to find out which parts of the model are well-resolved. They used 6213 picks from 281 shot gathers and projected the line geometry onto a straight line, maintaining the source-receiver offsets of the actual survey (Figure 2). We refined this well-constrained velocity model (to 2.5 km depth) by decreasing the grid spacing during optimization to improve resolution. Optimization with a grid spacing of 25 m took about 12 CPU hours on a Sun Sparc10 computer.

Line 9 runs from the Panamint Range in the west to the Greenwater Valley in the east (Figure 2). The prominent low-velocity region (1.8 to 2.4 km/s) in the optimization result corresponds to the southern Death Valley sedimentary basin. Beneath the basin, velocity increases to 4.5 km/s at 2.5 km depth (with respect to the datum at an elevation of 305 m). Below this depth, velocity increases to 5.5 km/s. The optimization scheme reconstructs higher velocities (4 km/s) at the Black and Panamint mountains, which we correlate to igneous or metamorphic rocks observed at the surface. The velocities and depths of the basin in this section are within 10% of those obtained by Geist and Brocher (1987) with iterative forward modeling using ray tracing and least-squares inversion. Velocity error increases to 0.5 km/s at 2 km depth below the mountains, but remains good down to 4 km beneath Death Valley.

**Kirchhoff prestack depth migration**

Data preprocessing before migration includes surgical muting to remove refracted arrivals and retain all other events, and trace equalization. We equalize using the first 4 s of the 16 s correlated traces. True amplitudes are normalized so that the mean-squared amplitude over the 4 s is the same for all traces.

A practical approach to image steeply dipping reflectors in this area of strong lateral velocity variations and crooked acquisition geometry is Kirchhoff migration. Its speed and flexibility in handling 3-D source-receiver geometry as compared...
with other techniques (e.g., reverse time and least-squares migration) is a main advantage of this application. The Kirchhoff prestack depth migration method we use is similar to that of Louie et al. (1988) and Louie and Qin (1991). The migration is a back projection of assumed primary reflection amplitudes into a depth section. It has been identified in Le Bras and Clayton (1988) as the tomographic inverse of the acoustic wave equation under the Born approximation in the far field using WKBJ rays for downward continuation and two-way reflection traveltimes for the imaging condition.

Because the back projection requires knowledge of the source wavelet for crosscorrelation with each seismic trace, we approximate this roughly by crosscorrelating with a boxcar function 0.4 s long. The net effect of this is to smooth the migration, center the reflection pulses, and avoid aliasing (Lumley et al., 1994). We compute first-arrival traveltimes with Vidale’s (1988) finite-difference solution to the eikonal equation, as the migration algorithm is similar to the two-eikonal method described in Reshef and Kosloff (1986). Each image is obtained by summing the data at traveltimes computed through the detailed velocity model, and the final result is obtained by stacking the migrated partial images for each gather. The final migrated image might be improved by velocity smoothing trials to further stabilize the traveltimes needed by Kirchhoff migration, by including an operator anti-aliasing criterion, by obtaining a reliable estimate of the source wavelet, or by low-pass filtering after migration (to remove artifacts).

To illustrate our reconstruction of fault-plane reflections, Figure 3 shows observed and synthetic shot gathers (computed with the fourth-order finite-difference solution of the full-wave acoustic wave equation described in Vidale, 1990) for VPs 531 and 554. Note that the fault reflection exhibits reverse moveout. Figure 4 shows the corresponding depth migrations of the observed and synthetic shot gathers of Figure 3. The fault-plane

![Figure 3](image-url)
reflections are labeled. Stronger reflections, like those of the fault plane, migrate more coherently than weaker ones.

RESULTS

Two aspects of the interpretation of Line 9 by Serpa et al. (1988) have been criticized in Smithson and Johnson (1989). First, the west-dipping listric fault they depicted is not imaged in their seismic section (Figure 5a); second, its surface projection, which coincides with the approximate trace of the Death Valley fault zone and a faulted cinder cone (Figures 1, 5b), may be pure coincidence. Our prestack migration result did not reveal the details of basin stratigraphy seen typically in conventional time or poststack depth imaging. Neither did it reproduce the shallow layered structure interpreted as a late Cenozoic basin deposit. However, it directly images in true depth (Figure 6a) the fault plane inferred by Serpa et al. (1988).

A part from the fault-plane geometry, Figure 6a also shows an enhanced depth image of the basin bottom. Strong, positive reflectivity spots (black arrows) clearly depict the bottom of this half-graben. Note how stronger reflections, like those of the fault plane, migrate more coherently than weaker ones. This influences the overall quality of the migrated image. Artifacts appear as elliptical trajectories that degrade image quality and resolution, mostly beneath the basin bottom. This occurs because of the sparse receiver (near offset 500 m, station spacing 100 m) and source coverage in the deep crustal data designed for much deeper targets.

Common-offset migration is a commonly used, intuitive and physically oriented validation test for migrated images in the context of migration velocity analysis. In our case, we have found, based on previous work with similar crustal scale data (e.g., Louie and Qin, 1991), that the Bayesian statistical method of Harlan et al. (1984) is a good indicator of the validity of the migrated images. Our validity check is to use Harlan’s non-Gaussian entropic measure from amplitude histograms of transformed data and of transformed “noise” (artificially incoherent data) to determine which migrated structures are real and which are artifacts (Figure 7a). This is done by remigrating the data after destroying coherence by randomly flipping the signs of data traces.

We obtain an image that displays migration artifacts from incoherent prestack data (Figure 7b). Then, we scale the raw migration by Harlan’s focusing measure at each image point (Figure 7c) to give a section that displays the principal events from coherent data. Following this procedure, the focused migration shows that the fault plane is not an imaging artifact (Figure 7d), nor an unknown structure below the basin, despite the loss of definition of the basin geometry.

DISCUSSION

The aim of our depth imaging methodology is to determine the geometry and the location of fault planes not shown but inferred by conventional time sections. We have achieved this in our images. However, our prestack migration result did not bring out all the details of basin strata seen in conventional time or poststack depth imaging, and it did not reproduce all the shallow layered structure interpreted as a late Cenozoic basin deposit (Figure 5b). This results mainly from masking of the signal by migration artifacts, sideswipe reflections, and lateral smearing of a complex 3-D velocity model, simplified into a complex 2-D velocity model.

We carefully reprocessed the records to corroborate Serpa et al.’s (1988) stacked section and found no clear evidence of some of the dipping events they used for their interpretation. For instance, their dipping event “A” (Figure 5a) resembles the case where muting is not properly done, or not done at all, to reject refracted arrivals from complex areas near faults.

![Fig. 4. Depth migration of the observed and synthetic shot gathers of Figure 3. (a) Shot gathers for source at VP531 and VP554. (b) Depth migration of the synthetic shot gathers assuming the source is located at VP531 and VP554. Note that some of the artifacts seen in the migration of the observed gathers are also observed in the migration of the synthetic gathers. Ellipses depict approximate locations where the fault-plane geometry and basin bottom are defined. Vertical exaggeration is 2.](image-url)
Our reprocessed stacked section (not shown) only defines basin strata and basin-bottom geometry. Abundant crustal time sections in the basin and range province have allowed researchers to delineate planar steeply dipping, listric, and subhorizontal low-angle normal fault geometries exhibiting several styles of extension (e.g., Wernicke and Burchfiel, 1982; Anderson et al., 1983; Cheadle et al., 1985, 1986; Okaya and Thompson, 1985; Von Tish et al., 1985; Thompson et al., 1989). Faulting has usually been inferred from the correlation of reflectors with mapped faults, and from bed truncations and displacement of horizontal reflectors and diffractions. Our results are unique in the sense that, to the best of our knowledge, this is the first time fault-plane geometry has been defined directly in the western basin and range province, accounting for lateral velocity variations and reverse-moveout fault reflections.

The nonplanar geometry of the fault (Figure 6a) is consistent with the concept of low-angle extension in the region and strengthens de Voogd et al.'s (1986) association of listric normal faulting with a proposed magma conduit traced to the surface location of a cinder cone. The fault clearly dips west, but our west-east section shows somewhat of an apparent dip for this north-northwest striking fault. The section may be exhibiting many subsidiary faults quite obliquely, with the possibility that we are looking at apparent dip of out-of-plane reflections. de Voogd et al. (1986) proposed, in addition, that the fault may dip down to the north to meet a midcrustal reflection bright spot, at a depth of approximately 15 km. The imaged fault (Figure 6b) dips at about 50° near the surface and flattens to less than 30° with depth. Its trend implies it would be roughly subhorizontal at about midcrustal depths (10 km), as to define a crustal detachment (Wright and Troxel, 1973).

Our work underscores the need for a combined depth imaging approach that uses the strengths of each method to enhance image quality. For instance, we could obtain a ballpark estimate of extension and depth to detachment by using poststack depth migration to image basin stratigraphy, complement the prestack results, and validate the geological plausibility of the depth images. This would allow us, in principle, to determine the angular relationship between shallow basin stratigraphy and the fault plane, and to construct the fault profile using hanging-wall rollover geometry (Rowan and Kligfield, 1989; Dula, 1991) with the aid of simple structural balancing techniques.

CONCLUSIONS

Our analysis demonstrates a two-step methodology (tomography and prestack depth imaging) for true depth processing of fault reflections to define fault plane geometry and depth in a complex land data set. Depth imaging of structures in the southern Death Valley Basin from COCORP
Fig. 6. (a) Our enhanced depth image and (b) depth interpretation of the basin and the fault plane. QB indicates the surface position of the faulted 690 000-yr-old basaltic cinder cone. Note the changes in topography. Vertical exaggeration is 2.

Line 9 shows a west-dipping basin-bounding listric normal fault (Black Mountains range-front fault) and a well-defined half graben basin bottom (Death Valley). This is the first true-depth image of a listric normal fault plane in the western basin and range province that accounts for strong lateral velocity variations. Its geometry is consistent with the concept of low-angle extension in the region and strengthens the association of listric normal faulting with a proposed magma conduit traced to the surface location of a cinder cone.

ACKNOWLEDGMENTS

The first author acknowledges financial support by CONACYT, Mexico’s National Council for Science and Technology. This work was also funded in part by the U.S. National Science Foundation, grant no. EAR-9405534. Glenn Biasi, Raymon L. Brown, Mark Stirling, and Serdar Özalaybey provided useful criticism and suggestions. Ernie Hauser kindly provided COCORP field records and locations from Death Valley. We also thank Julián Cabrera, William S. Harkan, and Reinaldo J. Michelena for their helpful reviews.

REFERENCES


Geist, E. L., and Brocher, T. M., 1987, Geomtery and subsurface lithology of southern Death Valley Basin, California, based on refraction analysis of multichannel seismic data: Geol., 15, 1159–1162.


