Numerical modeling of a fractured medium

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ABSTRACT

Fractures play an important role in hydrocarbon production. A fractured layer often induces a transverse anisotropy with a horizontal symmetry axis (HTI) layer in response to seismic wave propagation. We have created numerical 3D seismic data from a fractured model, using a 3D finite-difference anisotropic program called TIGER. The effect of the fractured layer on the seismic response has been examined, and it is observed that the HTI medium affected the amplitude and travel time of both P- and S-waves. P-wave amplitude is highest in the direction of fracture strike. The TIGER code was able to create an accurate 3D dataset with minimal dispersion. The investigation of synthetic data for a fractured layer will help in fracture detection and estimation from surface seismic data. This model will be used to calibrate a common-angle migration algorithm, whose purpose is to generate common-angle gathers essential in an amplitude-versus-angle and azimuth (AVAZ) analysis, an effective method in fracture detection.

INTRODUCTION

The increasing demand for oil and gas makes geoscientists put a great deal of effort into the exploration of different kinds of hydrocarbon reservoirs. Many of the reservoirs, such as carbonates, tight clastics, and basement reservoirs, are often fractured. Naturally fractured reservoirs hold large hydrocarbon resources and represent attractive economic targets in exploratory ventures. In many parts of the world, including the Middle East and Mexico, fractured reservoirs account for the bulk of production. In other areas, such as the Rocky mountain region of North America, fractured reservoirs that were once considered unconventional hydrocarbon resources are now quickly becoming mainstream. It is important to determine the effect of natural fractures in fractured reservoirs as early as possible so that our evaluations and planning can be done correctly from day one.

Fractures play important roles in hydrocarbon production. They may have a positive or negative impact. They can provide pore space in reservoir rocks to hold oil and gas in place, and also increase the permeability of the reservoir rocks so oil and gas flows easily to well bores. On the other hand, cemented or mineralized fractures may act as barriers to fluid flow. Consequently, the distribution and orientation of fractures are important to geophysicists, geologists and reservoir engineers when evaluating the reservoir and making development plans. In exploring, developing, or evaluating a fractured formation, the zones of highest fracture intensity (closest fracture spacing) must be found and penetrated (Nelson, 2001). To have the best way to produce oil, the production wells should be drilled perpendicular or slanted to the fracture orientation; wells parallel to fracture orientation will miss fractures. Therefore, the knowledge of fractures orientation and intensity helps in finding optimal drilling locations and predicting the production rates of new wells.

Characterization of natural fractures relies on direct and indirect sources of information. Fractures can be measured directly by logs (such as FMI) or by checking core samples, but only providing information around the well bores. The 3D seismic can provide indirect information on fractures intensity and orientation. When seismic waves travel through or reflected from the boundaries of fractured layers, the fractures will leave fingerprints in the seismic data. Generally speaking when seismic waves travel through or reflected from the fractures zone, the fractured rocks will affect the amplitude and travel time of both P- and S-waves. This provides an opportunity to extract the fracture information from seismic waves by measuring the amplitude and/or velocity anisotropy (Zheng, 2006). Historically, shear wave splitting (seismic birefringence) has been a diagnostic, informative and easily observable evidence of fractures (Crampin and Chastin, 2003). In addition to shear wave splitting in the mid 1990's, it began to be shown that there are measurable differences in the seismic AVO responses parallel and perpendicular to fracture orientation, suggesting that AVAZ would be a viable technology (Gray, 2008). AVAZ is useful for determining main fracture strike, fracture intensity and sometimes the types of fluid in fractures.

To examine the natural fractures, some basic geological aspects of naturally fractured reservoirs are reviewed. Regardless of the origin of the fractures, natural fractures are always vertical or near-vertical to the bedding layers. Major geological stress direction causes a dominant fracture orientation. Then, the effect of fractures on seismic response is reviewed. Fractures induce seismic azimuthal anisotropy to seismic data. A fractured layer acts as an HTI layer in response to seismic wave propagation. Finally, an HTI model is constructed, and a numerical 3D seismic data from this HTI model is created. With a known fracture intensity and orientation, the changes in amplitude and time are being investigated.

FRACTURES: GEOLOGICAL OVERVIEW

A natural fracture is defined as a macroscopic plane discontinuity that results from stresses that exceed the rupture strength of the rock (Stearns, 1994). Virtually all reservoirs contain at least some natural fractures (Aguilera, 2003). From a geologic point of view the fractures can be classified as tectonic (fold and fault related), regional and contractional, and surface related (Aguilera, 2003). Regardless of the origin of the fractures, natural fractures are always vertical or near-vertical to the bedding layers; however, depending on the origin of the fractures, they have different patterns. Fold and fault related fractures have x-patterns (Figures 1-a and 1-b), regional and contractional fractures have orthogonal patterns (Figure 2), and surface-related fractures due to dry-out have polygonal patterns.

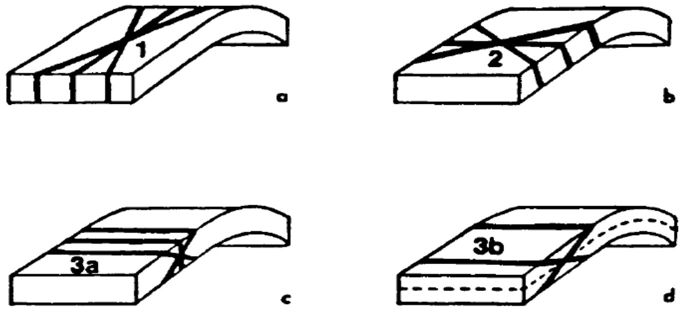

FIG. (1-a). A generalization of dominant fold-related fracture sets (Nelson, 2001).

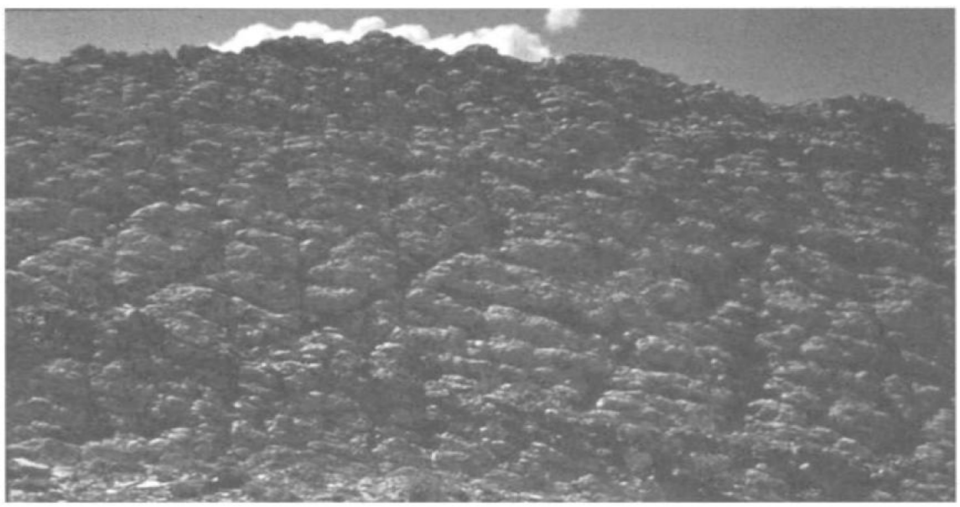

FIG. 1-b. Tectonic fold-related fractures expressed on the bedding surface of Black Canyon anticline in the Rocky Mountains Foreland near Rawlins, Wy. Field of view: 20 ft (Nelson, 2001).

FIG. 2. Orthogonal regional fractures in Devonian Antrim shale, Michigan Basin (Nelson 2001).

Fracture strike or orientation is the direction of a fracture face. For fold and fault related fractures the average direction of the x-pattern is considered the fracture strike. In geological field observations of the regularity of the fractures appearing in outcrops (fold and fault related), it might seem that fracture orientation is random, but measurement confirms a dominant fracture strike related to the major stress direction in the field.

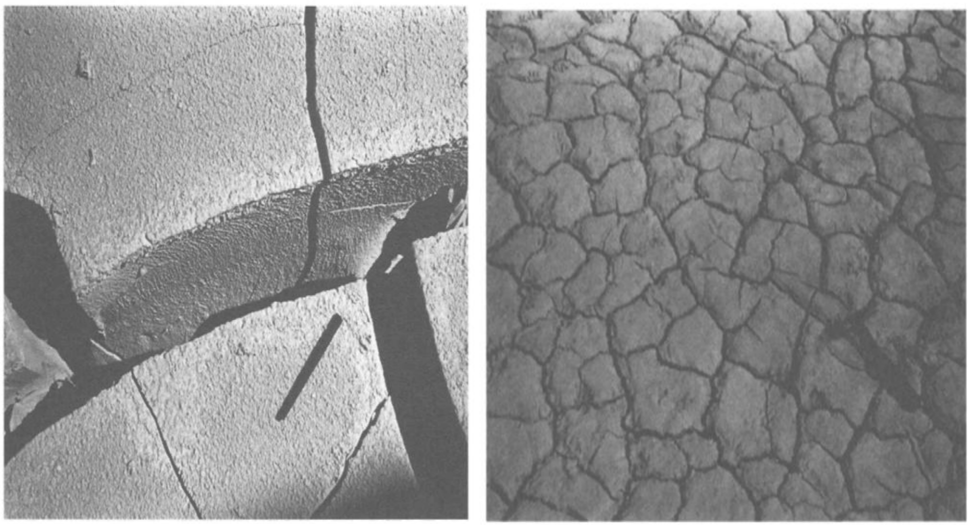

FIG. 3. Surface-related fractures. The left photo is a zoomed portion of a small part of the right photo (Nelson, 2001).

FRACTURE GEOPHYSICAL POINT OF VIEW

The presence of fractures gives a rock a greater strength in directions parallel to the fracturing compared with the perpendicular direction (Bale, 2006). With respect to seismic wave propagation, this makes for a variation of the seismic velocity with direction for both P-wave and S-waves in a fractured layer. Seismic waves travels faster in the direction of the fracture strike, thus the effect of fracture in seismic response is detected as a velocity anisotropy effect. This effect of fractures on seismic velocity is equivalent to transverse anisotropy (TI) with horizontal symmetry axis, known as HTI anisotropy. The plane parallel to the fractures strike is the isotropic plane, and the vertical plane perpendicular to the fracture strike is known as the symmetry plane, see Figure 5. Generally speaking, waves propagating parallel to the fracture strike (isotropic plane) experience travel with a higher velocity, than waves parallel to the symmetry plane (Bale, 2006). S-waves polarized parallel to the fracture strike propagate faster than S-waves polarized orthogonal to it (Bale, 2006).

When seismic waves travel through or are reflected from the fractures zone, the fractured rocks will affect the amplitude and travel time of both P- and S-waves. This provides an opportunity to extract fracture information from seismic waves by measuring the amplitude and/or velocity anisotropy (Zheng, 2006). Having a known fractured medium in term of fracture intensity and fracture strike, and studying its seismic response helps in quantitively study of fractures. To investigate the seismic response of a fractured layer, a numerical model has been generated for a fractured layer. We have created a numerical model involving HTI anisotropy, and compared its seismic response to the response of an isotropic model using a 3D anisotropic numerical model implemented in commercial software called TIGER.

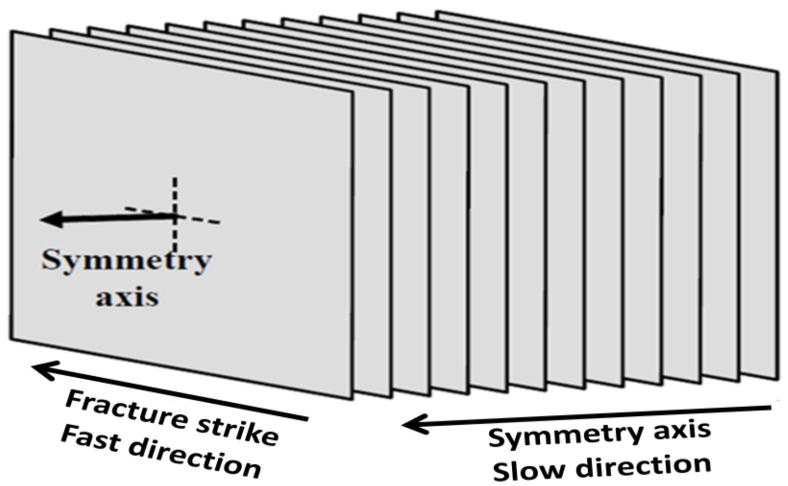

FIG. 5. (Courtesy of Bale (2006)) Schematic depiction of an HTI medium. The presence of vertical fractures causes different strengths of the rock parallel and perpendicular to the fractures.

NUMERICAL MODELING BY TIGER

The numerical modeling has been done using the 3D modelling software Tiger, by SINTEF Petroleum Research of Trondheim, Norway. This application is a very full-featured and technically sophisticated 3D finite difference modelling program for acoustic, elastic or visco-elastic media with or without anisotropy. Tiger uses 8_{th} order spatial differencing and, presumably, second order in time. The application is parallel aware and able to distribute the computation of individual shot records across a Linux cluster. (A single shot record is not run in parallel.) CREWES has successfully used TIGER since 2008 and currently has a three-seat license. In 2008, CREWES has successfully tested the acoustic and isotropic elastic capabilities for 3D modeling of a Canadian channel and reef structure model (Margrave and Copper, 2008). This HTI modeling is a next step in research toward creating geological models in CREWES.

Tiger is essentially a batch UNIX program with a rudimentary GUI front-end that builds the necessary job files. The documentation is minimal, and a considerable amount of technical knowledge is required to install and run the program. Running Tiger requires preparation of 3D volumes for each elastic parameter as disk files in a format that Tiger understands. Formats include SEGY, SU, and DIR. Since we developed our model in Matlab, it was a fairly simple matter to write a MATLAB function that outputs our model in SU format. In addition to the isotropic elastic parameters (P and S velocities and density) which we supplied, Tiger can also accept 3D volumes of Thomsen anisotropy parameters, polarization and azimuthal angles, and P and S quality factors. Once datasets have been loaded, then Tiger requires a wavelet, either created or imported, and a source/receiver geometry specification. The TIGER code has been implemented for general source and receiver geometry. Receivers can be placed in any arbitrary plane, such as an ocean-bottom or wellbore plane. The final step is to specify and quality-control the parameters of the simulation. An automatic stability and dispersion analysis can be run to help choose optimal parameters. Boundary reflections can be suppressed by the perfectly matched layer (PML) or absorbing boundary technique. The HTI scheme is not activated for PML boundary conditions yet, therefore for HTI modeling the absorbing boundary option is chosen.

TIGER INPUT PARAMETERS

To investigate the seismic response a of fractured layer, we used a layer with HTI anisotropy in between isotropic overburden and bottom layers. Figure 5 shows the velocities and density logs used for this modeling; the S-velocity log is calculated from a P-velocity log using the Mudrock relation ($V_P = 1360 + 1.16V_S$, velocities in m/s), while the density log is calculated using Gardner's relation ($\rho \approx V_P^{1/4}$, density in kg/m^3). Our 3D earth model consists of horizontal layers, a vertical slice of the velocity model is shown in Figure 6. The HTI layer is 200 m thick and located at the depth of 800 m. The Thomson parameters for the HTI layer are, $\varepsilon = 0.15$, $\gamma = 0.1$, and $\delta = 0.35$; the axis of symmetry is $90°$ azimuth, parallel to x-direction, see Figure 7.

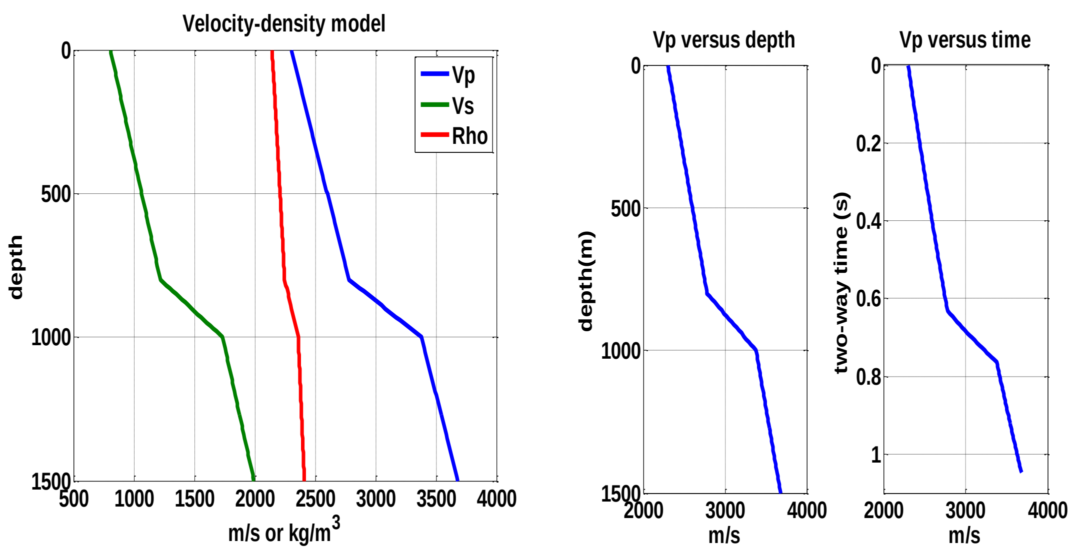

FIG. 5. (Left) The velocity and density log. (Right) The P-velocity log, displayed in both depth and 2-way P-wave vertical traveltime.

The TIGER code includes subroutines for transversely isotropic media with vertical and general tilted symmetry axis. The 3D finite-difference scheme is general and can be applied to any anisotropic symmetric system. For our model, we used a "GIT" scheme which is anisotropic elastic TI with a general tilted symmetry axis. In TIGER, a general tilted TI medium is defined by six physical parameters: density, vertical P-and S-wave velocities, and Thomson parameters δ, ε and γ. The Thomson parameters are defined relative to the direction of the symmetry axis. In addition, two angles are needed to give the orientation of the symmetry axis.

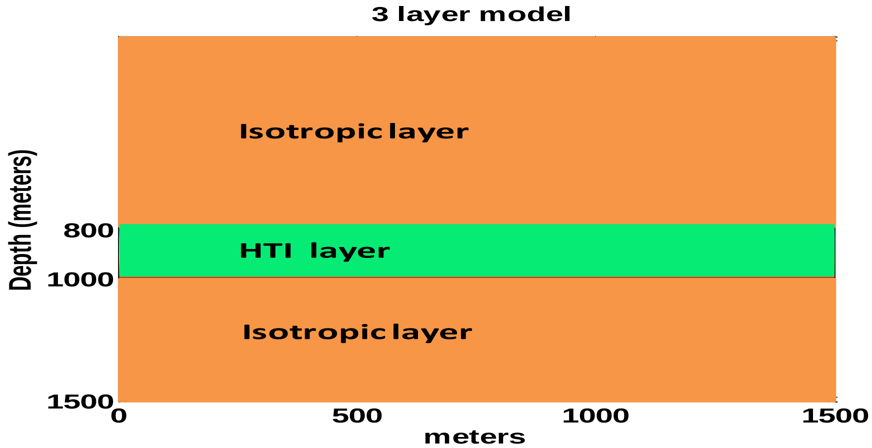

FIG. 6. Our 3D earth model, consisting of a horizontally layered isotropic medium overlaying and underlying a horizontal HTI medium with an axis of symmetry at 90° azimuth.

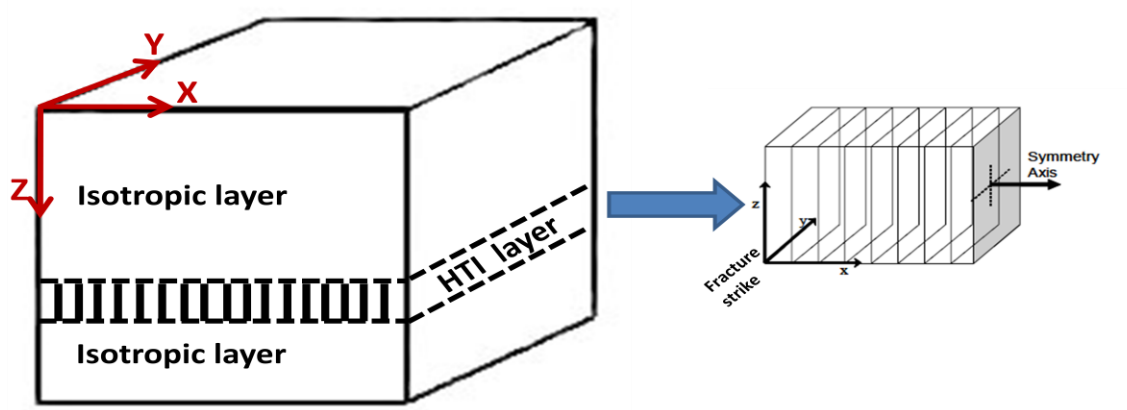

FIG. 7. Three-layer model consisting of the isotropic mediums overlaying and underlying an HTI layer with axis of symmetry at 90° azimuth (parallel to the x-direction), and the fracture strike parallel to the y-axis. The 3D model is $1500m \times 1500m \times 1500m$, the HTI layer is 200 m thick and located at a depth of 800m.

layer	z (m)	average ρ (kg/m^3)	average V_{P0} (m/s)	average V_{S0} (m/s)	δ	ε	Γ	θ (deg)	φ (deg)
1	0	2200	2500	1000	0	0	0	0	0
2	800	2300	3000	1400	0.35	0.15	0.1	90	90
3	1000	2400	3500	1800	0	0	0	0	0

Table. 1. Parameters of the horizontally layered 3D earth model. θ is the polar angle (with z-axis), and Φ is the azimuth angle of the symmetry axis. Velocities and Thomson parameters are defined relative to the direction of the symmetry axis.

TIGER was run for the described 3-layer model; the schematic view of the model of size ($1500\ \mathrm{m} \times 1500\ \mathrm{m} \times 1500\ \mathrm{m}$) is illustrated in Figure 7. The size of the model grid is $150 \times 150 \times 150$ nodes, and the node spacing is $\Delta x = \Delta y = \Delta z = 10.0$ m. The model parameters are given in Table 1. The source time function was a Ricker wavelet with a maximum frequency of 30 HZ. The source was located in the corner of the *xy*-plane at a depth of 10 m. Receivers were located at the surface, in an orthogonal grid of ($20m \times 20m$). Both the inline and crossline direction consisted of 74 receivers.

NUMERICAL MODELING DATA OF FRACTURE MODEL

The resulting 3D data for the HTI model is of excellent quality. Figures 8-10 show the z-component, x-component, and y-component of the common-shot seismograms recorded at y-offsets of 0 m, 750 m, and 1500 m.

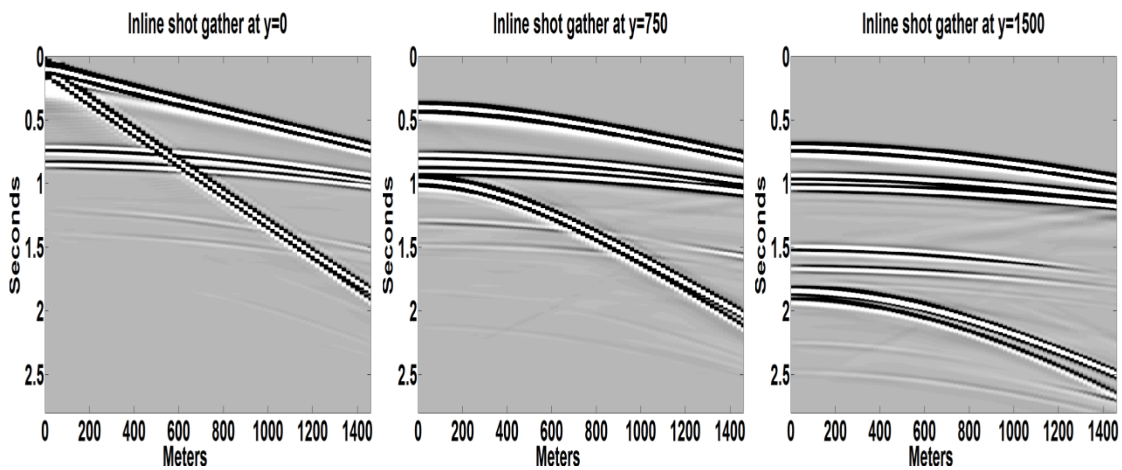

FIG. 8. HTI 3D elastic finite-difference modeling. Z-component of common-shot seismograms at y-offset of zero (left), 750m (middle), and (right) 1500m.

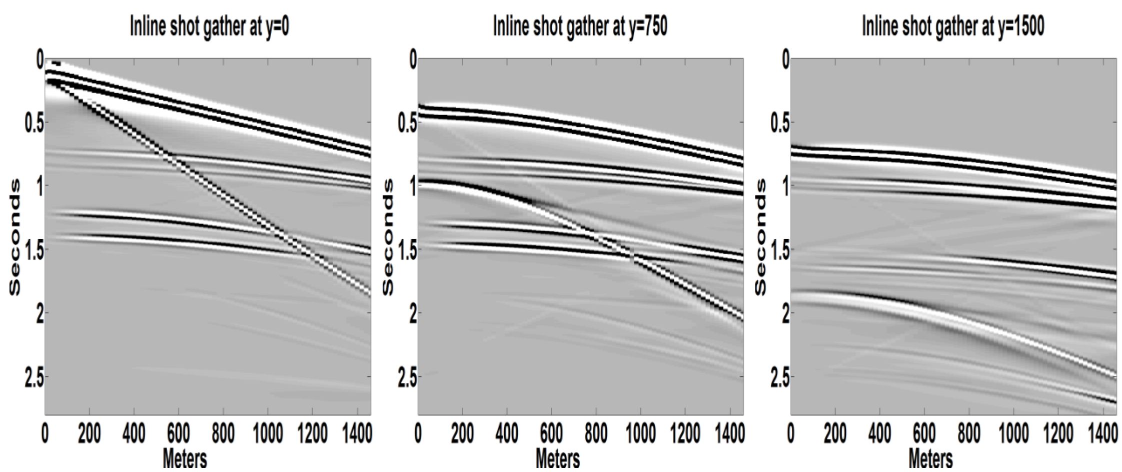

FIG. 9. HTI 3D elastic finite-difference modeling. X-component of common-shot seismograms at a y-offset of zero (left), 750m (middle), and (right) 1500m.

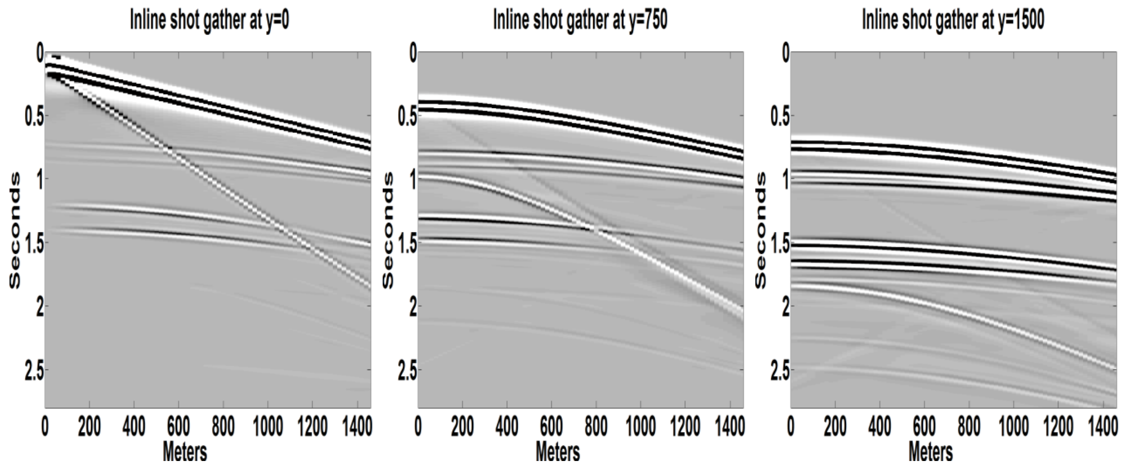

FIG. 10. HTI 3D elastic finite-difference modeling. Y-component of common-shot seismograms at y-offset of zero (left), 750m (middle), and (right) 1500m.

Figure 11 shows HTI 3D elastic finite-difference modeling results with TIGER for z-, x-, and y-components of the common-shot inline and cross-line seismograms recorded at zero y-offset (parallel to fracture strike), zero x-offset (parallel to symmetry axis), and their difference, respectively. The differences between the parallel to fracture strike direction and the parallel to symmetry-axis direction is due to the anisotropy of the HTI model. To confirm the effect of anisotropy on seismic response, a 3D model for an isotropic equivalent of our 3D model is implemented using an elastic isotropic scheme of TIGER. Figure 12 shows isotropic 3D elastic finite-difference modeling results from TIGER for the z-, x-, and y-component of the common-shot inline and cross-line seismograms. The zero differences are expected from isotropic modeling. In both Figures 11 and 12, results in a given row are in true relative amplitude to each other, but each row is independently scaled. This can be realized from inspection of the first breaks.

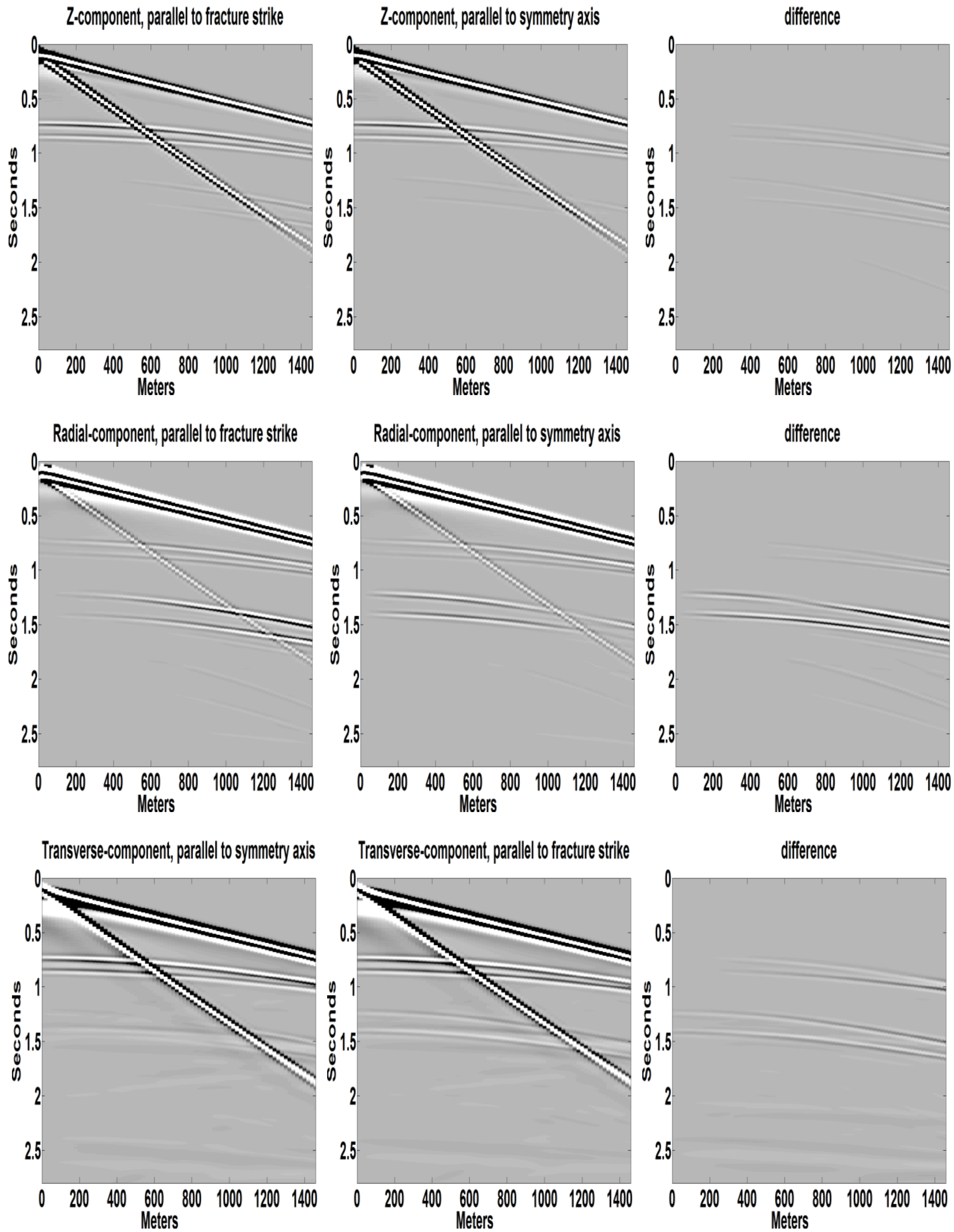

FIG. 11. HTI 3D elastic finite-difference modeling. (Top) Z-component, (middle) radial-component, (bottom) transverse-component of common-shot recorded at y-offset (parallel to fracture strike), at zero x-offset (parallel to symmetry axis), and their difference.

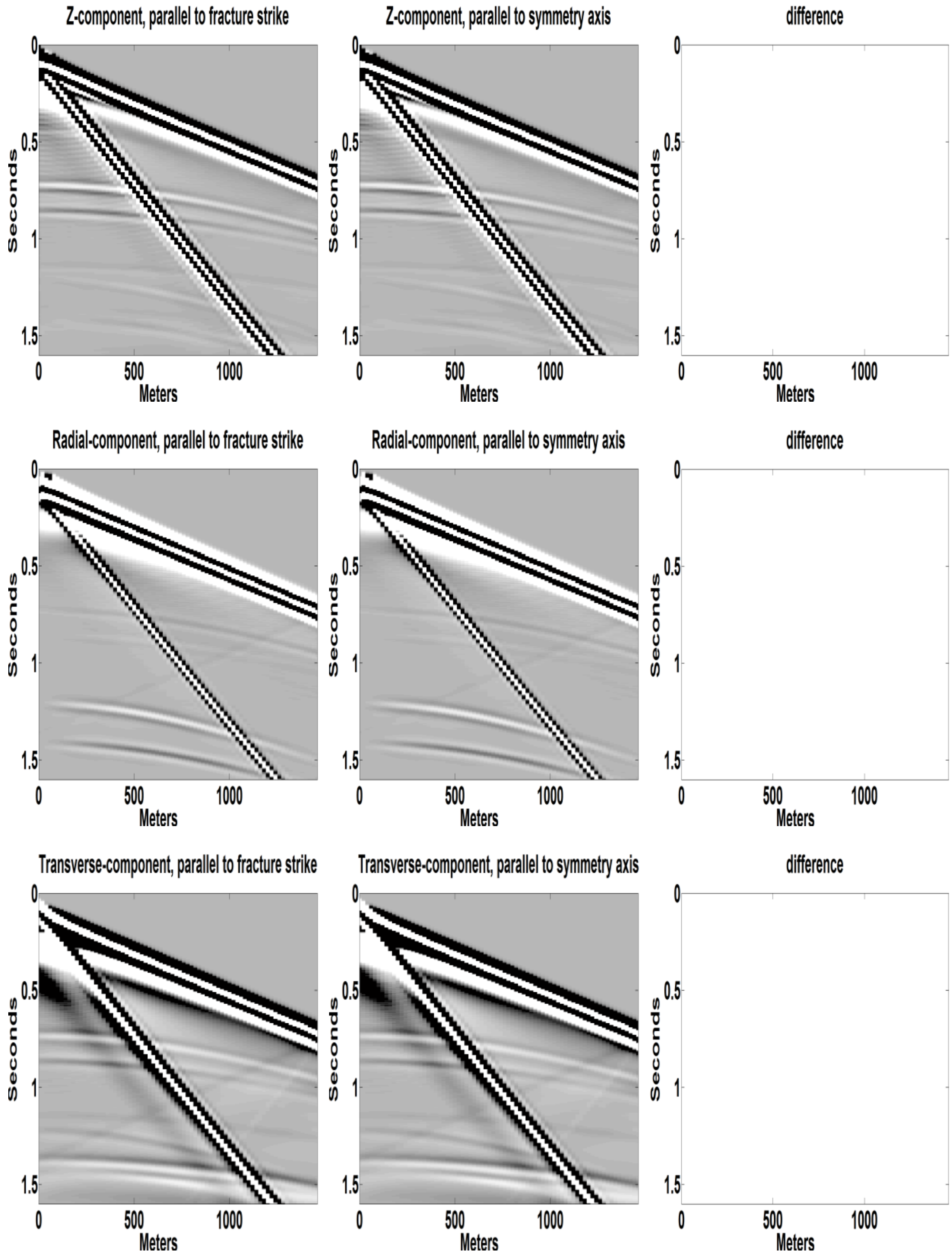

FIG. 12. Isotropic 3D elastic finite-difference modeling (Top) Z-component, (middle) radial-component, (bottom) transverse-component of common-shot recorded at y-offset (parallel to fracture strike), at zero x-offset (parallel to symmetry axis), and their difference.

CONCLUSIONS AND FUTURE WORK

We have created a simple model with a fracture layer modelled as an HTI layer, to investigate the seismic response of fractures. Our model will be modified to represent a more specific fracture zone for testing the ability of our common-angle migration techniques. We have illustrated several records here as created by the commercially available Tiger program by SINTEF Petroleum Research of Trondheim, Norway. A careful investigation of effects of fractures on both P-wave and S-wave data, in terms of changes in time and amplitudes, will be our immediate work.

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