The Conventional and Non-conventional Seismic Differencing

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Summary

We present a comparison between conventional time-lapse differencing and a new non-conventional differ-rencing method based on the inverse data matrix. We use 2D variable velocity models and their correspo-nding migrated synthetic seismograms to represent three snapshots in time-lapse. Conventional differencing performed on the time-lapse data captures no amplitude patterns and proves to be of limited use in reservoir characterization. On the other hand, non-conventional differencing by inverse data matrix captures some amplitude patters and offers more intuitive plots for interpretation.

Introduction

In this research, we evaluate time-lapse seismic differencing through numerical experiments of 2D data sets. We evaluate how the inverse data space (Berkhout and Verschuur, 2005) directly mapped into estimates of time-lapse differences (Inannen, 2009) benefit reservoir studies. We implement MATLAB code to illustrate both 2D data imaging after conventional and non-conventional seismic differencing then analyze fluid flow displacement imaging in time-lapse. The designed time-lapse study follows four stages: I) migration II) conventional and III) non-conventional differencing. Both conventional and non-conventional differencing method show valuable and trigger future research opportunities.

Theory

We use the 10th Comparative Solution Project data set (Christie and Blunt, 2001). Data set models, monitor-ring one producing and two injecting wells, a 100 % oil saturated reservoir as water saturation develops and breaks through in production after 28 days (Aarnes et al., 2007). We start with laterally varying 2D velocity models in time-lapse and through finite-difference algorithm deliver 2D synthetics. The synthetics are migrated and differenced.

Migration modelling

Stoffa et al. (1990) introduce the SSF migration algorithm, which handles lateral changes in velocity at each depth level taking dipping events into account. We assume 2D propagation of compressional (P) waves in acoustic medium and constant density defined as (Stoffa et al., 1990):

$$\nabla^2 d - u^2 \frac{\partial^2}{\partial t^2} d = 0, \tag{1}$$

where t , $d = d\,(x, z, t\,)$ and $u = u(x, z)$ are time, pressure and slowness, respectively. The inverse of the half of the propagation velocity $u(x, z) = 2/v(x, z)$, where v, x, z are velocity, horizontal and vertical distance, respectively, denotes slowness. As the migration by SSF takes place partially in the frequency domain, hence, equation (1) is Fourier transformed to:

$$\nabla^2 D + \omega^2 u^2 + D = 0, \tag{2}$$

where ω is frequency and $D = D(x,z,\omega) = \int_{-\infty}^{+\infty} d(x,z,t)e^{-i\omega t}dt$. Now, Stoffa et al. (1990) decompose the slowness term from equation (2) in two components: $u(x,z) = u_0(z) + \Delta u(x,z)$, where $u_0(z)$ and $\Delta u(x,z)$, are the reference and perturbation slowness. The reference slowness is the mean of $u(x,z)$. Thus the homogeneous wave equation transforms into the inhomogeneous, constant-slowness wave equation (Stoffa et al., 1990):

$$\nabla^2 D + \omega^2 {u_0}^2 D = -U(x,z,\omega), \tag{3}$$

where $U(x,z,\omega) = \omega^2[2u_0\Delta u(x,z,\omega) + \Delta u^2(x,z,\omega)]D$ is a source like term. The second order term in equation (3) is ignored as perturbation slowness is small when compared to the reference slowness. The solution of equation (3) is summarized in three steps (Du, 2007): transformation of wavefield from the spatial to the wavenumebr domain and apply a phase-shift based on the vertical wavenumber, *kz*, computed by the reference slowness; inversion of Fourier equation; in the space and frequency domains, generated by step II, we apply a second phase-shift due to the perturbation in the slowness:

$$D(z+\Delta z,x,\omega) = D^*(z+\Delta z,x,\omega)e^{\pm i\left(\frac{\omega}{v(x,z)}-\frac{\omega}{v_0(z)}\right)dz}. \tag{4}$$

Now integrate equation (4) over all frequencies of interest to deliver the migrated data (Mi, 2002).

Difference modeling

Time-lapse migrated seismic models are presented as matrices *Di* , where *i* denotes time step. These sections are differenced employing conventional matrix subtraction:

$$D_{diff} = D_i - D_{i+1}. \tag{5}$$

Equation (5) captures large scale physical changes of reservoir as production progresses. Namely, hydrocarbon volume and its displacement changes are expected to be interpretable for use in enhanced recovery schemes development and monitoring. The Berkhout and Verschuur (2005) method is developed as an improvement to conventional differencing. The method places migrated data in matrix D_0 to represent base study. Similarly, each migrated time step data is places in matrices denoted as D_i 's. All matrices have complex scaled entries in temporal frequency domain and their rows and columns denote receiver and shot recordings, respectively. Berkhout and Verschuur (2005) define the data matrices as: $D_i(z_0,z_0) = P(z_0,z_0)X_0(z_0,z_0)S(z_0)$, where *P*, X_0 and *S* denote receiver array, transfer function and source array recorded on the surface, z_0, respectively. The transfer function relates input and output data considering subsurface conditions. A feedback model is developed for recording a very complicated data set with nume-rous surface-realted multiples (Berkhout and Verschuur, 2005): $D = D_0 + (D_0A)D_0 + (D_0A)^2D_0\cdots$, where $A = S^{-1}R^*D^{-1}$ and R^* is surface reflectivity. The surface operator A does not contain traveltime. For the purpose of synthetic data the series expansion is simplified to:

$$D = [I - D_0A]^{-1}D_0. \tag{6}$$

Multiplication with (D_0A) in equation (6) represents spatial convolution, that is adding one roundtrip through subsurface (Berkhout and Verschuur, 2005). Simplifying equation (6), we get:

$$D = D_0 + D_0AD, \tag{7}$$

that is a multiple scattering equation of known Lippmann-Schwinger structure (Inannen, 2010). Employing matrix inversion, we move from multiple scattering data in forward data space (FDS), described by equation (7), to inverse data space (IDS) (Berkhout, 2006):

$$D^{-1} = {D_0}^{-1} - A. \tag{8}$$

Equation (8) describes a much simpler data set based on surface-free earth response and surface related properties at and around zero time. To analyze data in time-lapse recall migrated base and monitor surveys defined as (Berkhout, 2006):

$$D = D_0 + AD, \tag{9}$$

$$D' = D_0' + D_0' A' D'. \tag{10}$$

Due to change in acquisition system and surface conditions A and A' can be different for real data sets, however, dealing with synthetics allows to keep them constant. To account for reservoir parameters equation (10) can be further divided into smaller variables (Berkhout and Verschuur, 2005):

$$D = (D_0 + D_0 A' D') + (\delta D_0 + \delta D_0 A' D'), \tag{11}$$

where δD_0 denotes reservoir and overburden responses due to production. The use of inverse data space is hence summarized in four steps: I) Conversion of data from FDS to IDS through least-squares algorithm, II) Conversion of reflection data from IDS to FSD, III) Identify surface transfer function, in FDS and IDS and IV) Compute difference data employing least-squares subtraction to obtain $\delta X_0 = X_0 - F_{ls} X_0'$. The improved difference modelling is expected to capture both large and small scale physical changes as reservoir production progresses.

Examples

The saturation models, through Gassmann relations, deliver velocity models in time-lapse (Milicevic and Ferguson, 2009).

Zero-offset Synthetic Seismogram Models

The velocity models are passed to a finite-difference function MATLAB CREWES Project toolbox holds, *afd _explode*, that simulates exploding reflector concept. 2D synthetic seismograms are produced. Figure 1 shows zero-offset synthetics created after day 1, 14 and 28. The reservoir top and bottom are denoted by arrows 4 and 1, respectively, and the waterfronts are denoted by arrows 2 and 3. The reservoir top and bottom are stationary events in time-lapse whereas the waterfronts propagate upward in time creating a bow-tie effect. The overall amplitude of the reservoir dims with water saturation increase.

Migrated Models

Previously generated 2D zero-offset synthetics in time, *t*, and distance, *d*, domain are converted to frequency, f, and wavenumber, k_x, domain invoking Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) (Ferguson and Margrave, 2005). Data is migrated calling *ss_zero_mig*, a MATLAB routine of the CREWES Project toolbox, performing SSF depth migration (Ferguson, 2009). Figure 2 illustrates migrated sections after day 1, 14 and 28. The expected events, such as reservoir top and bottom and the waterfronts, denoted by arrows 4, 1 2 and 3, respectively. The amplitudes correspond to the amplitudes of the zero-offset unmigrated sections. The reservoir overall amplitude still shows linear reflections where saturated with water. These reflections are better focused and more white.

Conventional Differenced Models

We conventionally difference migrated sections. Figure 3(*a*) is a plot of conventional difference between day 1 and 14. Figure 3(*b*) is a plot of conventional difference between days 1 and 28. The reservoir top is not identifiable, as it is of the same amplitude on both models. The amplitude of reservoir bottom is of reverse polarity when compared to migrated sections. The reservoir bottom, denoted by arrow 1, is not a horizontal event, but an intersection of curves described as square root function and its inverse. The waterfronts, denoted by arrows 2 and 3, are of the same amplitude as seen on migrated sections. The amplitude of oil is purely white. The amplitude of the reservoir zone saturated by water is harder to distinguish from the reservoir zone saturated by oil, hence makes reserves hard to monitor.

Non-conventionally Differenced Models

We difference the same set of migrated sections employing the non-conventional differencing method based on Berkhout and Verschuur (2005). Figure 3(*c*) is a plot of non-conventional difference between days 1 and 14. Figure 3(*d*) is a plot of non-conventional difference between days 1 and 28. Reservoir top cannot be observed where as reservoir bottom is a white linear reflection. It is clear to note the waterfronts, denoted by arrows 2 and 3, belong to their progression after differenced days. The area between waterfronts is defined by weak white amplitude. The remaining oil reserves are easier to identify as weak white amplitude. Conventional differencing proves to be of limited use in reservoir characterization as it captures no certain amplitude patterns. Non-conventional differencing proves to be an improved tool in reservoir characterization although identification areas of remaining oil seems hard. Hence, method triggers future improvement.

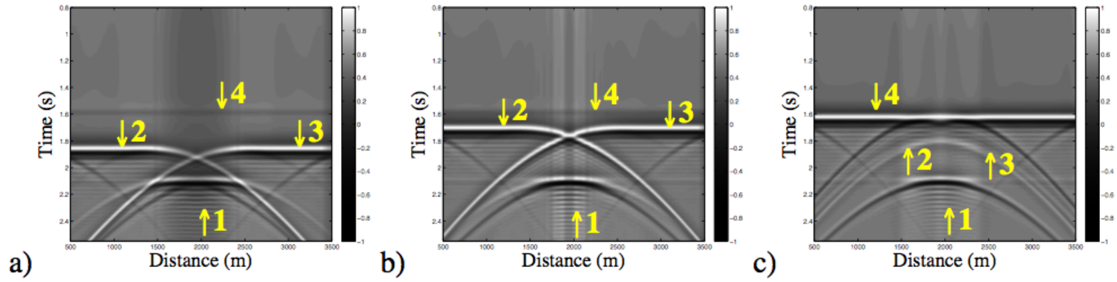

Figure 1: 2D synthetic seismic models generated employing exploding reflector algorithm. Models (a), (b) and (c) show reservoir in time-lapse steps after day τ =1, 14 and 28, respectively. Reservoir bottom, top, two waterfronts are denoted by arrows 1, 4, 2 and 3, respectively.

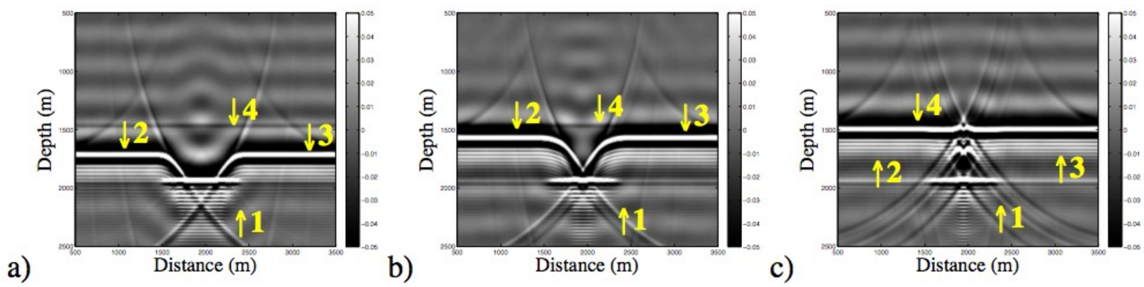

Figure 2: Split-step Fourier migrated seismic sections generated from velocity and synthetic models in Figure 1. Sections(a), (b), (c) capture flattening of hyperbolic events after day τ=1, 14 and 28, respectively.

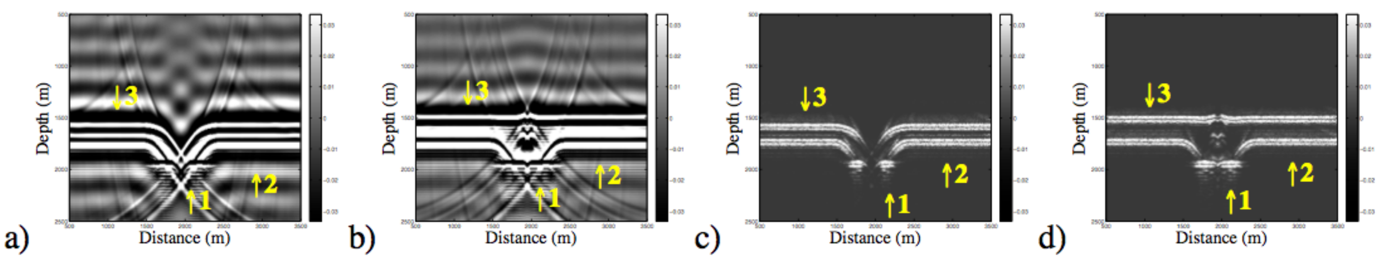

Figure 3: Differenced migrated models. Models (a) and (b) capture conventional difference of models after days 1 and 14 and days 1 and 28,respectively. Models (c) and (d) capture non-conventional difference of models after days 1 and 14 and days1 and 28, respectively. Arrows 1, 2 and 3 denote reservoir bottom, and two waterfronts, respectively.

Conclusions

Conventional seismic difference analysis study is performed on a 100% oil saturated reservoir in time-lapse. 2D variable velocity matrices are created. Velocity matrices, invoking finite-difference algorithm and simulating exploding reflector concept, generate zero-offset synthetic seismograms in time-lapse. Synthetics are migrated using Split-step Fourier algorithm. Migrated sections are conventionally and non-conventionally differenced and compared. Conventional seismic differencing presents little value to reservoir characterization and optimization as it does not capture certain amplitude patterns. Non-conventional seismic differrncing presents some improvement to reservoir characterization, however, triggers advancements as remainning oil in reservoir is hard to interpret. Linear algebra and pre-stack depth migration imaging are anticipated tools for differencing improvements.

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