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1 **Feasibility of time-lapse AVO and AVOA analysis to monitor compaction-**
2 **induced seismic anisotropy**

3

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10

11 **Abstract**

12 Hydrocarbon reservoir production generally results in observable time-lapse physical properties
13 changes, such as velocity increases within a compacting reservoir. However, the physical property
14 changes that lead to velocity changes can be difficult to isolate uniquely. Thus, integrated hydro-
15 mechanical simulation, stress-sensitive rock physics models and time-lapse seismic modelling
16 workflows can be employed to study the influence of velocity changes and induced seismic anisotropy
17 due to reservoir compaction. We study the influence of reservoir compaction and
18 compartmentalization on time-lapse seismic signatures for reflection amplitude variation with offset
19 (AVO) and azimuth (AVOA). Specifically, the time-lapse AVO and AVOA responses are predicted for
20 two models: a laterally homogeneous four-layer dipping model and a laterally heterogeneous graben
21 structure reservoir model. Seismic reflection coefficients for different offsets and azimuths are
22 calculated for compressional (P-P) and converted shear (P-S) waves using an anisotropic ray tracer
23 as well as using approximate equations for AVO and AVOA. The simulations help assess the
24 feasibility of using time-lapse AVO and AVOA signatures to monitor reservoir compartmentalization as
25 well as evaluate induced stress anisotropy due to changes in the effective stress field. The results of
26 this study indicate that time-lapse AVO and AVOA analysis can be applied as a potential means for
27 qualitatively and semi-quantitatively linking azimuthal anisotropy changes caused by reservoir
28 production to pressure/stress changes.

1 **Keywords:** Time-lapse Seismic Analysis, Reservoir Compaction, Hydro-mechanical Simulation,
2 Seismic Anisotropy, Azimuthal AVO

3 **1. Introduction**

4 Most crustal rocks are seismically anisotropic and as such seismic data can display various kinds
5 of azimuthal anisotropic patterns and anisotropic strength (e.g., Liu and Martinez 2012). The strength
6 or magnitude of seismic anisotropy typically ranges between 2%-6% (e.g., Jenner and Williams 2003;
7 Zheng 2006; Liu and Martinez 2012) and thus may contribute to difficulties in conventional seismic
8 processing, imaging and interpretation. Recently, it has been recognised that reservoir production can
9 induce seismic anisotropy within and surrounding the producing reservoir due to deformation and
10 changes in the stress field (e.g., Olofsson et al. 2003; Herwanger and Horne 2009). Thus measuring
11 time-lapse seismic anisotropy can be used to monitor the state of stress and strain within a producing
12 reservoir system, with potential to assess reservoir compartmentalization and reduce geomechanical
13 risk (e.g., He et al. 2015a; He et al. 2015b, in press).

14 The time-lapse seismic method is capable of monitoring changes in subsurface physical properties,
15 and can be grouped into two classes: travel-time methods and reflection amplitude methods (e.g.,
16 Calvert 2005; Dimri et al. 2012; Johnson 2013; Wang et al. 2010). Time-lapse seismic travel-time
17 shifts embody the path-averaged combined influence of velocity changes and strains. Time-lapse
18 seismic reflection amplitude changes are sensitive to perturbations in localised properties, such as
19 velocity and density changes across a boundary. Changes in reflectivity along the top and bottom of
20 reservoir horizons are mainly due to a combination of changes in pore pressure, fluid saturation and
21 rock deformation. For instance, the time-lapse seismic reflection amplitude variation with offset (AVO)
22 method has been applied with various degrees of success to discriminate between changes in
23 reservoir pressure and fluid saturation (e.g., Landrø 2001; Stovas and Landrø 2005; Herwanger and
24 Koutsabeloulis 2011). However, hydrocarbon depletion induced reservoir compaction and stress
25 arching can cause seismic anisotropy and hence distort the AVO response for wide-azimuth and long-
26 offset data (e.g., Herwanger and Horne 2009). Thus consideration of anisotropy effects on the
27 reflectivity response of a producing reservoir should be also incorporated.

28 The seismic P-wave amplitude variation with offset and azimuth (AVOA) technique was developed
29 for detecting sub-seismic vertical fracture sets. These vertical to sub-vertical fracture sets manifest in

1 the form of observable horizontal transverse isotropy (HTI) medium (e.g., Liu and Martinez 2012). HTI
2 is the simplest form of azimuthal anisotropy, and has been observed in both carbonate and sandstone
3 reservoirs (e.g., Rüger 1997, 1998; Jenner 2002; Hall and Kendall 2003; Olofsson et al. 2003;
4 Duxbury et al. 2012). Thus, in principal, detecting time-lapse changes in seismic azimuthal anisotropy
5 during hydrocarbon production using the AVOA technique might be feasible for monitoring subtle
6 subsurface changes in the stress field. Such changes in the stress field could be used to identify
7 reservoir compartmentalization, and hence allow for better dynamic reservoir characterization (e.g.,
8 Hall and MacBeth 2001; Shams and MacBeth 2003; Al-Naamani et al. 2004; Mattocks et al. 2005;
9 MacBeth and Shams 2006). However, subsurface structure, such as dipping horizons in an isotropic
10 medium, can generate 'false' azimuthal variations of amplitude reflectivity similar to that introduced by
11 seismic azimuthal anisotropy (e.g., Jenner and Williams 2003; Zheng 2006). Thus, the influence of
12 subsurface geometry must be accounted for prior to applying AVOA technique to interpret time-lapse
13 seismic observations.

14 In this study, the influence of reservoir production induced seismic anisotropy and velocity
15 heterogeneity on time-lapse AVO and AVOA responses is investigated. To do this, the effect of
16 inherent (or background) anisotropy and induced (or dynamic) anisotropy (i.e., seismic anisotropy
17 induced during reservoir depletion) on time-lapse seismic analysis is studied. The primary aim of this
18 research is to explore the potential of applying AVO and AVOA analysis as a time-lapse seismic
19 reservoir monitoring tool for geomechanical risk assessment and model calibration. Time-lapse
20 seismic P-P wave (incident P-wave reflected as P-wave) and P-S wave (incident P-wave reflected as
21 converted S-wave) AVO and AVOA analysis is implemented for wide-azimuth, long-offset data for two
22 synthetic models: a simple four-layer reservoir model with a dipping horizon and a hydro-mechanical
23 graben-style reservoir model having three compartments offset by two normal faults (see Angus et al.,
24 2010 for description of the hydro-mechanical model). The simple four-layer model is used to test the
25 influence of existing dip and production induced velocity anisotropy on the seismic azimuthal
26 response of the reflection coefficient for both P-P and P-S waves. The hydro-mechanical two-fault
27 model represents a more realistic scenario being applied to explore the influence of induced velocity
28 heterogeneity as well as induced seismic anisotropy on the time-lapse seismic reflection amplitude
29 response.

1 2. Theoretical background

2 To correctly model the seismic response due to 1-D structure one needs to consider the interaction
3 of the incident elastic wave with a discontinuity in material properties. The energy of the primary wave
4 can be converted into up to six secondary waves. Although Snell's law can be used to determine the
5 directional properties of all the secondary waves, it cannot provide information on waveform
6 amplitudes and pulse distortion (e.g., Yuan et al. 2014). Thus a more complete evaluation of the
7 reflection and transmission (R/T) properties is needed. Over the past several decades significant
8 contributions have been made in the evaluation of R/T coefficients for isotropic (e.g., Gilbert and
9 Backus 1966; Molotkov et al. 1976; Kennett 1983) and anisotropic (e.g., Garmany 1983; Fryer and
10 Frazer 1984; Guest et al. 1993) layered media. In most of these approaches, the solution to the R/T
11 response involves using a local plane-wave and plane-boundary approximation (see Hudson 1980;
12 Kennett1983), and thereby Guest and Kendall (1993) implement an anisotropic extension of the layer
13 matrix R/T coefficients (see Angus and Thomson 2012). For instance, an anisotropic ray tracer
14 ATRAK (Guest and Kendall 1993) is based on asymptotic ray theory and Hamiltonian solution, and
15 allows studying travel-time effects in smoothly varying heterogeneous and anisotropic media as well
16 as some amplitude effects and waveform distortions. These exact solutions for anisotropic media,
17 although elegant, may not be computationally tractable compared to approximate solutions. In this
18 section, we summarise the various approximate approaches developed from the Zoeppritz Equations
19 to calculate the reflection coefficients for AVO and AVOA analysis. For more details on the exact
20 solution of the reflection coefficient for plane interfaces the reader is referred to Kennett (1983) and
21 Angus and Thomson (2012).

22 For isotropic media, the approximate solution for the P-P wave reflection coefficient as a function of
23 incidence phase angle (θ) is written as (Rüger 1997)

$$24 R_p(\theta) = \frac{1}{2} \frac{\Delta Z}{\bar{Z}} + \frac{1}{2} \left\{ \frac{\Delta \alpha}{\bar{\alpha}} - \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \frac{\Delta G}{\bar{G}} \right\} \sin^2 \theta + \frac{1}{2} \frac{\Delta \alpha}{\bar{\alpha}} \sin^2 \theta \tan^2 \theta, \quad (1)$$

25 where $\alpha = \sqrt{c_{33}/\rho}$ and $\beta = \sqrt{c_{44}/\rho}$ are the vertical P- and S-wave velocities respectively, the
26 upper "bar" term represents the averaged value of the lower and upper medium elastic parameters,
27 Δ represents the physical property contrast across the reflecting boundary, $Z = \rho\alpha$ is the normal-

1 incidence P-wave impedance, and $G = \rho\beta^2$ is the shear modulus for normal-incidence S-wave.
 2 Equation (1) is valid for small discontinuities in elastic properties across the interface and is restricted
 3 to incidence angles of up to 30° . Equation (1) has been used to compute the AVO response in various
 4 studies (e.g., R ger 1997; Landr  2001; Jing et al. 2006).

5 AVO analysis has been applied also to converted (P-S) waves because they can provide useful
 6 additional information to that of conventional P-P wave AVO. For instance, converted shear waves
 7 are affected less during propagation through overburden gas clouds than compressional waves (e.g.,
 8 Jing et al. 2006) and they also provide higher resolution. For isotropic media, Ramos and Castagna
 9 (2001) approximate the P-S wave reflection coefficient as a function of incidence phase angle as

$$10 \quad R_{PS}(\theta) \approx A_1 \sin \theta + B_1 \sin^3 \theta + C_1 \sin^5 \theta, \quad (2a)$$

11 where

$$12 \quad A_1 = \left[-2 \frac{\bar{\beta}}{\bar{\alpha}} \frac{\Delta\beta}{\bar{\beta}} \right] - \left[\left(\frac{1}{2} + \frac{\bar{\beta}}{\bar{\alpha}} \right) \frac{\Delta\rho}{\bar{\rho}} \right], \quad (2b)$$

$$13 \quad B_1 = \left[\left(\frac{2\bar{\beta}^2}{\bar{\alpha}^2} + \frac{\bar{\beta}}{\bar{\alpha}} \right) \frac{\Delta\beta}{\bar{\beta}} \right] + \left[\left(\frac{3\bar{\beta}^2}{4\bar{\alpha}^2} + \frac{\bar{\beta}}{2\bar{\alpha}} \right) \frac{\Delta\rho}{\bar{\rho}} \right], \quad (2c)$$

$$14 \quad C_1 = \left[\left(\frac{\bar{\beta}}{\bar{\alpha}} \right)^4 \frac{\Delta\beta}{\bar{\beta}} \right] + \left[\frac{1}{2} \left(\frac{\bar{\beta}}{\bar{\alpha}} \right)^4 \frac{\Delta\rho}{\bar{\rho}} \right]. \quad (2d)$$

15 Equation (2) is valid for small elastic contrasts and is restricted to incidence angles of typically less
 16 than 30° .

17 For an interface between two vertical transverse isotropic (VTI) half-spaces, R ger (1997)
 18 approximates the P-P wave reflectivity variation with incidence angle using the linearized equation

$$19 \quad R_p^{VTI}(\theta) = \frac{1}{2} \frac{\Delta Z}{\bar{Z}} + \frac{1}{2} \left\{ \frac{\Delta\alpha}{\bar{\alpha}} - \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \frac{\Delta G}{\bar{G}} + \Delta\delta \right\} \sin^2 \theta + \frac{1}{2} \left\{ \frac{\Delta\alpha}{\bar{\alpha}} + \Delta\varepsilon \right\} \sin^2 \theta \tan^2 \theta, \quad (3)$$

20 where ε and δ are Thomsen's parameters for weakly anisotropic VTI media (Thomsen 1986).

21 Equation (3) is valid for small elastic contrasts and reduces to the isotropic AVO equation (1) when

1 the Thomsen anisotropy parameters ε and δ are both zero. For VTI media, there is no azimuthal
 2 dependence and so equation (3) is only a function of incidence angle (offset).

3 For HTI media, the seismic wave velocity varies with azimuth and so HTI media is often referred to
 4 as azimuthally anisotropic media. Therefore, for HTI media the reflection amplitude varies with
 5 incidence angle as well as azimuthal angle. It has been recognised that due to the presence of
 6 fractures and joints most crustal rocks down to 10 km to 20 km display features of effective azimuthal
 7 anisotropy (e.g., Crampin 1985). For an interface between two HTI half-spaces with the same
 8 symmetry axis orientation but not necessarily same anisotropic strength, Rüger (1997, 1998) extends
 9 equation (3) to approximate the P-P wave reflectivity. The approximate reflection coefficient for a
 10 compressional plane wave in HTI media as a function of incidence angle (θ) and azimuthal angle (ϕ)
 11) is given by Rüger (1998) as

$$12 \quad R_p^{HTI}(\theta, \phi) = \frac{1}{2} \frac{\Delta Z}{Z} + \frac{1}{2} \left\{ \frac{\Delta \alpha}{\bar{\alpha}} - \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \frac{\Delta G}{G} + \left[\Delta \delta^{(V)} + 2 \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \Delta \gamma \right] \cos^2 \phi \right\} \sin^2 \theta +$$

$$13 \quad \frac{1}{2} \left\{ \frac{\Delta \alpha}{\bar{\alpha}} + \Delta \varepsilon^{(V)} \cos^2 \phi + \Delta \delta^{(V)} \sin^2 \phi \cos^2 \phi \right\} \sin^2 \theta \tan^2 \theta \quad (4a)$$

13 where ϕ represents the azimuthal phase angle defined with respect to the symmetry axis and γ is
 14 the third Thomsen anisotropy parameter (Thomsen 1986). The effective Thomsen anisotropy
 15 parameters $\varepsilon^{(V)}$ and $\delta^{(V)}$ for HTI medium are defined as (e.g., Rüger 1997; Tsvankin 1997)

$$16 \quad \varepsilon^{(V)} = -\frac{\varepsilon}{1 + 2\varepsilon}, \quad (4b)$$

$$17 \quad \delta^{(V)} = \frac{\delta - 2\varepsilon[1 + (\varepsilon/f)]}{(1 + 2\varepsilon)[1 + (2\varepsilon/f)]}, \quad (4c)$$

$$18 \quad f = 1 - (\alpha/\beta)^2. \quad (4d)$$

19 For small incidence angles (typically $\leq 30^\circ$), the higher order $\sin^2 \theta \tan^2 \theta$ term can be ignored and
 20 the behaviour of $R_p^{HTI}(\theta, \phi)$ can be simplified by using the AVOA intercept (P-wave normal-incidence
 21 reflectivity A) and two gradients: an azimuthally invariant isotropic component G_{iso} and an
 22 azimuthally dependent anisotropic contribution G_{aniso} (see Rüger 1998; Jenner 2002)

$$1 \quad R_p^{HTI}(\theta, \phi) = A + (G_{iso} + G_{aniso} \cos^2 \phi) \sin^2 \theta, \quad (5a)$$

2 where

$$3 \quad A = \frac{1}{2} \frac{\Delta Z}{\bar{Z}}, \quad (5b)$$

$$4 \quad G_{iso} = \frac{1}{2} \left[\frac{\Delta \alpha}{\bar{\alpha}} - \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \frac{\Delta G}{\bar{G}} \right], \quad (5c)$$

$$5 \quad G_{aniso} = \frac{1}{2} \left[\Delta \delta^{(V)} + 2 \left(\frac{2\bar{\beta}}{\bar{\alpha}} \right)^2 \Delta \gamma \right]. \quad (5d)$$

6 It should be noted that the magnitude of the gradient G_{aniso} is a function of the contrast in the
7 anisotropy parameters $\delta^{(V)}$ and γ .

8 **3. Results for two synthetic models**

9 In this section, the results from numerical simulation from two models are discussed; a simple four-
10 layer reservoir model having a dipping reflector, and a hydro-mechanical graben-structure reservoir
11 model. We evaluate the approximate reflection amplitude coefficients to examine the feasibility of
12 applying time-lapse seismic AVO and AVOA response to assess the effect of reservoir compaction
13 induced triaxial stress changes and azimuthal velocity anisotropy. We seek to determine whether
14 these attributes can be used to help identify reservoir compartmentalization.

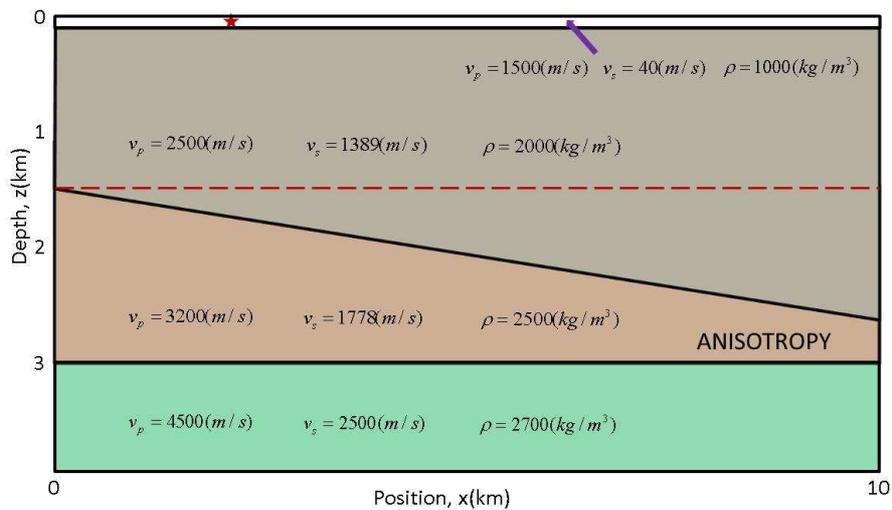
15 **3.1. Four-layer reservoir model**

16 **■ Methodology**

17 In Figure 1, a 2.5-D (invariant in the y-direction) four-layer elastic model is used to investigate the
18 impact of dip (6° with respect to the horizontal, x, axis) on time-lapse seismic reflection amplitude
19 azimuthal measurements. Jenner and Williams (2003) note that dips on the order of 10° can lead to
20 an apparent velocity anisotropy of 4% and so a dip of 6° should yield a comparable degree of
21 anisotropy to that expected of production-induced anisotropy. For this dipping-layered reservoir
22 model, the AVO and AVOA responses for both P-P and P-S waves are examined.

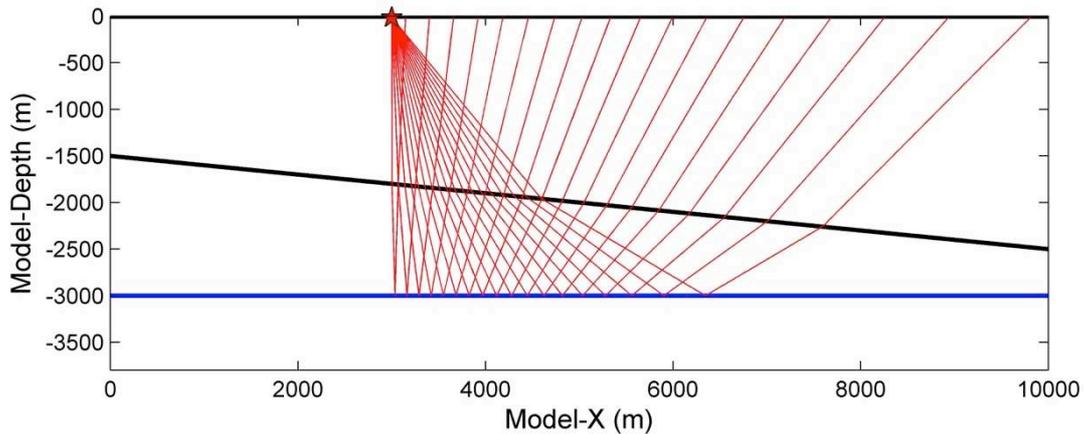
1 In this model, the third layer represents the producing reservoir that develops induced seismic
 2 anisotropy caused by changes in the effective stress field. The other layers within the model are
 3 static, and are homogeneous and isotropic. Three cases of induced anisotropy are examined within
 4 the reservoir and their values are based on sandstone measurements taken from the more realistic
 5 hydro-mechanical two-fault reservoir model of Angus et al. (2010). The three cases are all VTI and vary
 6 in terms of anisotropy strength: (i) weak anisotropy $\epsilon = 0.026$, $\gamma = 0.018$ and $\delta = 0.007$
 7 (anisotropy1); (ii) moderate anisotropy $\epsilon = 0.046$, $\gamma = 0.057$ and $\delta = 0.007$ (anisotropy2); and (iii)
 8 strong anisotropy $\epsilon = 0.105$, $\gamma = 0.102$ and $\delta = 0.006$ (anisotropy3). Figure 2 shows an example of
 9 rays traced in the dipping layer model using the anisotropic ray tracer ATRAK. For the selected
 10 horizon, ATRAK is used to calculate the reflection amplitude for each ray as a function of offset and
 11 azimuth for both the P-P and P-S waves. In this model, only the elastic properties within the reservoir
 12 change.

13



14

15 **Figure 1.** A 2.5-D synthetic four-layer earth model having a dipping reflector used in the ray tracing to compute
 16 the reflection amplitude variation with offset and azimuth. The third layer (i.e., reservoir unit) is modelled as
 17 initially isotropic that subsequently develops induced anisotropy due to reservoir production. The other layers are
 18 isotropic. The top layer represents the ocean (or water) layer (the arrow). The dashed red line represents a
 19 scenario where the top reservoir is horizontal flat, and the red star represents the source location. Velocities and
 20 bulk density are displayed within the figure.



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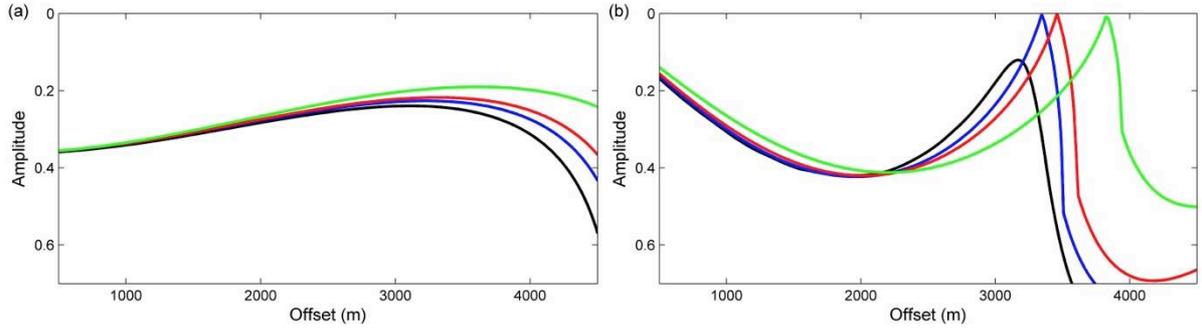
2 **Figure 2.** Rays traced through the four-layer elastic model (see Figure 1) from a source within the water layer at
 3 $X=3000$ m, and reflected off the bottom reservoir interface at 3000 m depth (blue line) for the P-P wave. The
 4 geophones are fixed along the bottom of the water layer.

5

6 **■ Results**

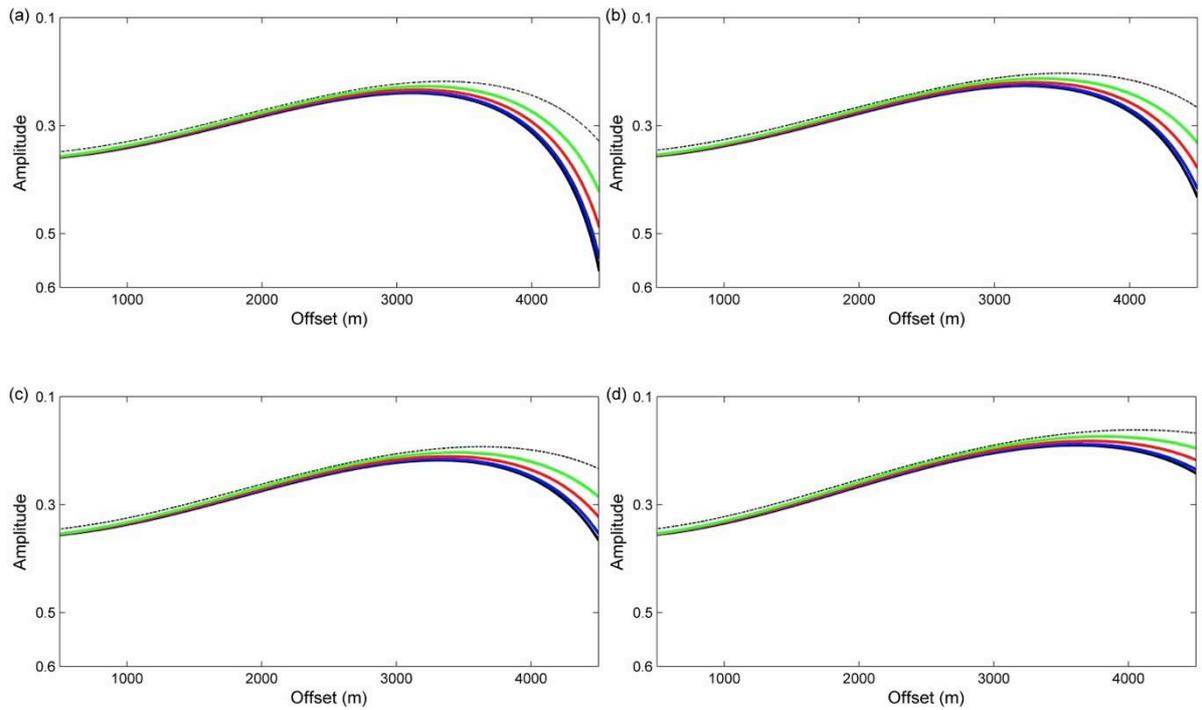
7 In Figure 3, the P-P wave and P-S₁ wave (S₁ being the fast S-wave) reflection coefficients are
 8 shown for azimuth $\phi = 0^\circ$ (i.e., the shot-receiver gather is perpendicular to the strike of the dipping
 9 layer). As expected, the development of induced anisotropy within the layer from the background
 10 isotropy leads to noticeable changes in the P-P and P-S wave amplitudes. In Figures 4 and 5, the P-P
 11 and P-S₁ wave reflection coefficients for several azimuths ($\phi = 0^\circ, 30^\circ, 60^\circ$ and 90°) are displayed
 12 for the background isotropic as well as the induced anisotropic models. It can be observed that for the
 13 VTI medium model, where there should be no azimuthal variation in elastic properties, the presence
 14 of dip influences the measurements for the different azimuths on the same order of magnitude as the
 15 induced anisotropy. This highlights the need to properly compensate for subsurface structure prior to
 16 time-lapse AVO and AVOA analysis.

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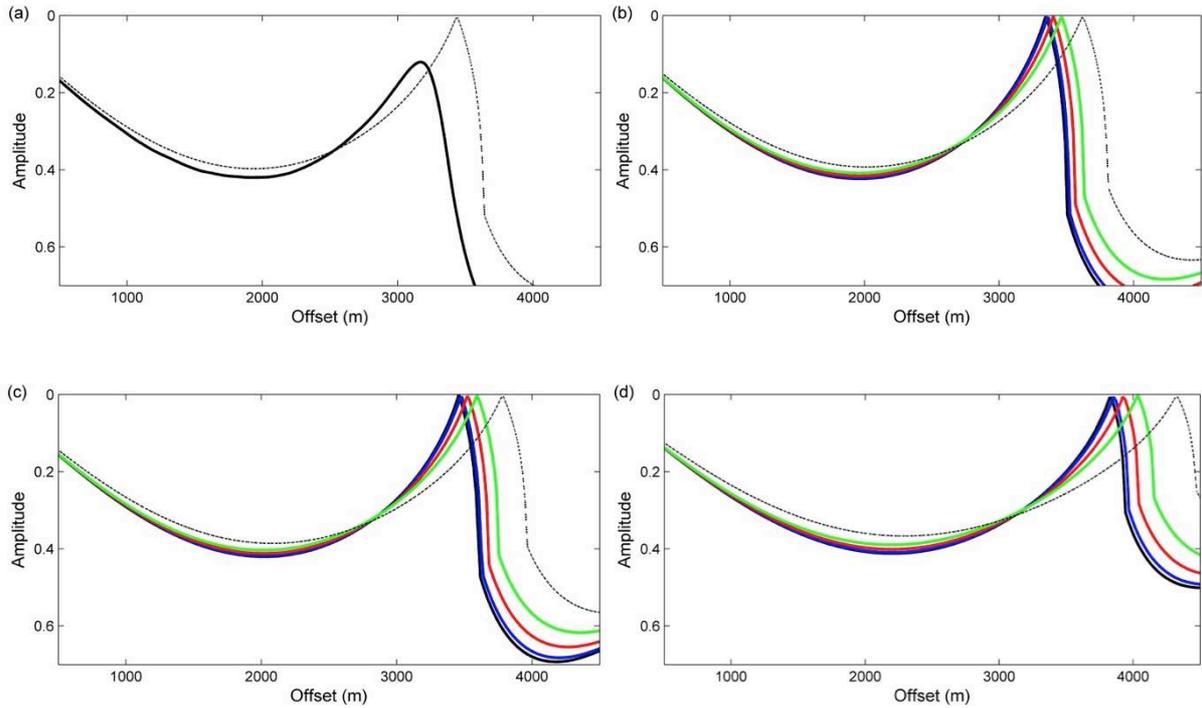
2 **Figure 3.** Seismic reflection coefficients for the (a) P-P and (b) P-S₁ waves are shown for the background
 3 isotropic and induced anisotropic models, using the ray tracer along the X-direction (i.e., azimuth of $\phi = 0^\circ$).
 4 The computed reflection coefficients are shown, with the black curve for the isotropic model, the blue curve for
 5 the weak anisotropic (anisotropy1) model, the red curve for the moderate anisotropic (anisotropy2) model and the
 6 green curve for the strong anisotropic (anisotropy3) model.



7

8

9 **Figure 4.** Seismic reflection coefficients for P-P waves are shown for the (a) isotropic, (b) weak anisotropic
 10 (anisotropy1), (c) moderate anisotropic (anisotropy2) and (d) strong anisotropic (anisotropy3) models, calculated
 11 using the ray tracer at four azimuths. The computed reflection coefficients are shown for azimuths: $\phi = 0^\circ$
 12 (black curve), $\phi = 30^\circ$ (blue curve), $\phi = 60^\circ$ (red curve) and $\phi = 90^\circ$ (green curve). For comparison, the
 13 dotted-black curve represents the reflection amplitudes for the flat horizon model (shown by the dashed red line
 14 in Figure 1). Since the anisotropic models are VTI, there is no variation with azimuth for the flat horizon model.



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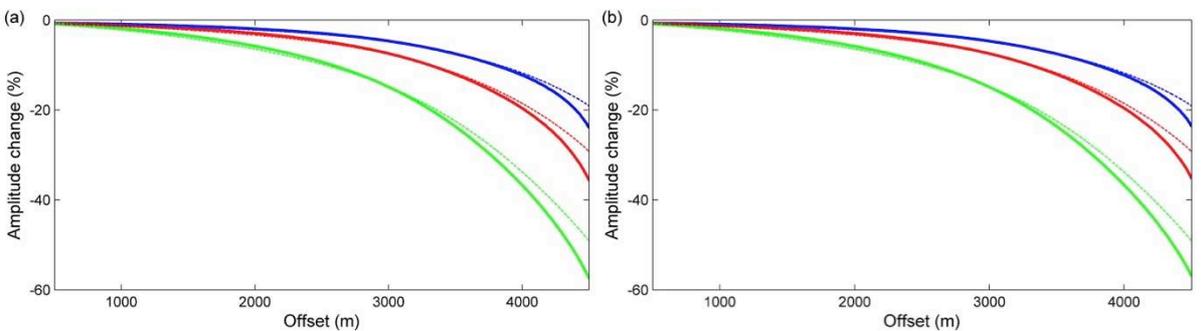
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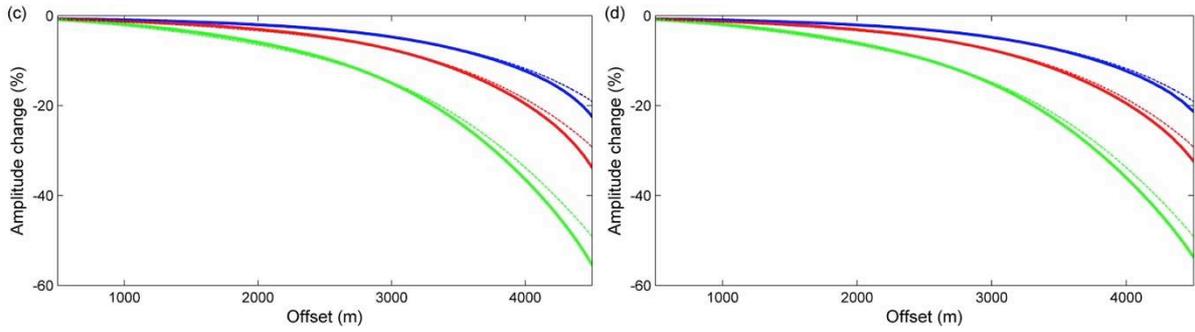
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Figure 5. Seismic reflection coefficients for P-S₁ waves are shown for the (a) isotropic, (b) weak anisotropic (anisotropy1), (c) moderate anisotropic (anisotropy2) and (d) strong anisotropic (anisotropy3) models, calculated using the ray tracer at four azimuths. The computed reflection coefficients are shown for azimuths: $\phi = 0^\circ$ (black curve), $\phi = 30^\circ$ (blue curve), $\phi = 60^\circ$ (red curve) and $\phi = 90^\circ$ (green curve). For comparison, the dotted-black curve represents the reflection amplitudes for the flat horizon model (shown by the dashed red line in Figure 1). Since the anisotropic models are VTI, there is no variation with azimuth for the flat horizon model. P-S₁ waves reflection coefficients for the isotropic model at the other three azimuths (i.e., $\phi = 30^\circ$, 60° and 90°) are too small and thus not displayed.



12



1

2 **Figure 6.** Time-lapse changes in P-P wave reflection coefficients due to the modelled induced velocity anisotropy

3 calculated with respect to the baseline isotropic model at four azimuths: (a) $\phi = 0^\circ$, (b) $\phi = 30^\circ$, (c) $\phi = 60^\circ$,

4 and (d) $\phi = 90^\circ$. The dotted-thin curves represent the measurements for the flat horizon model and the solid-

5 thick curves represent the measurements for the dipping horizon model. The reflection amplitude changes from

6 the isotropic model are: blue for weak anisotropic (anisotropy1) model, red for moderate anisotropic (anisotropy2)

7 model and green for strong anisotropic (anisotropy3) model.

8

9 In Figure 6, time-lapse P-P wave AVOA changes due to the induced velocity anisotropy calculated

10 with respect to the baseline isotropic model at four azimuths are compared between the flat and

11 dipping horizon models. It can be seen that the azimuthal variations in the time-lapse reflection

12 amplitude changes for the dipping-layered model are more marked when compared with the flat

13 horizon model at far offsets, whereas at near offsets the changes are indistinguishable.

14 3.2. Hydro-mechanical graben-style reservoir model

15 ■ Methodology

16 In this reservoir model, we explore the influence of subsurface geometry on the time-lapse AVO

17 and AVOA response using a graben-structure reservoir geometry consisting of three reservoir

18 compartments separated by two normal faults (see Angus et al. 2010). Numerical hydro-mechanical

19 simulation is applied to the geometry to predict the influence of fluid extraction on the elastic

20 properties of the reservoir system, specifically the time-lapse reflection amplitude response. Two

21 production cases are examined, one where the faults have high fluid-flow transmissibility (i.e., the

22 faults are not barriers to fluid flow, HFT) and one where the faults have low fluid-flow transmissibility

23 (i.e., the faults act as fluid flow barriers, LFT). The hydro-mechanical simulations are performed using

24 a two-way iteratively coupled approach (Segura et al. 2011) linking the reservoir flow simulator

1 Tempest with the geomechanical solver Elfen. In this coupled approach the geomechanical simulator
 2 uses the pore pressure evolution calculated in the reservoir simulator to update the geomechanical
 3 loading, and the reservoir simulator uses the updated pore volume calculated in the geomechanical
 4 simulator to update the fluid-flow properties. Due to the 3D geometry, it is expected that fluid extraction
 5 within the two-fault graben reservoir model will yield fully triaxial stress perturbations and hence
 6 seismic anisotropy will develop (e.g., Herwanger and Koutsabeloulis 2011). Monitoring the effective
 7 stress and reservoir pore pressure evolution across the faults and within the compartments is therefore of
 8 considerable significance to improve hydrocarbon extraction strategies as well as avert drilling and
 9 depletion related geomechanical problems. Thus this model is of practical significance because it will
 10 allow us to examine whether time-lapse AVO and AVOA analysis can be used to monitor reservoir
 11 compartmentalization.

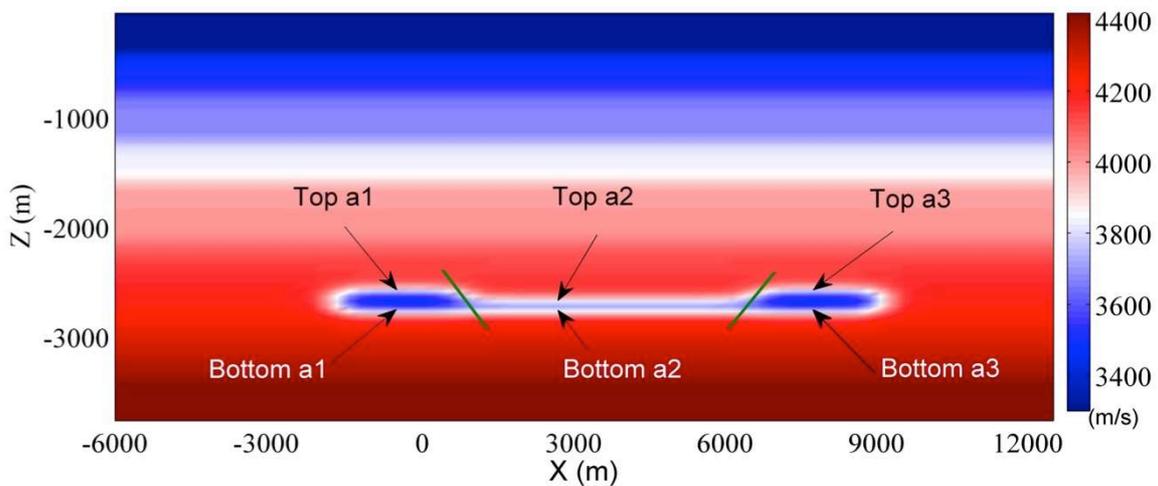
12 For both the high (HFT) and low (LFT) flow transmissibility cases, the outputs from the hydro-
 13 mechanical simulations are used to construct dynamic elastic models (i.e., elasticity suitable for
 14 seismic frequencies) for the anisotropic ray tracing (see Angus et al. 2011). Three elastic models are
 15 generated: an isotropic baseline model and two generally anisotropic monitor models (monitor1 for
 16 five years of depletion and monitor2 for ten years of depletion). The monitor models are anisotropic
 17 due to the evolution of the triaxial effective stress field during fluid extraction. The seismic anisotropy
 18 is predicted based on the stress-sensitive microcrack rock physics transform of Verdon et al. (2008)
 19 (see Appendix A for descriptions of dynamic elasticity construction from the output of hydro-
 20 mechanical simulations using the microcrack rock physics model). In order to examine the influence
 21 of induced velocity heterogeneity and induced velocity anisotropy due to reservoir depletion on the
 22 time-lapse seismic amplitude response, time-lapse isotropic and anisotropic elastic models are
 23 considered.

24 There are eight distinct symmetry classes for anisotropic media: triclinic, monoclinic, orthorhombic,
 25 tetragonal, trigonal, hexagonal, cubic and isotropic (e.g., Babuska and Cara 1991; Liu and Martinez
 26 2012). Browaeys and Chevrot (2004) show that a given vector T belonging to any anisotropic
 27 symmetry class can be decomposed into a sum of anisotropic components belonging to the eight
 28 elastic symmetry groups

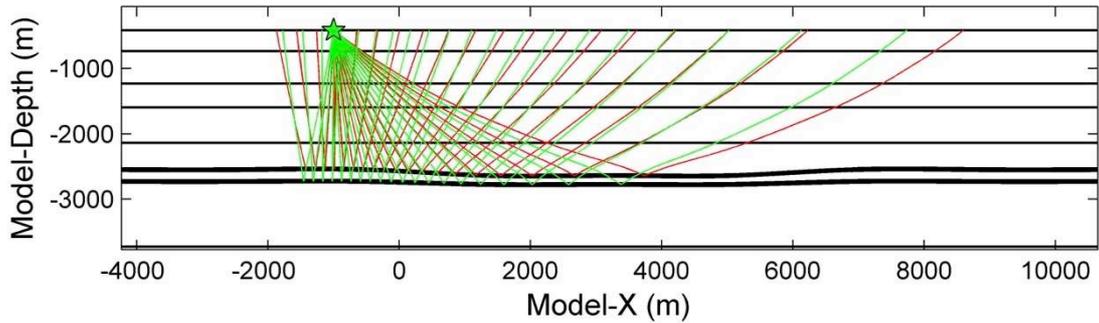
$$29 \quad T = T_{tric} + T_{mon} + T_{ort} + T_{tet} + T_{trig} + T_{hex} + T_{cub} + T_{iso}, \quad (6)$$

1 where T_{tric} , T_{mon} , T_{ort} , T_{tet} , T_{trig} , T_{hex} , T_{cub} and T_{iso} are elastic vectors belonging to the triclinic,
 2 monoclinic, orthorhombic, tetragonal, trigonal, hexagonal, cubic and isotropic elastic symmetry
 3 classes, respectively. This formulation allows any generally anisotropic elastic tensor to be
 4 approximated by an optimal hexagonal (i.e., TI) elastic medium, consisting of an isotropic part T_{iso}
 5 and an hexagonal part T_{hex} , reducing the number of independent elastic parameters from 21 to 5
 6 using Thomsen (1986) anisotropy parameters.

7 In the time-lapse isotropic case, it is assumed that no velocity anisotropy is induced and only
 8 isotropic velocity changes occur. In the time-lapse anisotropic case, the development of velocity
 9 heterogeneity occurs, but where induced velocity anisotropy also develops. For both the isotropic and
 10 anisotropic cases, the initial baseline elastic model is isotropic (V_{iso1}). For the isotropic time-lapse
 11 case, an isotropic equivalent monitor elastic model is derived from the anisotropic model assuming
 12 only vertical effective stress changes (i.e., uniaxial strain), and hence the elastic tensor components
 13 C_{33} and C_{44} are used to compute the P- and S-wave velocities (V_{iso2}), respectively. Based on the
 14 decomposition approach of Browaeys and Chevrot (2004), the induced anisotropic elasticity
 15 calculated using the hydro-mechanical simulations is approximated to TI anisotropy, allowing the
 16 induced anisotropy to be characterised by Thomsen (1986) anisotropy parameters suitable to be used
 17 in equations (3)-(5). The Thomsen (1986) anisotropy parameters approximated for the anisotropic
 18 model (V_{aniso}) of monitor1 within the reservoir are: $\epsilon = 0.16$, $\gamma = 0.10$ and $\delta = 0.01$ for the HFT
 19 model, and $\epsilon = -0.02$, $\gamma = -0.01$ and $\delta = -0.01$ for the LFT model.



20



1

2 **Figure 7.** Top: Baseline P-wave velocity vertical section (X-Z) through the middle of the graben reservoir model
 3 (see Angus et al. 2010). The six arrows represent locations within the model where the elastic parameters are
 4 taken for Table 1. The two green lines represent the locations of the normal faults. Bottom: Example of rays
 5 traced through the graben reservoir model and reflected from two interfaces; the top and base reservoir reflected
 6 rays are indicated by the red and green lines respectively, from a source at X=-1000 m. The thin layer between
 7 the two interfaces (thick-black horizons) is the producing reservoir.

8

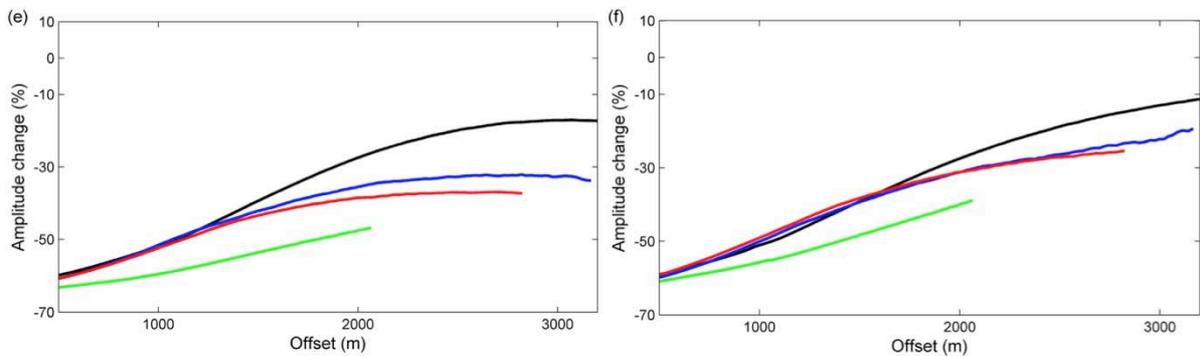
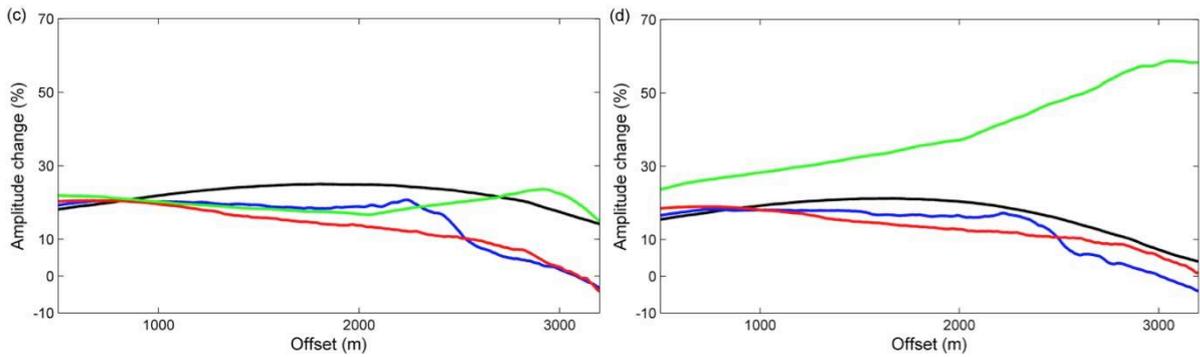
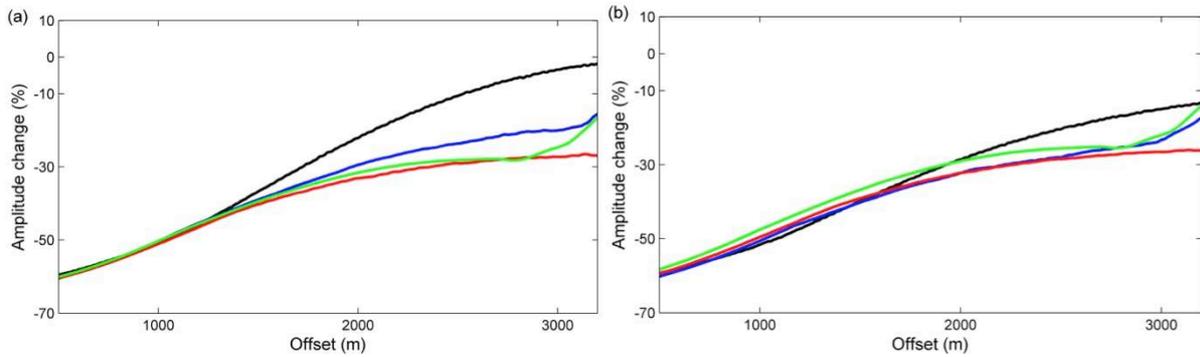
9 As was done in the previous section, we use the anisotropic ray tracer ATRAK to calculate the
 10 reflection amplitudes for different azimuths. The influence of induced isotropic velocity heterogeneity
 11 (i.e., V_{iso1} to V_{iso2}) and induced seismic anisotropy (i.e., V_{iso1} to V_{aniso}) is investigated for both the P-P
 12 and P-S waves. Figure 7 shows an example of P-P rays traced through the graben reservoir model
 13 from a common source-point (X=-1000 m) and tracking reflections from two interfaces (i.e., the top
 14 and the bottom reservoir horizons). Since we are concerned with evaluating the changes within the
 15 producing reservoir, only the rays reflected from the bottom reservoir interface are investigated.

16 **■ Results**

17 Figure 8 displays the time-lapse seismic changes in reflection coefficients calculated between the
 18 isotropic baseline (V_{iso1}) and the induced isotropic monitor1 (V_{iso2}) and anisotropic monitor1 (V_{aniso})
 19 HFT and LFT models at four azimuths for P-P and P-S₁ waves, respectively. It can be seen that the
 20 impact of induced velocity heterogeneity and anisotropy is noticeable on the P-P reflection coefficients
 21 changes for all azimuths, and the changes in P-P reflection coefficients decrease with increasing
 22 offset. There are observable differences in reflection amplitude changes (~5%) for P-P wave between
 23 the induced isotropic and induced anisotropic models and this indicates that it is important to include
 24 the influence of induced anisotropy. The azimuthal variation is related to the geometry, where the

1 influence of the fault along azimuth $\phi = 0^\circ$ differs from the influence of the reservoir edges along the
 2 other azimuths $\phi = 30^\circ$, $\phi = 60^\circ$ and $\phi = 90^\circ$. The azimuthal variation suggests that the reservoir is
 3 not undergoing uniaxial deformation and this is expected since the reservoir does not have infinite
 4 extent. It is important to note that the P-P and P-S₁ waves show different offset dependence as well
 5 as sign in reflection amplitude changes (negative for P-P and positive for P-S₁). In addition, the time-
 6 lapse reflection amplitude changes for the P-P waves are much larger than that of the P-S₁ waves.
 7 For the LFT model, there is significantly less azimuthal variation in P-P reflection coefficients due to
 8 reservoir geometry, whereas there appears to be an increased sensitivity in the P-S reflection
 9 coefficient especially for the 90° azimuth.

10



1 **Figure 8.** Time-lapse changes in reflection amplitudes for P-P and P-S₁ waves for the 5 year monitor (monitor1)
2 HFT (left) and LFT (right) graben reservoir model. Panels (a), (b), (c) and (d) assume isotropic (V_{iso2}) changes,
3 and panels (e) and (f) assume anisotropic (V_{aniso}) changes in elasticity at four azimuths: $\phi = 0^\circ$ (black curve),
4 $\phi = 30^\circ$ (blue curve), $\phi = 60^\circ$ (red curve) and $\phi = 90^\circ$ (green curve). Panels (a), (b), (e) and (f) represent P-P
5 P wave results, and panels (c) and (d) represent P-S₁ wave results.

6

Parameter Model	α (km/s)	β (km/s)	ρ (g/cm ³)	ε	γ	δ
Top a1	4.183	1.261	2.7	0	0	0
	3.364	1.942	2.7	0	0	0
Top a2	4.195	1.265	2.7	0	0	0
	3.375	1.949	2.7	0	0	0
Top a3	4.183	1.261	2.7	0	0	0
	3.364	1.942	2.7	0	0	0
Bottom a1	3.377	1.950	2.7	0	0	0
	4.232	1.276	2.7	0	0	0
Bottom a2	3.375	1.949	2.7	0	0	0
	4.246	1.280	2.7	0	0	0
Bottom a3	3.377	1.950	2.7	0	0	0
	4.232	1.276	2.7	0	0	0

Parameter Model	α (km/s)	β (km/s)	ρ (g/cm ³)	ε	γ	δ
Top a1	4.021	1.257	2.7	-0.01	0	-0.01
	3.759	2.095	2.7	0.17	0.06	0.17
Top a2	4.124	1.263	2.7	0	0	0
	3.832	2.119	2.7	0.19	0.06	0.2
Top a3	4.110	1.259	2.7	0	0	0
	3.708	2.082	2.7	0.16	0.05	0.16
Bottom a1	3.773	2.102	2.7	0.17	0.06	0.17
	4.086	1.272	2.7	0	0	0
Bottom a2	3.832	2.119	2.7	0.19	0.06	0.2
	4.136	1.278	2.7	-0.01	0	-0.01
Bottom a3	3.696	2.081	2.7	0.14	0.05	0.14
	4.146	1.274	2.7	0	0	0

7

Parameter Model	α (km/s)	β (km/s)	ρ (g/cm ³)	ε	γ	δ
Top a1	3.910	1.254	2.7	-0.01	0	-0.01
	3.834	2.112	2.7	0.19	0.06	0.19
Top a2	4.028	1.260	2.7	-0.01	0	-0.01
	3.949	2.144	2.7	0.21	0.07	0.22
Top a3	3.960	1.256	2.7	-0.01	0	-0.01
	3.817	2.108	2.7	0.18	0.06	0.19
Bottom a1	3.852	2.120	2.7	0.19	0.06	0.19
	4.023	1.271	2.7	-0.01	0	-0.01
Bottom a2	3.949	2.144	2.7	0.21	0.07	0.22
	4.086	1.277	2.7	-0.01	0	-0.01
Bottom a3	3.834	2.116	2.7	0.18	0.06	0.18
	4.094	1.272	2.7	0	0	0

Parameter Model	α (km/s)	β (km/s)	ρ (g/cm ³)	ε	γ	δ
Top a1	3.944	1.255	2.7	-0.01	0	-0.01
	3.364	1.942	2.7	0	0	0
Top a2	4.267	1.266	2.7	0	0	0
	3.375	1.949	2.7	0	0	0
Top a3	4.222	1.262	2.7	0	0	0
	3.364	1.942	2.7	0	0	0
Bottom a1	3.377	1.950	2.7	0	0	0
	3.983	1.269	2.7	-0.01	0	-0.01
Bottom a2	3.375	1.949	2.7	0	0	0
	4.359	1.282	2.7	0.01	0	0.01
Bottom a3	3.377	1.950	2.7	0	0	0
	4.267	1.276	2.7	0	0	0

8

(e)

Parameter Model	α (km/s)	β (km/s)	ρ (g/cm ³)	ε	γ	δ
Top a1	3.569	1.242	2.7	-0.03	-0.01	-0.03
	3.364	1.942	2.7	0	0	0
Top a2	4.280	1.267	2.7	0	0	0
	3.375	1.949	2.7	0	0	0
Top a3	4.224	1.262	2.7	0	0	0
	3.364	1.942	2.7	0	0	0
Bottom a1	3.377	1.950	2.7	0	0	0
	3.731	1.259	2.7	-0.01	0	-0.01
Bottom a2	3.375	1.949	2.7	0	0	0
	4.380	1.283	2.7	0	0	0
Bottom a3	3.377	1.950	2.7	0	0	0
	4.267	1.276	2.7	0	0	0

1

2

Table 1 The elastic parameters calculated at three locations along the top and bottom reservoir horizons; the lateral locations are a1=-711 m, a2=2714 m and a3=7120 m. These values are extracted from the output of the hydro-mechanical simulations for the (a) baseline, (b) and (d) monitor survey after 5 years of production (monitor1) and (c) and (e) monitor survey after 10 years of production (monitor2). Where (b) and (c) are for the HFT reservoir models, and (d) and (e) are for the LFT reservoir models. In this table, α and β are the vertical P- and S-wave velocities respectively, ρ is the bulk density, and ε , γ and δ are the Thomsen (1986) anisotropy parameters.

8

9

10

To gain some physical insight into the approximate AVO and AVOA equations (1)-(5), we extract elastic properties across the top and bottom reservoir horizons at three lateral locations: -711 m, 2714 m and 7120 m. These three points are shown in Figure 7 and represent the central horizon point of each compartment. The values in Table 1 are given for the baseline, monitor1 and monitor2 elastic models for the high and low fluid-flow fault transmissibility cases. The elasticity values are then used to compute the approximate time-lapse AVO and AVOA responses within each reservoir compartment.

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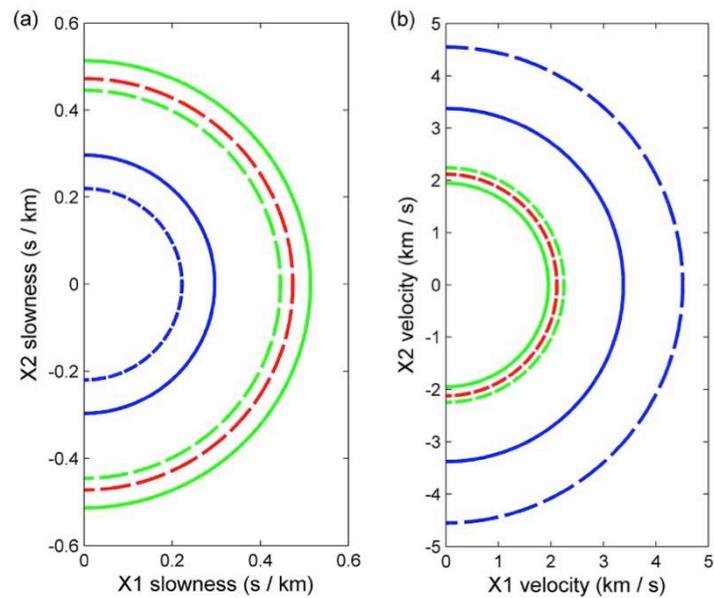
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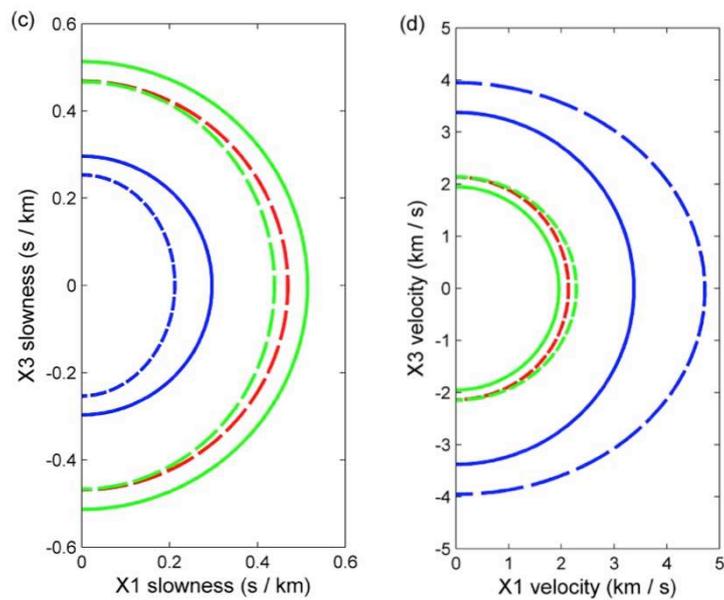
In Figure 9, reservoir depletion induced seismic anisotropy (due to triaxial changes in the stress state) is illustrated for a specific location within the center of the middle reservoir compartment in the middle of the layer (X=4000 m) for the HFT models. Figure 9 shows horizontal and vertical cross-sections of the slowness and group velocity surfaces of the P-, S₁- and S₂-waves for the baseline and 5 year monitor (monitor1) models. Since the baseline model is isotropic, the slowness and group

1 velocity surfaces are circular and only one shear-wave exists. For the horizontal sections, there is an
2 increase in P- and S-wave velocity as well as the development of fast and slow S-waves. However,
3 the surfaces are more or less circular indicating very weak azimuthal anisotropy. For the vertical
4 sections, there is an increase in P- and S-wave velocity as well as the development of shear-wave
5 splitting as the direction of wave propagation moves from vertical to horizontal (typical of VTI
6 symmetry). These results indicate uniaxial deformation due to a larger effective stress change
7 occurring in the vertical direction than in the horizontal direction, which is expected for this central
8 region of the middle compartment.

9

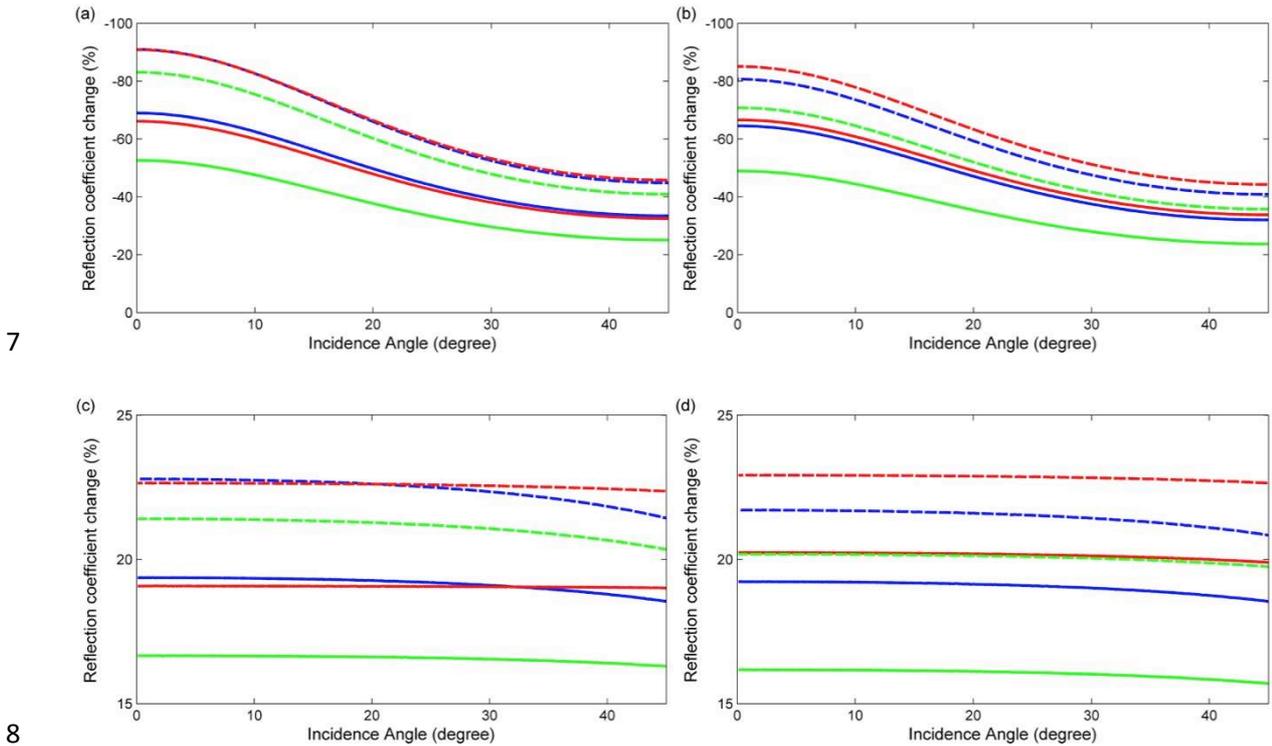


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11

1 **Figure 9.** Shown are the slowness and group velocity surfaces for the HFT graben reservoir model for the
 2 baseline isotropic elastic tensor and the induced anisotropic elastic tensor after 5 years of production (monitor1)
 3 within the middle reservoir compartment (X=4000 m): (top) horizontal cross-section and (bottom) vertical cross-
 4 section. The solid curve represents the baseline model and the dashed curve represents the 5 year monitor
 5 model; blue for the P-wave, red for the fast S₁-wave and green for the slow S₂-wave.
 6

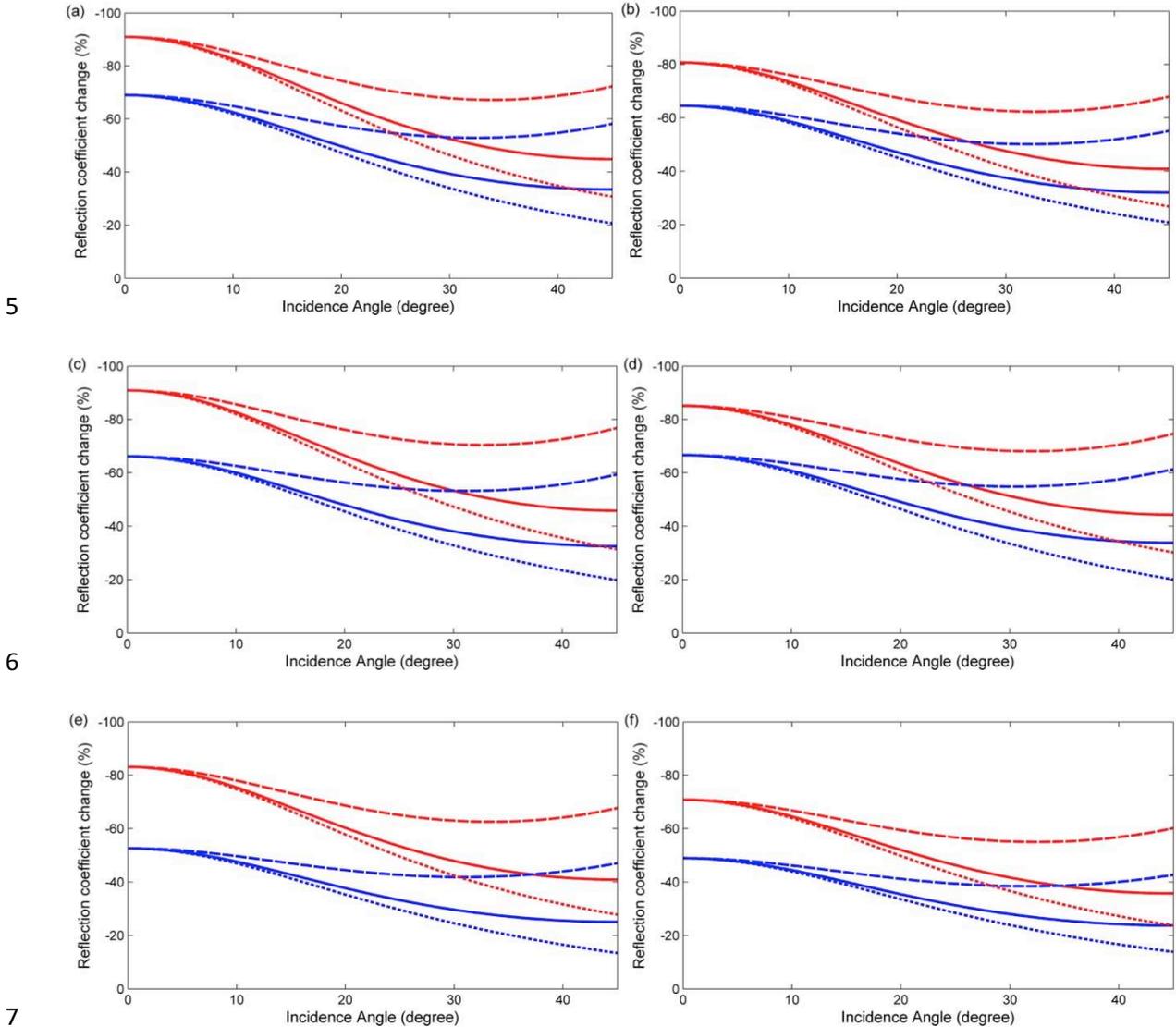


7
 8 **Figure 10.** Time-lapse changes in P-P (a and b) and P-S (c and d) AVO response calculated with respect to the
 9 isotropic baseline model assuming only isotropic changes in elasticity for the HFT graben reservoir model. The
 10 left column represents the top horizon and the right column represents the bottom horizon. The blue curve is the
 11 AVO response change for point a1, the red curve for point 2 and green curve for point 3. The solid curve is
 12 reflection coefficient change for the 5 year monitor (monitor1) model and dashed curve for the 10 year monitor
 13 (monitor2) model.
 14

15
 16 For the model where only induced isotropic changes in elastic properties occur, the time-lapse P-P
 17 AVO response change between the baseline and monitor1, and baseline and monitor2 HFT models is
 18 more sensitive than the P-S AVO response change on both the top and bottom reservoir interfaces for
 19 the selected locations. In Figure 10, the time-lapse changes in the P-P AVO curves (using equation 1)
 20 are on the order of 50% to 90%, whereas the time-lapse changes in the P-S AVO curves (using

1 equation 2) are much smaller (i.e., 16% to 22%). However, the time-lapse changes in the P-P and P-
 2 S AVO response have differing signs and so this could potentially be an indication of
 3 reservoir/pressure compartmentalization related to fluid properties and pore pressure modifications.

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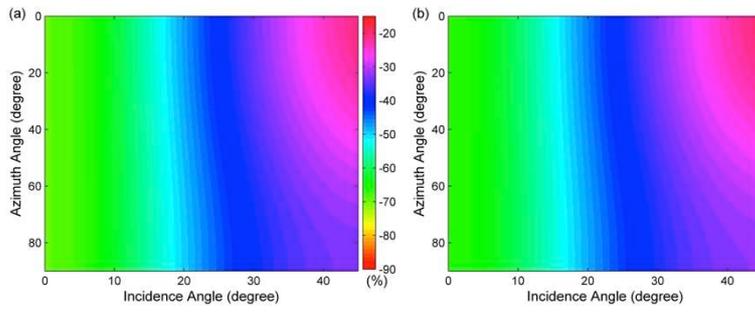
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8 **Figure 11.** Time-lapse changes in P-P AVO response calculated with respect to the isotropic baseline model for
 9 the induced isotropic and anisotropic changes in elasticity for the HFT graben reservoir model. The left column
 10 represents the top horizon and the right column represents the bottom horizon. The top row represents the AVO
 11 response change for point a1, the middle for point a2 and the bottom for point a3. The solid curve represents the
 12 induced isotropic model AVO response, the dashed curve represents the induced anisotropic model with VTI
 13 symmetry and the dotted curve represents the induced anisotropic model with HTI symmetry, with blue for the 5
 14 year monitor (monitor1) model and red for the 10 year monitor (monitor2) model.

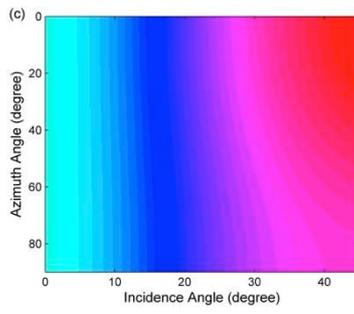
1 For the model where induced anisotropic changes in the elastic properties occur, we explore the
2 signature of VTI and HTI caused by reservoir pressure depletion. In Figure 11, the time-lapse
3 changes in P-P AVO curves are compared for isotropic, VTI and HTI changes for two monitor
4 (monitor1 and monitor2) models of HFT calculated respect to the isotropic baseline model, where the
5 VTI response is computed using equation (3) and for HTI using equation (4). Time-lapse AVO
6 changes increase with reservoir fluid extraction. Both the VTI and HTI cases produce significantly
7 different responses to that of the isotropic case. In all cases the time-lapse AVO changes are all
8 negative and decline with increasing incidence angle. While the time-lapse AVO changes for HTI are
9 smaller than that of the isotropic model, the results for VTI are much larger than the isotropic model.
10 In monitor1, the time-lapse AVO changes have similar magnitude (i.e., $\pm 5\%$ differences) for the top
11 and the bottom reservoir horizons. In monitor2 the time-lapse AVO changes for the top and the
12 bottom reservoir horizons can differ by up to $\pm 13\%$. This might be indicative of the greater influence of
13 reservoir compaction due to increasing effective stress within the producing reservoir being larger
14 than the overburden and underburden extension (e.g., Sayers 2010).

15 Figure 12 displays the time-lapse changes in P-P AVOA due to induced HTI anisotropy (equation 4)
16 for the top and bottom reservoir horizons between the baseline and monitor1, and baseline and
17 monitor2 models at the three lateral locations (a1, a2 and a3) using the elastic parameters in Table 1
18 for the HFT model. Fluid depletion induced HTI anisotropy produces different AVOA responses at the
19 selected locations. It can be noted that time-lapse AVOA changes range from -90% to -15% for
20 increasing incidence angles (i.e., 0° to 45°). As well, the time-lapse AVO changes with azimuth (i.e.,
21 0° to 90°) are significant, especially for incidence angles larger than 30° .

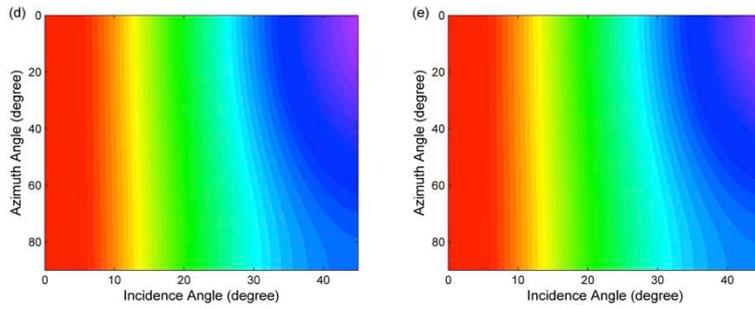
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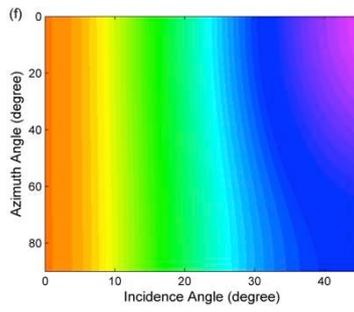
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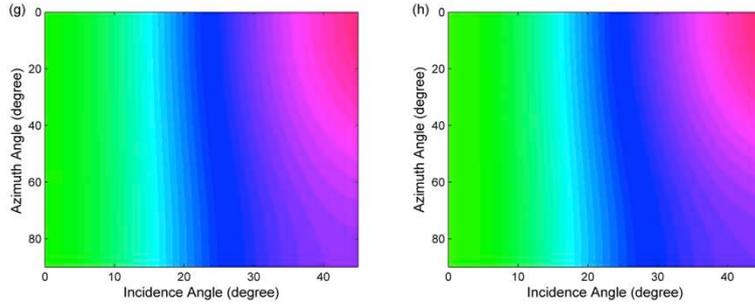


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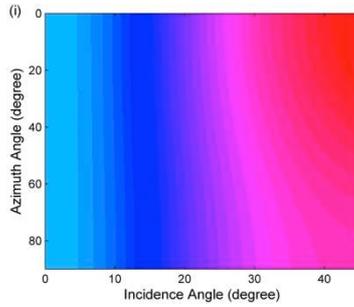


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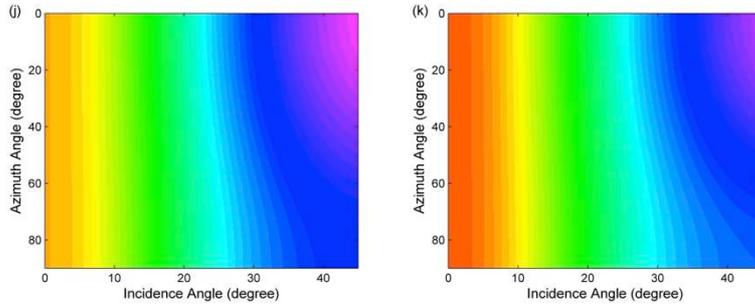
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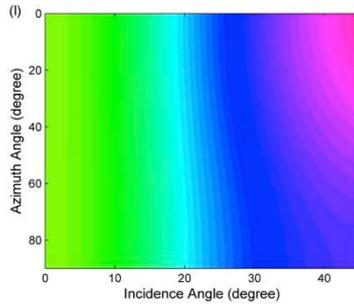
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5 **Figure 12.** Time-lapse changes in P-P AVOA response calculated with respect to the isotropic baseline model for
 6 the induced anisotropic changes in elasticity for the HFT graben reservoir model. The top two rows represent the
 7 top reservoir horizon and the bottom two rows represent the bottom reservoir horizon. The left column represents
 8 the AVOA response change for point a1, the middle column for point a2 and the right column for point a3. The
 9 first and third rows are AVOA response change for the 5 year monitor (monitor1) model and the second and
 10 bottom rows for the 10 year monitor (monitor2) model.

Parameter Model	A	G _{iso}	G _{aniso}	Parameter Model	A	G _{iso}	G _{aniso}
Baseline a1	-0.1085	-0.4016	0	Baseline a1	0.1124	0.4002	0
Baseline a2	-0.1083	-0.4019	0	Baseline a2	0.1143	0.3996	0
Baseline a3	-0.1085	-0.4016	0	Baseline a3	0.1124	0.4002	0
Mon1(HFT) a1	-0.0337	-0.3831	-0.0240	Mon1(HFT) a1	0.0398	0.3819	0.0192
Mon1(HFT) a2	-0.0367	-0.3806	-0.0231	Mon1(HFT) a2	0.0382	0.3773	0.0280
Mon1(HFT) a3	-0.0514	-0.3907	-0.0241	Mon1(HFT) a3	0.0574	0.3903	0.0181
Mon2(HFT) a1	-0.0098	-0.3716	-0.0286	Mon2(HFT) a1	0.0217	0.3712	0.0294
Mon2(HFT) a2	-0.0099	-0.3643	-0.0259	Mon2(HFT) a2	0.0171	0.3624	0.0261
Mon2(HFT) a3	-0.0184	-0.3746	-0.0240	Mon2(HFT) a3	0.0328	0.3755	0.0223
Mon1(LFT) a1	-0.0794	-0.3938	-0.0051	Mon1(LFT) a1	0.0823	0.3922	0.0051
Mon1(LFT) a2	-0.1167	-0.4045	0	Mon1(LFT) a2	0.1272	0.4037	-0.0049
Mon1(LFT) a3	-0.1131	-0.4029	0	Mon1(LFT) a3	0.1164	0.4017	0
Mon2(LFT) a1	-0.0296	-0.3834	-0.0075	Mon2(LFT) a1	0.0823	0.3922	0.0051
Mon2(LFT) a2	-0.1182	-0.4048	0	Mon2(LFT) a2	0.1272	0.4037	-0.0049
Mon2(LFT) a3	-0.1133	-0.4030	0	Mon2(LFT) a3	0.1164	0.4017	0

1

2

Table 2 The AVOA intercept (A) and gradients (G_{iso} and G_{aniso}) calculated on the top horizon (left) and the bottom horizon (right) at three lateral locations (a1, a2 and a3) for the graben-style reservoir models of baseline, monitor1 and monitor2 having high (HFT) and low (LFT) fluid-flow fault transmissibility.

3

4

5

Azimuth Model	0°	30°	60°	90°	Azimuth Model	0°	30°	60°	90°
Baseline a1	-0.4016	-0.4016	-0.4016	-0.4016	Baseline a1	0.4002	0.4002	0.4002	0.4002
Baseline a2	-0.4019	-0.4019	-0.4019	-0.4019	Baseline a2	0.3996	0.3996	0.3996	0.3996
Baseline a3	-0.4016	-0.4016	-0.4016	-0.4016	Baseline a3	0.4002	0.4002	0.4002	0.4002
Mon1(HFT) a1	-0.4071	-0.4011	-0.3891	-0.3831	Mon1(HFT) a1	0.4011	0.3962	0.3866	0.3819
Mon1(HFT) a2	-0.4037	-0.3979	-0.3863	-0.3806	Mon1(HFT) a2	0.4053	0.3983	0.3843	0.3774
Mon1(HFT) a3	-0.4148	-0.4088	-0.3967	-0.3907	Mon1(HFT) a3	0.4084	0.4039	0.3948	0.3903
Mon2(HFT) a1	-0.4002	-0.3930	-0.3787	-0.3716	Mon2(HFT) a1	0.4006	0.3933	0.3785	0.3712
Mon2(HFT) a2	-0.3902	-0.3837	-0.3708	-0.3643	Mon2(HFT) a2	0.3885	0.382	0.3689	0.3624
Mon2(HFT) a3	-0.3986	-0.3926	-0.3806	-0.3746	Mon2(HFT) a3	0.3978	0.3922	0.3811	0.3755
Mon1(LFT) a1	-0.3989	-0.3977	-0.3951	-0.3938	Mon1(LFT) a1	0.3973	0.3960	0.3935	0.3922
Mon1(LFT) a2	-0.4045	-0.4045	-0.4045	-0.4045	Mon1(LFT) a2	0.3988	0.4000	0.4025	0.4037
Mon1(LFT) a3	-0.4029	-0.4029	-0.4029	-0.4029	Mon1(LFT) a3	0.4017	0.4017	0.4017	0.4017
Mon2(LFT) a1	-0.3909	-0.3891	-0.3853	-0.3834	Mon2(LFT) a1	0.3905	0.3892	0.3866	0.3854
Mon2(LFT) a2	-0.4048	-0.4048	-0.4048	-0.4048	Mon2(LFT) a2	0.4043	0.4043	0.4043	0.4043
Mon2(LFT) a3	-0.4030	-0.4030	-0.4030	-0.4030	Mon2(LFT) a3	0.4017	0.4017	0.4017	0.4017

6

7

Table 3 The AVOA gradients versus azimuths $G_{iso}+G_{aniso}\cos^2\phi$ ($\phi = 0^\circ, 30^\circ, 60^\circ$ and 90°) for the top horizon (left) and the bottom horizon (right) at three lateral locations (a1, a2 and a3) for the graben-style reservoir models of baseline, monitor1 and monitor2 having high (HFT) and low (LFT) fluid-flow fault transmissibility.

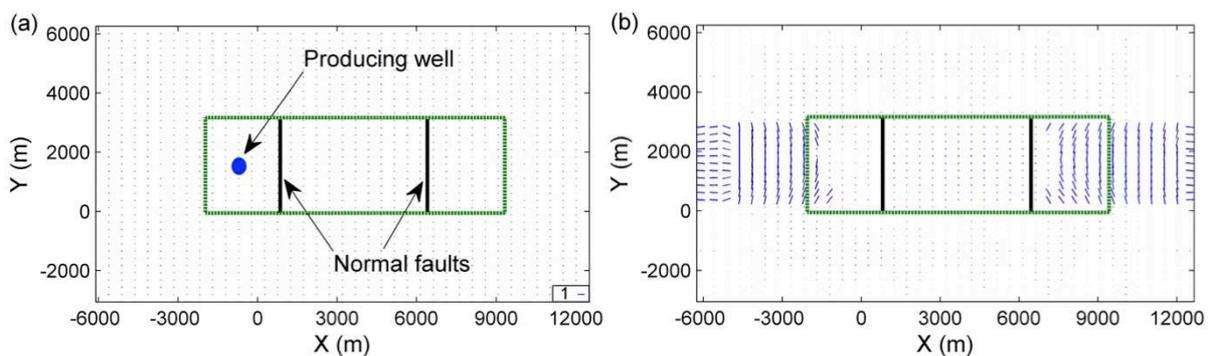
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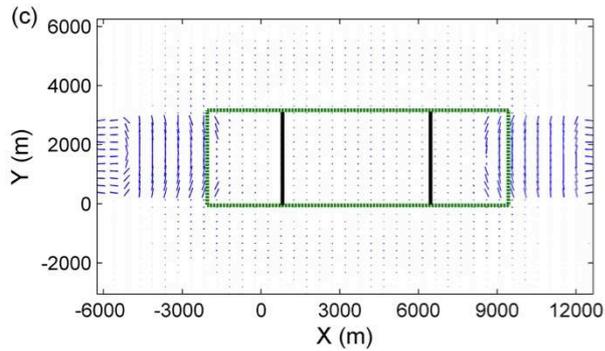
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1 The AVOA intercept A and gradients G_{iso} and G_{aniso} are calculated using equation (5) for the top
2 and bottom reservoir horizons at the three lateral locations in the HFT and LFT reservoir models (see
3 Table 2). For low to moderate source-receiver offset, the P-P AVOA gradient variation
4 $G_{iso} + G_{aniso} \cos^2 \phi$ with azimuths $\phi = 0^\circ, 30^\circ, 60^\circ$ and 90° for the top and bottom reservoir
5 horizons for the baseline, monitor1 and monitor2 models are shown in Table 3. In HFT models, as the
6 azimuth increases the AVOA gradients decrease for both monitor1 and monitor2 models, with no
7 variation for the baseline model as expected. The estimates for the top and bottom horizons have
8 opposing signs (i.e., negative for the top horizon and positive for the bottom horizon). While the
9 gradients within the two end compartments are similar, the gradients in the middle compartment are
10 smaller. This suggests different effective stress states within these compartments due to reservoir
11 geometry and stress arching (see Angus et al. 2010). In LFT models, as the azimuth increases the
12 AVOA gradients decrease for both monitor1 and monitor2 models at the left producing compartment
13 and are constant for the middle and right compartments, except for the monitor1 model at bottom
14 horizon where the AVOA gradients increase with increasing azimuth. This indicates that the major
15 effective stress changes are constrained to the left compartment, and none (or negligible) induced
16 effective stress changes occur across the faults due to low fluid-flow transmissibility (i.e., reservoir
17 compartmentalization).

18 In general, P-P AVOA analysis has been used extensively to characterise *in situ* fracture networks
19 (e.g., Hall and Kendall 2003; Shams and MacBeth 2003). However, there have been studies where
20 the AVOA technique has been used as a time-lapse seismic attribute to monitor reservoir
21 compartmentalization and fluid-flow (e.g., Hall and MacBeth 2001). Angus et al. (2013) and Angus et
22 al. (2015) make the first attempt at linking field measurements of AVOA with hydro-mechanical
23 simulation, yielding reasonable first-order matches for several horizons.



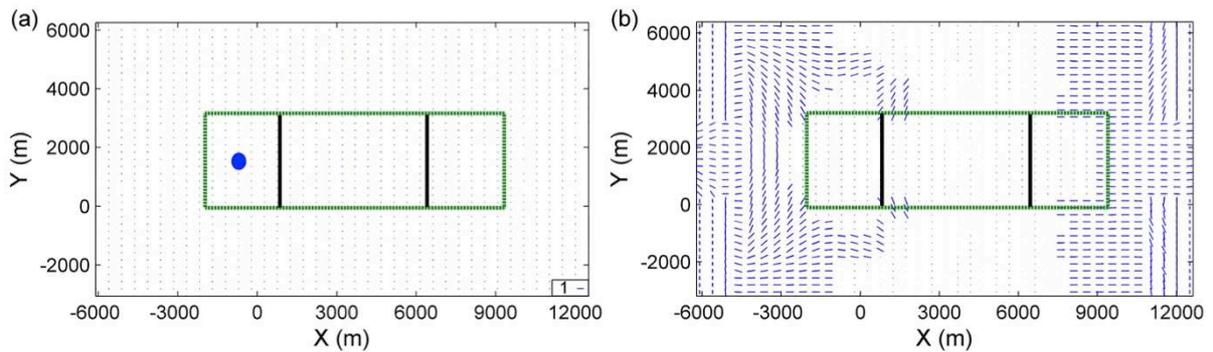
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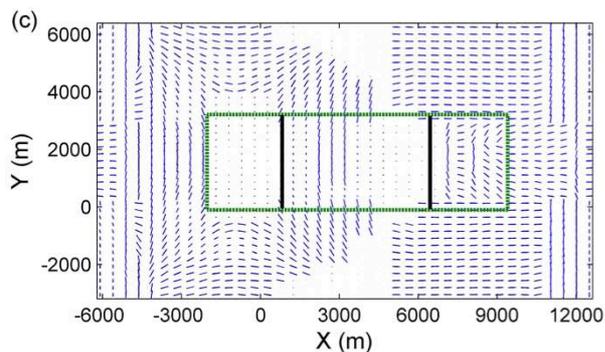
1

2 **Figure 13.** The predicted AVOA response for the top horizon of the high fluid-flow fault transmissibility graben
 3 reservoir model calculated from the output of the hydro-mechanical simulation for the (a) baseline, (b) monitor1
 4 and (c) monitor2 cases. The three reservoir compartments are subdivided by the two normal faults (two black
 5 lines). The producing well (defined by a blue dot) is situated in the left compartment. In this Figure and Figure 14,
 6 the sticks represent the fast direction of the P-wave anisotropy.

7



8



9

10 **Figure 14.** The predicted AVOA response for the top horizon of the low fluid-flow fault transmissibility graben
 11 reservoir model calculated from the output of the hydro-mechanical simulation for the (a) baseline, (b) monitor1
 12 and (c) monitor2 cases. The three reservoir compartments are subdivided by the two normal faults (two black
 13 lines).

14

1 In Figures 13 and 14, the AVOA response calculated using the output from the hydro-mechanical
2 graben reservoir model is shown for the top reservoir horizon for the HFT and the LFT models,
3 respectively. It should be noted that we only display the fast anisotropy direction and not the AVOA
4 magnitude. To predict the AVOA response, we calculate the complex valued reflection coefficients
5 using an anisotropic layer-matrix approach (e.g., see Angus & Thomson 2012 for description of the
6 theory). The reflection coefficient of any interface between two layers is evaluated using the elasticity
7 tensor of the upper and lower layer, where the algorithm subsequently provides synthetic amplitudes
8 at specified offsets and azimuths for each grid point along the chosen horizon. It should be stressed
9 that the predicted AVOA response will be sensitive to not only the geometry of the model but also the
10 stress-dependence of the nonlinear rock physics transform. In Figure 13, the AVOA response is
11 shown for the baseline, monitor1 and monitor2 models for the case of high fluid-flow fault
12 transmissibility. For the baseline there is no azimuthal dependence. However, due to reservoir
13 production both the monitor1 and monitor2 models develop induced anisotropy primarily along the
14 outer edges of the reservoir compartments. In Figure 14, the AVOA response is shown for the
15 baseline, monitor1 and monitor2 models for the case of low fluid-flow fault transmissibility. In this
16 example, there is significant heterogeneity in the AVOA pattern, where induced anisotropy develops
17 around the left-hand (i.e., the compartment with the producing well).

18 **4. Discussion and conclusion**

19 In this paper, we explore the impact of reservoir azimuthal anisotropy on time-lapse seismic
20 reflection amplitude changes using anisotropic ray tracing simulation, as well as the exact and
21 approximate reflectivity solutions. Large deviations in reflection amplitude are observed for ray tracing
22 calculations through the models experiencing isotropic and anisotropic induced elasticity changes.
23 The time-lapse amplitude changes for both P-P and P-S waves are significant for the four-layer
24 dipping model and the hydro-mechanical graben-style reservoir model. The results stress the need to
25 suitably compensate for the influence of subsurface structure, such as dipping horizons in an isotropic
26 medium which might lead to 'false' azimuthal variations of reflection amplitude similar to that caused
27 by seismic azimuthal anisotropy, prior to apply AVOA technique to analyse time-lapse seismic
28 observations. There are observable differences in reflection amplitude perturbations between the

1 induced isotropic and induced anisotropic models and this indicates the importance of including the
2 influence of induced anisotropy.

3 The time-lapse AVO and AVOA signatures, calculated by applying approximate reflectivity
4 formulations and elasticity derived from the hydro-mechanical graben-style reservoir model, indicate
5 noticeable deviations between models experiencing isotropic and anisotropic TI (VTI and HTI)
6 elasticity changes due to triaxial changes in the stress state. It is worth noting that seismic reflection
7 amplitude is sensitive to the pressure and fluids properties perturbations, which can lead to varied
8 AVO responses. For instance, Landrø (2001) and Stovas and Landrø (2005) use the time-lapse AVO
9 technique to discriminate between pressure and fluid saturation changes with some degree of
10 success.

11 The P-P AVOA predictions show significant time-lapse changes within the graben-style reservoir
12 hydro-mechanical model. The AVOA patterns are consistent with the expected induced seismic
13 anisotropy due to the triaxial changes in effective stress field related to fluid extraction,
14 geomechanical compaction and reservoir compartmentalization. For the HFT model (see Figure 13),
15 although there is observable induced anisotropy on the right compartment (furthest from the
16 producing well), the reservoir compartments display broadly similar characteristics and thus indicate
17 that all compartments are experiencing the same pore pressure reduction (as expected). In other
18 words, the AVOA pattern is consistent with uniaxial deformation, where VTI anisotropy can develop
19 but not azimuthal or HTI anisotropy. For the LFT model (see Figure 14), the AVOA pattern suggests
20 the development of reservoir compartmentalization and also indicates that the reservoir is not
21 experiencing uniaxial deformation but rather a more complicated stress regime. Thus, time-lapse
22 AVOA technique can be applied not only to assess reservoir compartmentalization and fluid flow, but
23 also as an aid in detecting and understanding changes in the stress state as well as calibrate hydro-
24 mechanical models.

25 Nevertheless, the employed synthetic reservoir models in this study are far less complex for
26 practical utility. For subsurface earth models having more complicated geological settings,
27 discriminating the influence of compaction-induced velocity heterogeneity from that of seismic
28 anisotropy is still difficult. Hence, in the presence of azimuthal velocity variations, time-lapse seismic
29 analysis might be biased if static azimuthal anisotropic velocity variations are not taken into

1 consideration. However, errors in estimating induced seismic anisotropy from time-lapse
2 measurements may be smaller compared to other sources of time-lapse error, such as survey
3 repeatability.

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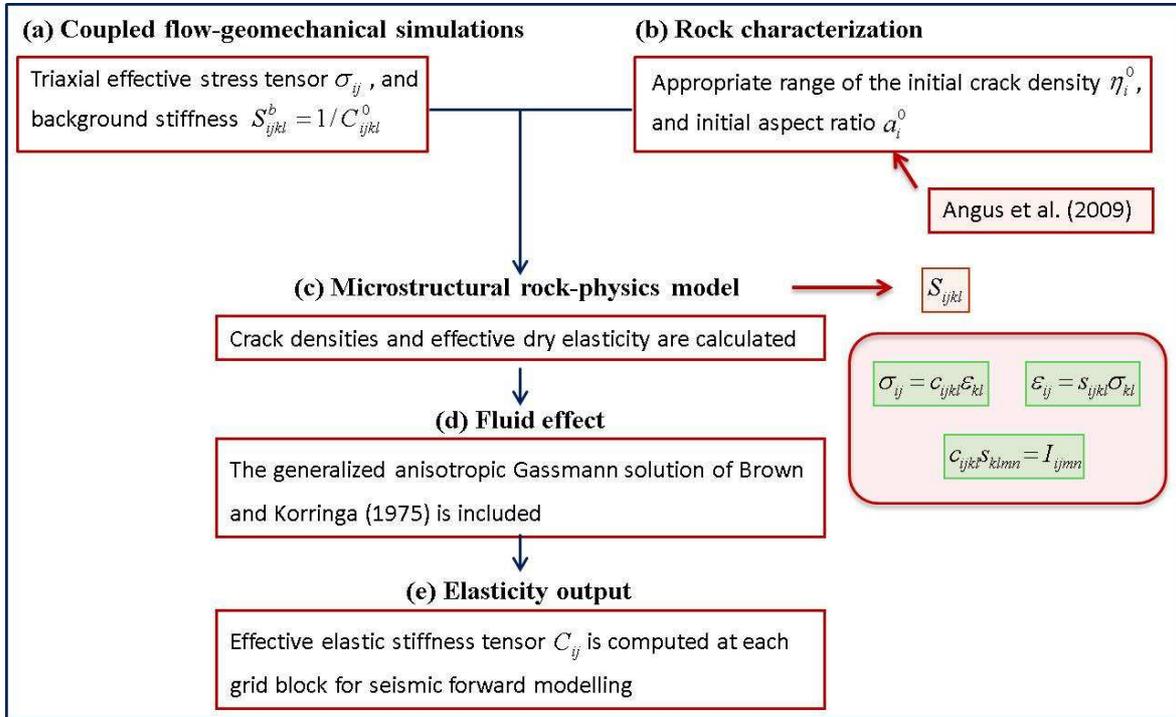
7 **Appendix A. Dynamic elastic model construction from the output of integrated** 8 **hydro-mechanical simulations**

9 For the two-fault graben-style reservoir model having high and low fault fluid-flow transmissibility,
10 the integrated reservoir fluid-flow and geomechanical simulations were implemented through explicitly
11 coupling (two-way iteratively or loosely) the TEMPEST reservoir simulation model (Roxar Ltd.) for the
12 fluid-flow calculations within the producing reservoir and the finite element based ELFEN simulator
13 (Rockfield Ltd.) for the geomechanical deformation predictions and stress path evolutions within the
14 reservoir and the bounding rocks. An MPI interface is used to pass pore pressure calculations from
15 TEMPEST to ELFEN and pore volume changes from ELFEN to update TEMPEST (Angus et al. 2011;
16 Segura et al. 2011). Geomechanical deformation is dependent on the Young's modulus (E) and
17 Poisson's ratio (ν), as well as the porosity (ϕ). The assumed Young's modulus and Poisson's ratio
18 are: $E = 5.35\phi^{-0.372}$ GPa and $\nu = 0.45$ for the bounding material, and $E = 13.8\phi^{-0.4}$ GPa and
19 $\nu = 0.25$ for the non-sandstone reservoir (Segura et al. 2011).

20 The effective stress tensor, pore-fluid pressure and static stiffness (high strain magnitude, low
21 strain rate) are output every six month of the coupled simulation and are used as input for the micro-
22 crack rock physics model (Verdon et al. 2008; Angus et al. 2009) to construct the dynamic elastic
23 models (dynamic stiffness) for seismic response prediction (see Figure A.1). An initial crack density
24 η^0 and an initial aspect ratio a^0 are used for the micro-crack rock physics model and have been
25 calibrated using dry and saturated core data from the literatures. For the graben reservoir model, the
26 values used are: $\eta^0 = 0.25$ and $a^0 = 0.001$ for the sandstone reservoir and $\eta^0 = 0.125$ and
27 $a^0 = 0.0005$ for the non-reservoir shale (Angus et al. 2009). The stress-dependent rock physics

1 model creates the 21 components of the full dynamic stiffness tensor, to describe the full seismic
 2 response for wave propagation through anisotropic media.

3



4

5 Figure A.1. Workflow to construct stress-dependent dynamic elastic model based on the output of
 6 coupled fluid-flow and geomechanical simulations using the analytical microcrack nonlinear stress
 7 elasticity dependency rock-physics model. Figure from Verdon et al. (2008) and Angus et al. (2009)
 8 with some modifications.