Quantitatively understanding the imprint of fractures in the seismic wave-field

Ekaterina Vsemirnova (1), Alan Roberts* (1), Richard Hobbs (2), Jon Long (1), Richard Jones (1) & Ken McCaffrey (2) *contact: alan@geospatial-research.co.uk

(1) Geospatial Research Ltd, Suite 7, 1, Harrison House, Hawthorn Terrace, Durham DH1 4EL, UK; (2) Durham University, Department of Earth Sciences, Durham DH1 3LE, UK

Introduction

Understanding fracture connectivity in the shallow crust is of major importance for the development and production of hydrocarbon fields. **Fracture datasets collected from wells have limited spatial coverage compared to remote sensing methods such as seismic imaging**, Ground Penetrating Radar (GPR), electromagnetic recording, Terrestrial Laser Scanning (TLS), and Unmanned Aerial Vehicles ("drones"). **In this study we focus on quantitatively understanding the imprint of several classes of realistic fracture network on the seismic wave-field.**

The thin, often rough sheet-like form of fractures (Fig. 1) **poses challenges for reliable imaging** of fracture networks using seismic methods, and the seismic response can be significantly altered by the highly variable dip of the fractures. A number of studies have been published showing the effect of the presence of simple fracture configurations on the synthetic seismic wave-field. **At present**, however, due to the inherent complexity of real fracture networks, **there is limited understanding about the extraction of network characteristics from seismic data**.

Our work involves **forward seismic wave-field simulation of a range of complex fracture networks** derived from detailed quantitative characterisation of fractures in outcrop. **We aim to build a library of calibrated examples from which to both develop understanding of the information contained in a seismic dataset related to the fracture network, and further research into the quantitative inversion and imaging of such information.** Here we show the results of a 2D case study on several simple configurations of fractures, and a more complex case, and show the effect of the fractures on the wave-field using a range of quantitative measures. We are developing this approach for a 3D setting.

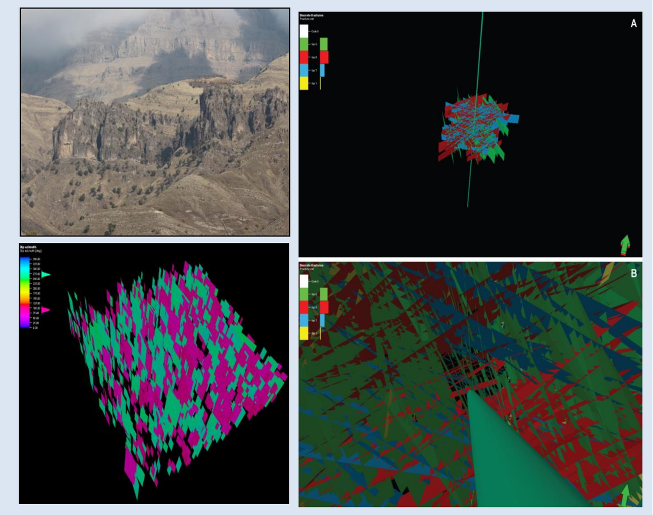


Fig.1. Fractured rocks in the field, and example Discrete Fracture Network models built in Petrel. Fractures are commonly modelled as arrays of intersecting sheets.

Methodology

We use the **2D Finite Difference (FD) modelling code** FDELMODC (Thorbecke and Draganov 2011) to simulate the 2D wavefield for a **range of fracture networks**. To develop our analysis framework, we concentrate on **three simple cases** (Fig. 2). In a similar manner to Stallone (2012), we consider the "hard scattering regime" (Levander et al., 1994), with model properties as shown in Table 1.

	Backg'd	Fracture	Base
Vp km/s	5490	1690	6500
Vs km/s	3169	975	3752
Cp kgm^{-3}	2650	1000	3500

Table.1. Model properties

11 shots were modelled located equidistantly across the top of the model (**separation 500m**), and receivers with a 4ms time sampling positioned along the top of the model with a 5m spacing. A **Ricker wavelet** with an 8Hz peak frequency and 0.12ms sampling interval was used as a source. A delay of 350ms was introduced to the wavelet to avoid issues with wraparound. We aim to **study the effect of the fracture network on the basement reflection**. Therefore, for each of the model cases (a), (b) & (c) (Fig. 2), 3 simulations were performed:

1) using a **"clean" reservoir** (no fractures)
2) A model simply consisting of the fractures (**no basement**)
3) Both **fractures and basement** present.

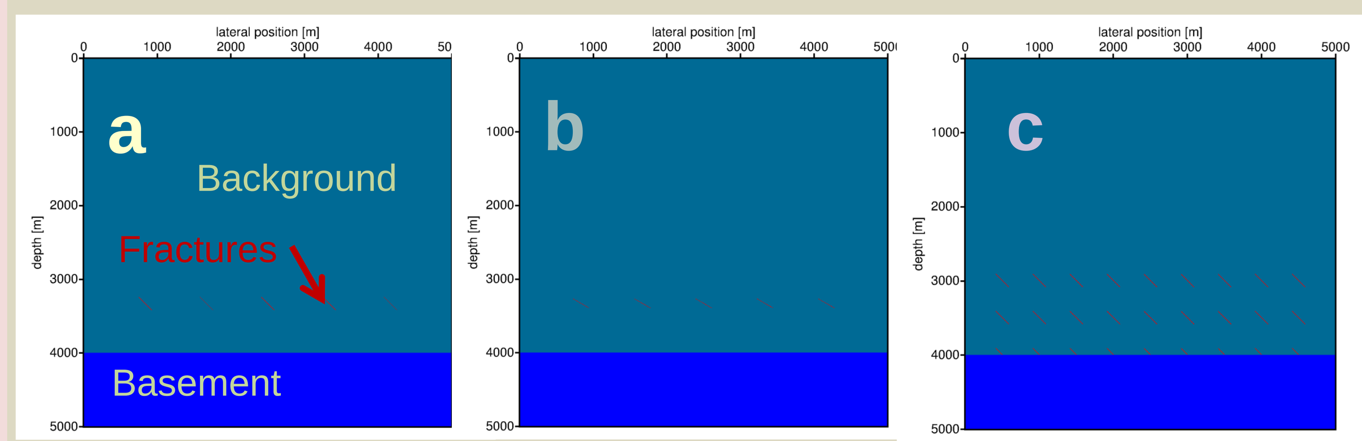


Fig.2. Three simple synthetic fractured reservoir models. **(a) 5 fractures inclined at 45° to vertical; (b) 5 fractures inclined at 60° to vertical; (c) Dual layered 9 fractures at 45° to vertical.** The seismic properties are shown in Table 1.

In each case 1-3, **shot gathers and time snapshots** of the wave-field were generated, and by **differencing** the cases 1-3, the **effect of the fractures on the basement reflection** can be isolated.

To understand the simulation results we display the results (see right) for each of the PP and SS wave-fields for single shots for the fractured reservoirs shown in Fig. 2 in a number of domains; (1) **time-offset** (t-x) domain to present the original synthetics, (2) the **frequency-offset** domain to see the frequency content in a variety of models, (3) the **phase spectrum-offset** domain and (4) **intercept time-slowness** (tau-p) domain. Each of these domains reveal different aspects of seismic record. In addition, we consider the **effect of the fractures on the amplitude of the CDP-stacked basement reflection**.

Technical background notes:

*The **phase component** of the spectrum (FFT) is an extremely important characterisation tool for seismic signals originating from local medium objects. Examples of such signals are reflections of different types, in particular, PP and PS waves, related to the thin layer objects. The phase component of the spectrum contains more information than its amplitude component, which is the usual tool for dynamic analysis of seismic data. In fact, the amplitude spectrum mostly represents information about the integral or energy characteristics of the signal, while the phase spectrum contains information about differential characteristics (Mitrofanov & Priimenko, 2008).*

*The **tau-p transform** maps linear event onto points and hyperbolic moveout curves onto ellipses (Diebol & Stoffa, 1981, Van der Baan, 2009). It also provides pertinent information on the horizontal slowness of the recorded wave-field (Snell's law). Snell's law states that the horizontal slowness is conserved in layered media. Thus the tau-p domain reveals the horizontal slowness at all depths.*

*In wave theory the **horizontal slowness plays an important role**. In stratified media, for instance, the complete response requires the coupling between P and SV waves to be considered, both at the free surface and throughout the stratification. The horizontal slowness is conserved under conversion of wave type, so the **entire reflection response of a portion of the stratified medium can be written in terms of p & either frequency or time** (Kennett, 1981).*

Although the travel time curve T(X) is not necessarily single valued, the tau(p) relation has the advantage of being single valued almost everywhere (Kennett, 1981) and also being monotonically decreasing with increasing p.

A velocity model discontinuity (reservoir base, for example) leads to a triplication in travel time if reflected waves are taken into account. If only refracted waves are used, there is a gap in the tau(p) relation for slowness corresponding to the jump at the interface. For small p (high velocities) there will be both reflected and refracted tau(p) branch.

Discussion and Conclusions

Results for models a-c are shown in the panels on the right. Based on work so far, we make the following general observations from the single shot multi-domain plots:

(a) The **seismograms** overall demonstrate **scattering and constructive interference effects dependent on the number of fractures and azimuth of fractures** (currently set to the same value for the whole fracture distribution). We have also modelled finite aperture azimuthal variation, however for simplicity we show results only for the fixed azimuth cases.
(b) A relatively simple **spectral amplitude** pattern is seen with **little model-dependent variation**.
(c) The **phase spectrum is sensitive**, particularly at higher frequencies, **to both the number and azimuth of fractures**. Notice in particular the higher phase wrap-around rate for the more steeply oriented fractures in both the PP and SS cases.
(d) The **tau-p domain shows multiple branches** at low p values **depending on the model complexity**. In particular, for the higher fracture density cases, we see multiple events at higher slowness values, indicating a retarding effect of the fracture network on the basement reflection energy.

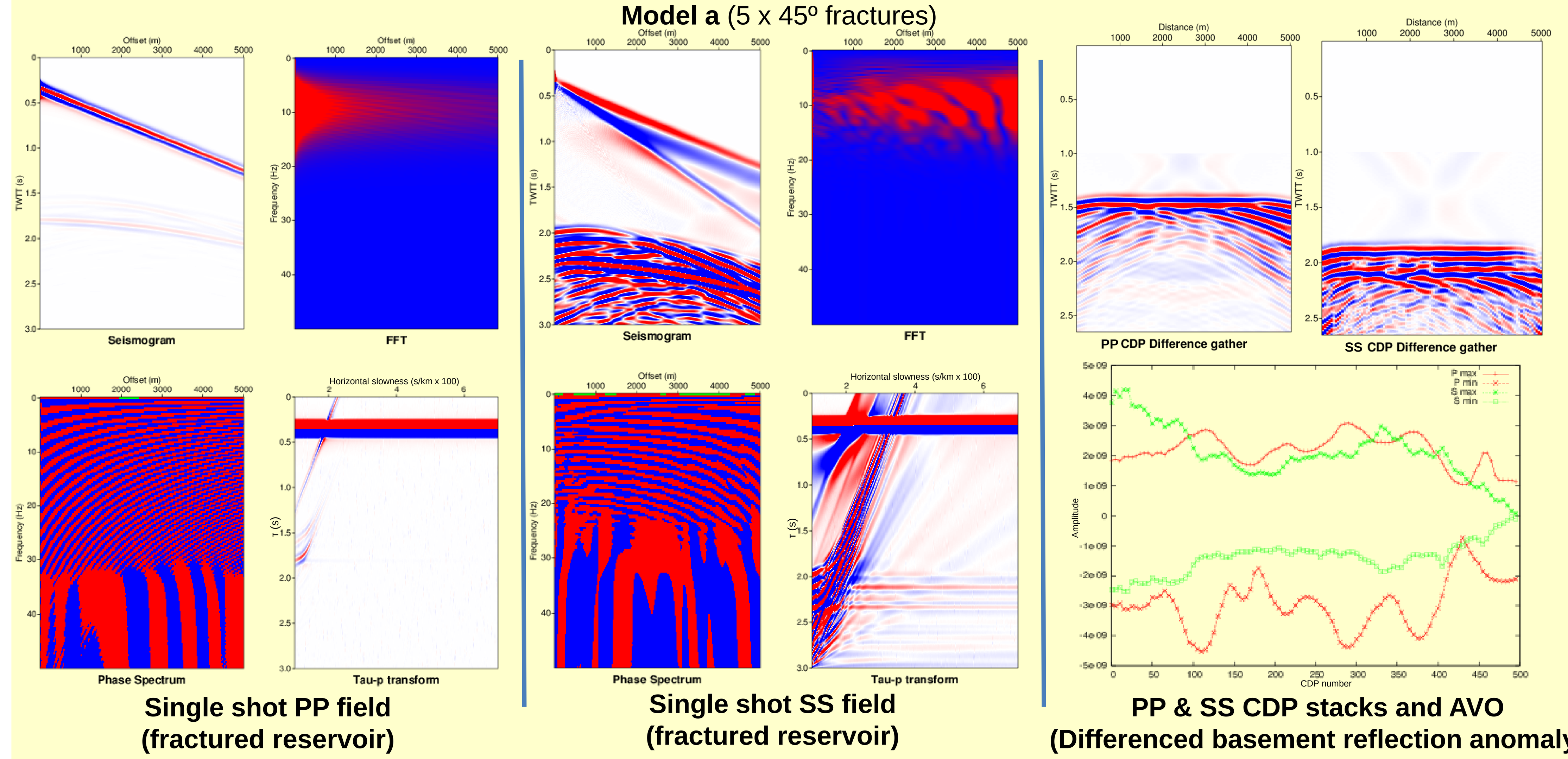
In addition to the cases shown here, we modelled the case of a single fracture using the properties indicated. Little discernible effect on the wave-field was seen in each of the domains in comparison to the "clean reservoir" wave-field.

From the **stacked CDP amplitude plots**, we draw the following conclusions:

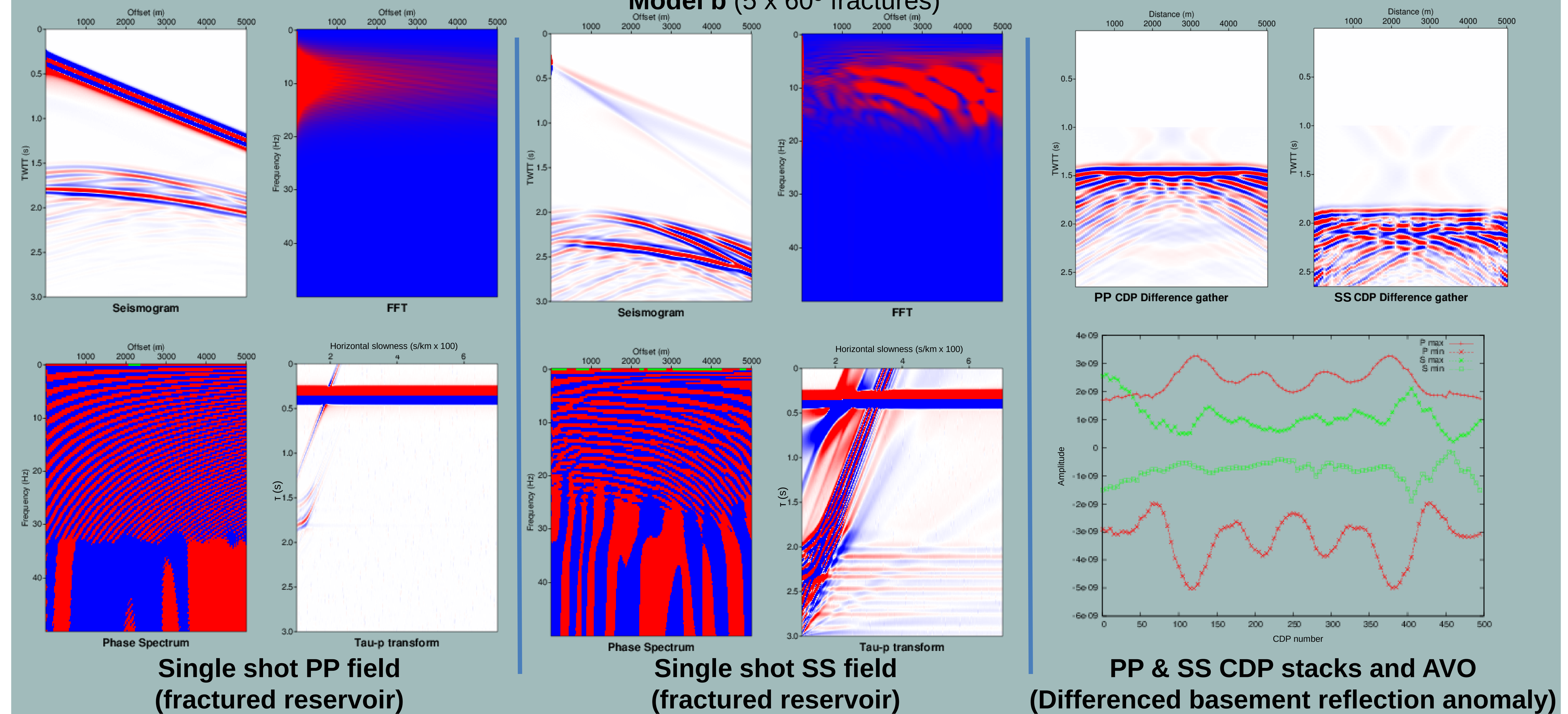
(a) The **amplitude spatial distribution contains periodicity** which may be useful for characterising fracture **density** and **orientation for low fracture densities**.
(b) The relative effect on the P-wave and S-wave amplitudes shows dependence on the fracture density.

Results

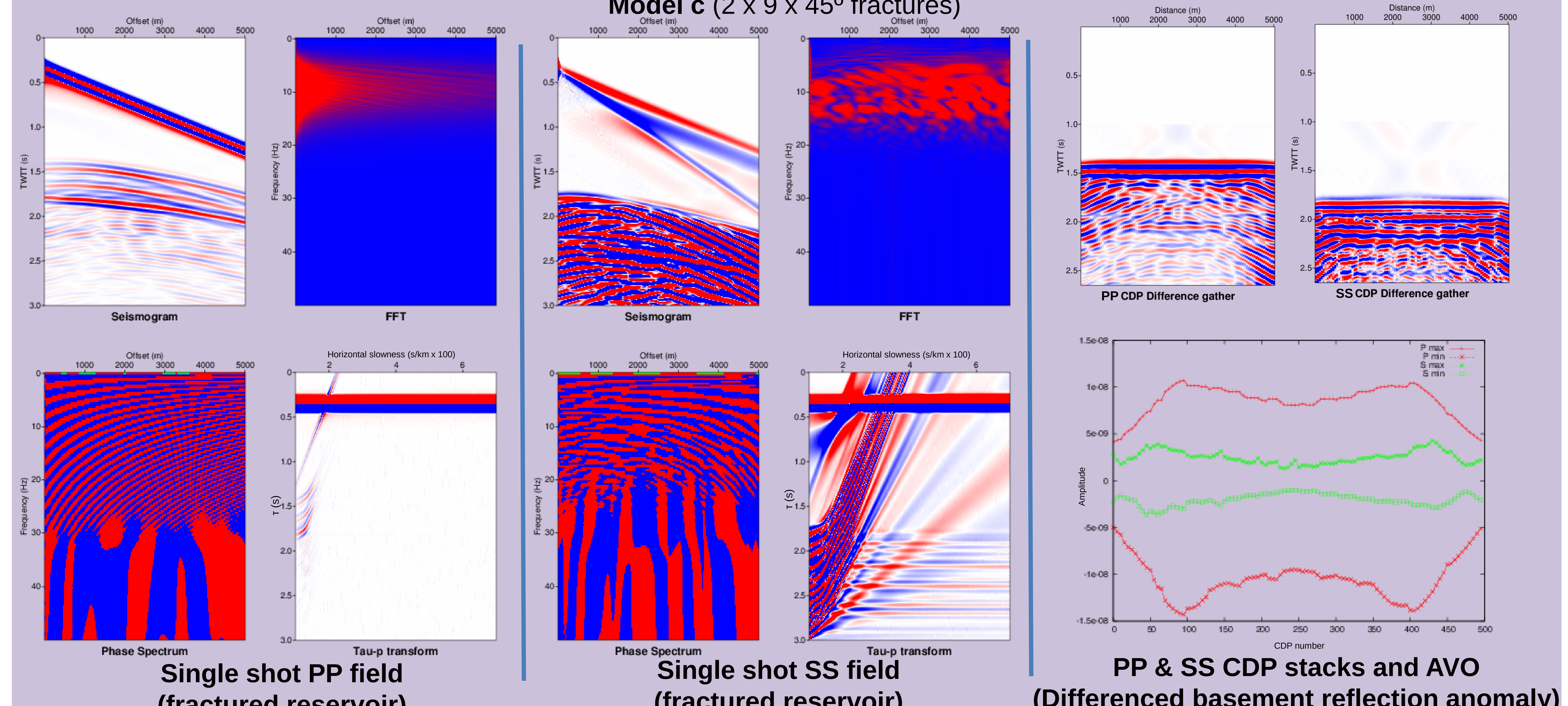
Model a (5 x 45º fractures)



Model b (5 x 60º fractures)



Model c (2 x 9 x 45º fractures)



References

Diebold, J.B. & Stoffa, P.L., 1981. The traveltime equation, tau-p mapping, and inversion of common midpoint data, Geophysics, 46, 238–254.
Kennett, B.L.N., 1981, Slowness techniques in seismic interpretation, J. Geophys.Res., 86, B12, 11575-11584.
Levander, A., R. W. Hobbs, S.K. Smith, R. W. England, D. B. Snyder & K. Holliger, 1994. The crust as a heterogeneous optical medium, or crocodiles in the mist. Tectonophysics 232 (1-4), pp 281-97
McMechan, G. A. & Yedlin, M. J., 1981, Analysis of dispersive waves by wave-field transformation. Geophysics 46(6), pp 869-874
Mitrofanov, G., & V. Priimenko, 2008, Phase Spectra in Seismic Data Processing, Intern. Conf. On Math. Methods in Geophysics "MMG-2008", Novosibirsk, Russia.
Stallone, A., 2012, Seismic signatures of 2D fracture networks, Master's Thesis, Delft University of Technology.
Thorbecke, J. and Draganov, D., 2011, Finite-Difference modeling experiments for seismic interferometry, Geophysics, 76 (6), pp H1-H18, doi: 10.1190/GEO2010-0039.1
Van der Baan, M., 2009, The origin of SH-wave resonance frequencies in sedimentary layers, Geophys.J.Int., 2009, 178, 1587-1596.