Final report VISTA 2015

SEISMIC WAVEFORM INVERSION FOR FRACTURE PARAMETERS

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Institution:	University of Bergen
Project duration:	3 years
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Project number:	6263

Background

A large percentage of the worlds remaining hydrocarbon reserves are associated with fractures, either in the context of naturally fractured (carbonate or tight sandstone) reservoirs or unconventional resources like gas shales. Fractures are also relevant for CO2 sequestration and geothermal energy.

Fractures can have a significant effect on seismic wave propagation and fluid flow, suggesting that it may be possible to derive information about fracture parameters related to permeability from seismic data alone or in combination with production data. Since fractures tend to have a preferred orientation, anisotropy effects are important in this context.

Project goals

The principal aim of this 3 years project was to investigate if an improved characterization of fractured reservoirs can be obtained via a combination of seismic waveform inversion methods and anisotropic effective medium theory.

A further aim was to investigate if some of the waveform inversion methods developed in this project can also be used for seismic imaging and characterization of conventional (unfractured) reservoirs.

1. Popular presentation of the project (written by the scholar)

The title of the project was *Seismic waveform inversion for fracture parameters*. The goal of the project was to understand fractures in reservoirs and how to glean the fracture properties from seismic data.

Seismic data is recordings of waves that have travelled through the earth. These waves may originate from a natural earthquake or from artificial shots. In both cases will the wave be altered by the rock that it travels through and with theoretical models it is possible to invert for which conditions that have caused the recorded signal. Thus are we able to look inside rocks and the earth itself. Some of the conditions that alters the waves can be the type of rock that the wave travels through, it can be big faults or it can be small fractures or cracks in the rock that are filled with water or oil and gas. This project has focused on the latter. We call such small fractures sub-seismic. This means that the fractures are smaller than the wavelength that we study. In such conditions, we cannot see the individual fracture, but we can detect the gathered response of many. Although these fractures are small, they are very important to understand for those that search for fluids beneath our feet, as these fractures can contain much of the fluids we can extract and they can be crucial in the fluids ability to flow within the rock.

A seismic wave is generally an elastic wave. That means that many independent factors that determine the behavior of the wave. In this project, we have used a rock physic model to reduce this number to only a few. Thus increased the calculation speed and made elastic wave inversion more accessible. Also by inverting only for fracture parameters, we do not only reduce the number of unknown model parameters, but also obtain a more stable and robust solution to the inverse problem. The most important advantage for this method from a geological point of view is that fracture parameters are much more relevant for interpreting the rock.

We have made the theoretical foundation and the first proof of concept of using a transport matrix for one fracture set to invert for fracture density. We have also investigated effects of pore fluid pressure communication between aligned fractures and pores. Our methods can in principle also deal with multiple fracture sets, and numerical experiments related to this can now easily be performed in future projects.

2. Comment on the overall progress (written by the scholar)

I have participated at several international and national conferences and seminars with both talks and posters, and much of the research that has been done by me as VISTA scholar as been presented through peer-reviewed conference papers and oral presentations at these. We have prioritized to go further with the project rather than publish the papers that were described in the project description. We are currently working on two papers that will contain the main findings of the project in as journal papers.

Due to time constraints, I did not manage to develop the acoustic T-matrix approach beyond what was already done by the project director and his international collaborators. Therefore, I concentrated on the development of the elastic approach as that was considered more novel. Though, during the project I have produced several working notes. The two most important is mentioned below. The second note was used as a basis for the relevant work of the master student Kenneth Muhumuza which I co-supervised for one year. His work continued what I presented in that working paper and this can be extended to a published paper given time. This work was also continued in the collaboration with Director Ru-Shan Wu of the Modeling and Imaging Laboratory at University of California, Santa Cruz.

This prioritizing was a necessary adjustment to achieve the main goal of the project and since much of the things that were prioritized away has been continued by collaborators, I feel that we have covered most of the promised aspects of the project. I have also had the possibility to obtain other relevant experiences at through the project by participating in teaching and advising at the department.

3. Publications (scholar)

Journal papers

1. **Pilskog, I.** and Jakobsen, M., 2016. Fracture model based seismic waveform inversion in HTI media: Effects of fracture-fracture interaction.
   Journal of Geophysics and Engineering, under preparation.

2. Jakobsen, M. and **Pilskog, I**., 2016. Elastic Born inversion for fracture density using a Gassmann-consistent model of fractured porous media.
   Geophysical Journal International, under preparation.

Peer-reviewed conference papers

1. Jakobsen, M. and **Pilskog, I.,** 2016. Gassmann-consistent Born inversion for fracture density. Extended abstract, 78th EAGE meeting, Vienna (submitted).

2. **Pilskog, I.**, Lopez, M. and Jakobsen, M., 2015. T-matrix FWI for fracture parameters. Peer-reviewed extended abstract, 77th EAGE annual meeting, Madrid, Spain.

3. Jakobsen, M., **Pilskog, I.**, and Lopez, M., 2015. Generalized T-matrix approach to seismic modeling in fractured reservoirs and related anisotropic systems. Peer-reviewed extended abstract, 77th EAGE Annual Meeting, Madrid, Spain.

4. **Pilskog,** I., Lopez, M. and Jakobsen, M., 2014. Linearized waveform inversion for fracture density, extended abstract, 16th International Workshop on Seismic Anisotropy (16IWSA), Natal, Brazil.

Oral presentations

1. **Pilskog,** I., Lopez, M. and Jakobsen, M., 2015. Linearized waveform inversion for fracture density, extended abstract, 16th International Workshop on Seismic Anisotropy (16IWSA), Natal, Brazil.

2. **Pilskog, I.**, Lopez, M. and Jakobsen, M., 2015. Elastic Born inversion for fracture density. Abstract and oral presentation, Lofoten seminar in Petroleum Geophysics, 14-17 April, Svalbard, Norway.

E-poster presentation

1. **Pilskog, I.**, Lopez, M. and Jakobsen, M., 2015. T-matrix FWI for fracture parameters. Peer-reviewed extended abstract, 77th EAGE annual meeting, Madrid, Spain.

Work notes

1. **Pilskog, I.** and Jakobsen, M., 2014. Multi-parameter waveform inversion in acoustic media, work note.

2. **Pilskog, I.** and Jakobsen, M., 2014. Distorted T-matrix approach to FWI, work note.

4 . Other relevant publications (project director)

Papers published in international peer-reviewed journals

1. **Jakobsen, M.** and Ursin, B., 2015. Full waveform inversion in the frequency domain using direct iterative T-matrix methods. Journal of Geophysics and Engineering, 12, 400-418.

2. Ali, A. and **Jakobsen, M.**, 2014. On the relative importance of global and squirt flow in cracked porous media. Acts Geodetic et Geophysica, 49, 105-123.

3. Sævik, P.M., **Jakobsen, M.**, Lien, M. and Berre, I., 2014. Anisotropic effective conductivity in fractured rocks by explicit effective medium methods. Geophysical Prospecting, 62, 1297-1314.

3. Sævik, P.M., Berre, I., **Jakobsen, M.**, and Lien, M., 2013. 3D computational study of applied to effective medium models of fractured media. Transport in Porous Media, 100, 115-142.

4. Ali, A. and **Jakobsen, M., 2013**. Anisotropic permeability in fractured reservoirs from frequency-dependent seismic AVAZ analysis. Geophysical Prospecting, 62, 294-314.

Papers submitted to international peer-reviewed journals

1. **Jakobsen, M.** and Wu, R.S., 2015a. Renormalized scattering series for frequency domain waveform modeling in the presence of strong contrasts, Geophysical Journal International, submitted (minor revision).

2. **Jakobsen, M.**,, Wu., R.S., 2015b. Scattering-path operator approach to frequency domain waveform inversion in the presence of strong contrasts. Journal of Applied Geophysics, submitted (major revision).

3. Eikrem, K.S., Nævdal, G., **Jakobsen, M.** and Chen, Y., 2015. Bayesian estimation of reservoir properties - effects of uncertainty quantification of 4D seismic data. Computational Geosciences, submitted (major revision).

Peer-reviewed conference papers

1. **Jakobsen, M.** and Wu, R.S., 2015c. T-matrix representation of the De Wolf series for modeling and inversion in strongly scattering media. Peer-reviewed expanded abstract, SEG annual meeting, New Orleans.

2. Wu, R.S., Wang, B. and **Jakobsen, M.,** 2015. Green's function and T-matrix reconstruction using surface data for direct nonlinear inversion. Peer-reviewed expanded abstract, SEG annual meeting, New Orleans.

3. Wang., B., **Jakobsen, M.** and Wu, R.S., 2015. Efficient velocity estimation using domain decomposition strategy. Peer-reviewed expanded abstract, SEG annual meeting, New Orleans.

4. Wu, R.S., Hu, S.C. and **Jakobsen, M.**, 2014. Nonlinear sensitivity operator and its de Wolf approximation in T-matrix formalism, 76th EAGE annual meeting, Amsterdam.

Oral presentations at international meetings

1. Nævdal, G., Eikrem, K., **Jakobsen, M.** and Chen, Y., 2015. Ensemble based reservoir characterization using seismic and production data. SIAM Conference on Mathematical and Computational Issues in the Geosciences, Stanford, USA.

2. **Jakobsen, M.** and Ursin, B., 2013. Nonlinear seismic waveform inversion. KSEG Symposium on Geophysics for Discovery and Exloration, Sourh Korea.

3. **Jakobsen, M.** and Ursin, B., 2013. Nonlinear waveform inversion as a sequence of linear inverse problems, International Workshop on Full Waveform Inversion, Muscat, Oman.

Research student theses and a technical report

1. Muhumuza, K., 2015. Modelling and inversion of time-lapse seismic data using scattering theory. M.Sc. thesis, University of Bergen (supervised by **Jakobsen, M. et al.**).

2. Sævik, P.N., 2015 Analytical methods for upscaling of fractured geological reservoirs. PhD thesis, University of Bergen (co-supervised by **Jakobsen, M.**).

3. Lopez, M., 2015. Ray-Born inversion in anisotropic media with isotropic stiffness perturbations. Report from long term visit to the consortium for seismic waves in complex 3D media, Czech Academy of Sciences. (Supervised by Psencik, I. and **Jakobsen, M.**, in collaboration with the scholar).

5. Reflections on the continuation of the project (written by the project director)

Since the development of methods for full seismic waveform inversion in anisotropic media with fractures is a highly challenging task, the project director proposed that the candidate should first do some work based on the relatively simple acoustic approximation. This turned out to be a very good idea, since the scholar (with a PhD degree in atomic physics) actually needed a lot of time to become familiar with his new field of study during his first year.

In accordance with the plan of work for year 1, the scholar produced one work note called «Multi-parameter waveform inversion in acoustic media» and another work note called «Distorted T-matrix approach to FWI». These work notes did not contain many novel results but gave the scholar valuable experience and could have been transformed into one or two applied papers (e.g., Muhumuza, 2015) if the scholar had more time. However, we decided to follow the project descriptions and start working on the development of elastic Born inversion methods for fracture parameters at the beginning of year 2.

The idea here was that the candidate could return to the acoustic approximation after during some work based on the elastic wave equation. However, it turned out that the elastic waveform inversion problem in anisotropic fractured media required all the attention and energy of the scholar during years 2 and 3. Also, we felt that there was a larger potential for producing novel results by focusing on the anisotropic elastic case.

Since the project director and his collaborators (Jakobsen and Ursin, 2015; Jakobsen and Wu, 2015a,b; Wu et al., 2014, 2015; Wang et al., 2015) and research students (e.g., Muhumuza, 2015; Lopez, M., 2015) also worked with the development of methods for full waveform inversion in acoustic (and elastic) media, we have nevertheless reached all the goals we had set for the first year. The overview of other relevant publications (project director) does not represent all the work we have done based on the acoustic approximation; since we have also developed a T-matrix approach for acoustic media with variable density, velocity and even attenuation.

When it comes to the continuation of the work based on the acoustic approximation (which may be more useful for imaging than reservoir characterization and monitoring), our plans for future research includes a further development of the domain decomposition method of Jakobsen and Wu (2015b) and the renormalization procedure to reduce the sensitivity to the initial model developed by Jakobsen and Wu (2015a).

Although we have already developed methods for multi-parameter waveform inversion in elastic media, it can also be useful to look more into the multi-parameter waveform inversion problem in acoustic media, since the estimation of mass density variations is particularly difficult and since acoustic approximation is characterized by a lower computational cost than the corresponding approach based on the elastic wave equation (see Jakobsen and Ursin, 2015; Jakobsen et al., 2015).

The main goal of this project was to develop a method and code for seismic waveform inversion for fracture parameters in anisotropic elastic media. As documented by the published (peer-reviewed) extended abstracts of Pilskog et al. (2014, 2015) and the journal papers (under preparation) by Pilskog and Jakobsen (2016) and Jakobsen and Pilskog (2016), we have reached the main goal of this paper. However, the scholar did not have time to give much attention to the estimation of fracture orientation and aperture, which can be important for the seismic prediction of anisotropic permeability in fractured porous media (see Ali and Jakobsen, 2013). The methods and codes developed by the scholar in collaboration with the project director can deal with multiple fracture sets, but we have not performed many numerical experiments related to this. Therefore, there is also a potential for further work related to multiple fracture sets and these additional parameters of the fractures.

The Gassmann-consistent method for Born inversion for fracture density developed by Jakobsen and Pilskog (2016) represents the low-frequency limit of the theory of visco-elastic waves in materials with interconnected fractures and pores developed by the project director and his associates some years ago. This implies that we have investigated the frequency-dependent phenomenon of wave-induced fluid flow (e.g., Ali and Jakobsen, 2014) although we choose to focus on the Gassmann-consistent low-frequency limit in our publications. However, it could definitely be interesting to give more attention to the effects of seismic attenuation by wave-induced fluid flow in the future.

The scholar have been involved in the development of a generalized T-matrix approach to seismic modeling in reservoirs containing a relatively small number of larger discrete fractures as well as population of many sub-seismic fractures (Jakobsen et al., 2015). The generalized T-matrix in the T-matrix approach of Jakobsen et al. (2015) represents an infinite sum of all effects of multiple scattering, so we have here employed elastic scattering theory beyond the (single scattering) Born approximation. As discussed by Jakobsen and Ursin (2015), the generalized T-matrix approach of Jakobsen et al. (2015) can be used as the forward model in a scattering based system for full (frequency domain) elastic waveform inversion in anisotropic (visco-)elastic media. Therefore, we have found that some of the results that we have developed for seismic fracture characterization in this project can indeed be used for seismic imaging and characterization of conventional (unfractured) reservoirs.

The scholar focused on the problem of estimating fracture density fields from seismic waveform data, but the project director has also developed consistent stiffness-permeability-conductivity models in collaboration with mathematicians at the University of Bergen (Sævik et al., 2014, 2015). As a continuation of this project, another scholar could integrate the various results we have obtained so that one can predict the effective permeability tensor of a fractured porous media from an information about the parameters of the fractures obtained via elastic waveform inversion, similar to the fracture model based method for seismic amplitude versus offset and azimuth analysis developed by Ali and Jakobsen (2013). The project director has also developed Bayesian methods for seismic waveform inversion that provides information about uncertainties required for quantitative integration of seismic data and production data (Eikrem et al., 2015). The scholar did not find time to contribute much to this interdisciplinary research; but given his theoretical background, we think it was wise for him to concentrate on the fracture model based approach to FWI in anisotropic media.