The National IOR Centre of Norway

Data assimilation using 4D seismic data

Project 2.7.4

Project manager: Geir Nævdal

PhD students and postdocs: Willian Chalub Cruz (PhD student), Tuhin Bhakta, Kjersti S. Eikrem (PostDocs)

Other key personnel: Tuhin Bhakta, Kjersti S. Eikrem, Morten Jakobsen (NORCE/University of Bergen), Rolf J. Lorentzen, Xiaodong Luo

Project duration: 2014-2021

Final Project Report

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1. Executive summary

This project was the main project addressing history matching at the IOR Centre. The project focused on being able to meet the target of full field history matching using 4D seismic. Several novel ideas were developed, and eventually they were put together to history match the Norne field using production and 4D seismic data. Work was also done on history matching Ekofisk with production and 4D seismic data. This added several complications, including the fact that Ekofisk has been through significant compaction during production. The work on Ekofisk is mainly presented in Task 2.7.5 which is considering compacting reservoirs. Beside the work on 4D seismic history matching, some related work was also done in this task. That considered both some development on ensemble-based data assimilation, but also more applications focused on seismic inversion.

2. Introduction and background

To make decisions for planning of the future production of a reservoir the model should be consistent with available data, so it should be history matched. This project was the main project addressing history matching at the IOR Centre. The project focused on being able to meet the target of full field history matching using 4D seismic and tracer data. The first demonstration case was to history match the Norne field using production and 4D seismic data. The second selected field study is the Ekofisk field, which is more challenging due to the size of the reservoir, but also because it has a significant compaction. The study of history matching of compacting reservoir is the theme of Task 2.7.5, so this work is reported there. The PhD student William C. Cruz has been working on history matching using production, 4D seismic and tracer data.

The primary objective of this project was to include 4D seismic data in ensemble-based history matching for full fields. The secondary objectives included establishing and adapting the following for the specific fields selected for demonstrations:

- Establishing real fields and gathering required data

- Investigating which form of 4D seismic data is most suitable for inclusion
- Developing suitable rock physic models
- Uncertainty quantification of the seismic data
- Adapting the ensemble-based methods to work with the large amount of seismic data

By including 4D seismic information into an ensemble of reservoir models we aim to improve reservoir management, improve uncertainty quantification, identify remaining oil zones, and, finally to contribute to improved decision making and optimal strategies leading to improved volumetric sweep. The main aim was to develop, verify and demonstrate a robust methodology.

The first field selected for demonstration was a sandstone reservoir, the Norne field. An available data set provided through NTNU was used, but some additional information was provided by Equinor. TNO also did work on history matching the Norne field through the IOR center, and for a period frequent web-based meetings were held to share experiences. TNO's work is reported as a separate task. The second field chosen for demonstration was a chalk field, the Ekofisk field, provided by ConocoPhillips. This is also a more demanding test of the methodology due to the size and complexity of the reservoir. Issues addressing compaction effects are treated under Task 2.7.5. As 4D seismic data, acoustic impedances were used.

In addition, we have investigated the use of full-waveform inversion for 4D seismic history matching in cooperation with University of Bergen. This work was partially supported by a Petromaks2 Researcher project awarded as an IOR Centre spin off project in 2016. In addition, there is one work on exploiting time-lapse seismic data for estimation of reservoir properties, and a couple of work discussing issues related to ensemble-based data assimilation. The PhD student attached to the project focused on adding tracer data into the workflow, alongside production and 4D seismic data.

Tuhin Bhakta visited Dario Grana at University of Wyoming for an extended stay, and professor Grana also contributed to the Norne field study, as well as visited a National IOR Center workshop, and some topical workshops on 4D seismic history matching.

3. Results

The state-of-the-art of 4D seismic history matching has been described in a review paper [OFB+21] published in the final year of the IOR center. In this paper, we review the literature on 4D seismic history matching (SHM), focusing discussions on the aspects of the problem that make it more difficult than the more traditional production history matching. In particular, we discuss the possible choices for seismic attributes that can be used for comparison between observed or modeled attribute to determine the properties of the reservoir and the difficulty of estimating the magnitude of the noise or bias in the data. Depending on the level of matching, the bias may result from errors in the forward modeling, or errors in the inversion. Much of the practical literature has

focused on methodologies for reducing the effect of bias or modeling error either through choice of attribute, or by appropriate weighting of data. Applications to field cases appear to have been at least partially successful, although quantitative assessment of the history matches and the improvements in forecast is difficult.

History matching of the Norne field utilizing 4D seismic data was a long-term goal for our work. The work was done using ensemble-based methods and depended on several of the results developed during this project. We outline first the results that were made as preparation for history matching the Norne field, before we point to the papers presenting the actual history matching of the Norne field.

In one work [LB17], we have focused on estimating observation errors of seismic data using an image processing approach. Three types of image denoising methods were considered, namely, local moving average with different window functions, non-local means denoising and wavelet denoising. The performance of these three algorithms was compared using both synthetic and field seismic data. It was found that, in the investigated cases, the wavelet denoising method leads to the best performance most of the time.

A correlation-based localization scheme for ensemble-based history matching was developed in [LBN18]. The correlation-based scheme is suitable for 4D seismic history matching. The scheme was used in history matching using production data on the Norne field [LLVE18]. This approach for correlation-based localization was further improved with respect to the efficiency and accuracy of making it run in an automatic manner but without incurring substantial extra computational costs in [LB20]. The authors applied the resulting automatic and adaptive correlation-based localization to a 2D and a 3D case investigated in the previous study [LBN18] and showed that it leads to better history matching performance (in terms of efficiency and/or estimation accuracy) than that is achieved in the previous work.

A framework for adopting wavelet-based sparse representation to reduce data size and estimate noise level in 4D seismic history matching was developed and tested in a couple of papers [LBJN17,LBJN18].

Initially, we performed the Norne study by first matching the production data, then updating the ensemble of reservoir models that was conditioned to production data to match the 4D seismic data [LBG+18]. Further investigations revealed that the final solution did not have an improved match of the 4D seismic data compared to the initial ensemble (unconditioned both to production and 4D seismic data). Therefore, a further study was undertaken, doing a match to production and 4D seismic data simultaneously. Through this approach it was possible to get an ensemble of reservoir models that had better match to both data types, compared to the initial ensemble [LBG+20]. An initial test of the approach on synthetic data from the Norne field was published in [LLBV19]

Besides the work aimed at history matching full field reservoir models, some other lines of research have also been pursued. We outline some of the output of this research as well.

The paper [EE18] discusses strategies for conditioning reservoir models on rate data using ensemble smoothers. In particular, a significant redundancy in the rate data makes it possible to subsample the rate data. The alternative to sub-sampling is to model the unknown measurement error correlations and specify the full measurement error covariance matrix. We demonstrate the proposed strategies using different ensemble smoothers with the Norne full-field reservoir model.

The paper [Bha18] presented methods for improvement of the conventional method to estimate changes in reservoir parameters from time-lapse seismic. The applicability of the new method was tested in two different reservoir scenarios, i.e., unconsolidated sand reservoir and compacting chalk reservoir. The new method can handle any type of rock physics model and works better than the conventional method even in the presence of noise in the input. Further research into this area was performed in Task 2.7.5 with a focus on a compacting chalk reservoir.

A history matching workflow using 4D seismic data where the uncertainty in the 4D seismic data comes from Bayesian seismic waveform inversion has been developed and studied. The results (test on a synthetic case) have been published in [ENJC16].

Several publications on full-waveform inversion were prepared in cooperation with Morten Jakobsen and students at University of Bergen. The paper [ENJ21] gave a practical approach to find preconditioners to speed up the convergence of scattering series solving the Lippmann-Schwinger equation, which can be utilized for seismic wave field modeling, but also other applications as inversion of electromagnetic data. The paper [ENJ21] was motivated by some prior works done with partial support from the IOR Centre [HJW20,JHW20,JWH20]. The method for constructing preconditioners developed in [ENJ21] was applied for solving seismic forward modelling with variable density and velocity in [XEJN21]. A Bayesian approach to full-waveform inversion in anisotropic elastic media using the iterated extended Kalman filter is developed in [HEJN20]. This paper built on the previous work [EJN19] on iterated extended Kalman filter method for time-lapse seismic full-waveform inversion. The paper [HJEN20] studied target-oriented inversion of time-lapse seismic waveform data with the aim of reducing the computational cost by focusing the inversion on a target domain where the changes is expected to occur between two seismic surveys.

Finally, the paper [SN17] presented a generalization of the randomized maximum likelihood and ensemble based maximum likelihood (RML/EnRML) approach to Bayesian history matching.

4. Conclusions

This project has both been focusing on research driven by a practical aim – 4D seismic history matching. To perform 4D seismic history matching on a real field several new tools have been developed. These tools have served their needs for the initial application, as shown by the successful history matching of the Norne

field, but the developed tools might also (and in some cases already have) find applications elsewhere. The long-term view of the IOR Centre was very useful in developing a set of tools that in the end could be put together to improve on 4D seismic history matching. In addition, both the preparing a review paper and a recommended practice document in the final couple of years of the IOR Centre gave a useful wrap-up of the state of the art for 4D seismic history matching. In addition, some more academic work was done, mostly in the direction of full-waveform inversion. In total this Task has contributed more than 20 journal papers, including a review paper on 4D seismic history matching. In addition, comes conference papers and other dissemination efforts, including arranging several workshops.

5. Future work/plans

The PhD student associated with the project, William C. Calub, has a number of planned publications:

"Data assimilation with soft constraints (DASC) through a generalized iterative ensemble smoother", by Xiaodong Luo and William C. Cruz is submitted to Computational Geosciences. Another paper, with title "Joint history matching of production and tracer data through an iterative ensemble smoother: A 3D field-scale case study", by William C. Cruz, Xiaodong Luo and the co-advisor from Equinor, Kurt R. Petvipusit, is planned to be submitted to Journal of Petroleum Science and Engineering. In addition, two conference papers are planned for 2022. These are "Joint history matching of production and tracer data through an iterative ensemble smoother: A 3D field-scale case study", by William C. Cruz, Xiaodong Luo and Kurt R. Petvipusit, to be submitted to International Petroleum Technology Conference (IPTC) 2022 and " Joint History Matching of Production, Tracer, and Seismic Data in a 3D Field-scale Case Study", by William C. Cruz, Xiaodong Luo and Kurt R. Petvipusit, where the abstract is accepted for SPE Norway Subsurface Conference 2022.

6. Dissemination of results

A recommended practices document [BHL+21] has been prepared describing a substantial part of the methodology developed in this project.

Equinor has started to implement correlation-based local analysis in their open ERT (ensemble reservoir tool) system.

Several meetings with user partners and some additional presentations to companies outside the IOR Centre was held. These included presentations to Eni at their Milan office (2016), Statoil (in Bergen), Aker BP (Stavanger), Eni (Milan) (all in 2017), Norske Shell (Stavanger), ConocoPhillips (Stavanger) (both in 2018).

A number of workshops related to this project were arranged. This includes “Workshop on 4D seismic and history matching”, April 2016 (in connection with the IOR Norway conference). A workshop was also held in April 2018 in connection with IOR Norway. The online event “Workshop on ensemble-based 4D seis-

mic history matching" was held October 14-15, 2020, with more than 50 participants.

Several presentations at IOR Norway were given by speakers working on this task. The presentations were held by Geir Nævdal, NORCE, (2015), Dario Grana, University of Wyoming (2018), Morten Jakobsen, University of Bergen/NORCE (2018), and Rolf J. Lorentzen, NORCE, (2019).

A presentation was also given at the IEA-EOR Energy Technology Network Symposium in Copenhagen, September, 2018. In addition, a number of presentations related to his project was given at EnKF workshops held in or near Bergen every year since 2006 (except 2020, due to corona) as well as the IOR Centre workshops mentioned above.

A number of presentations was also given at SEG Annual Meetings, SPE Norway, EAGE and ECMOR in addition to the events mentioned above.

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