Novel Principles for Effective Earth Model Grid Management while Geosteering

by

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Preface

This thesis is submitted in fulfilment of the requirements for the degree of Philosophiae Doctor (PhD) at the University of Stavanger (UiS), Norway.

My main supervisor is Dr. Terje Kårstad (UiS) and my co-supervisors are Drs. Alejandro Escalona (UiS) and Erlend Vefring (IRIS). The work has mainly been carried out at IRIS (International Research Institute of Stavanger).

The research has resulted in one peer-reviewed article and five conference papers. I have presented my work at multiple seminars and conferences, covering several different scientific disciplines.

Erich Suter
Stavanger, September 2018

Abstract

The aim of geosteering is to place the well optimally in the reservoir, based on the available measurements and interpretations of the geology. The interpretations are captured in earth models that are used for decision support. But real-time decision processes such as geosteering are poorly supported by current earth modelling methods. While drilling, new measurements received from the well allow revisions of the pre-drill geological interpretations. However, the current modelling tools are not capable of updating their representations of the interpretations in real-time. 3D earth models are typically kept unchanged during the drilling operation, while updated 2D models capture the geological interpretations only in a simplistic manner. Furthermore, uncertainties in the interpretation of the geological structures are not accounted for. Such strategies are inadequate for geosteering support when drilling in geologically complex regimes, and may lead to poor decisions.

Current 3D modelling technologies are typically based on an inflexible, global grid that is used to represent geological structures and petrophysical properties. The management of this grid is slow and time consuming. To pave the way for a more effective earth model management, novel principles for i) local updates of the geological structure in an existing grid, ii) local control of the resolution of the geological structure and consequently the grid, and iii) local scale uncertainty management including the geological structure are proposed. The principles are demonstrated in a 2D software prototype. The ultimate aim is to enable an always updated multi-realization 3D model at optimal resolution while drilling, suitable for real-time decision support under uncertainty.

Acknowledgements

My sincere thanks go to a number of people who have contributed, advised or otherwise supported in the course of this work.

My main supervisor Terje Kårstad has always been available for discussions and manuscript reviews. Moreover, he has shared from his knowledge within reservoir simulation algorithms and earth model development. My co-supervisor Alejandro Escalona has also reviewed and commented my manuscripts. Moreover, he and the rest of the Petroleum Geosciences group at the University of Stavanger, including Reidar Bratvold and Christopher Townsend, gave me a background in geology, geological interpretation and geological modelling. Extending my initial background from mathematics and computer science with an understanding of geology has been an invaluable contribution in the developments.

A number of colleagues and friends at IRIS are thanked for constructive discussions. Eric Cayeux provided the initial idea for local model updates (Suter et al. (2010)). Helmer André Friis has always been available for discussions regarding the development of the numerical foundation. Erlend Vefring, Sergey Alyaev, Xiaodong Luo and Yan Chen are thanked for discussions regarding EnKF-based uncertainty management. Kanokwan Kullawan contributed with her profound knowledge within decision analytics. I highly appreciate the guidance offered by Fridtjof Riis within geological interpretation. Lars Irgens Næsheim, Lars Kollbotn, Alexey Khrulenko and Arild Lohne are discussion partners. The rest of the Drilling and Well Modelling team at IRIS, as well as the rest of IRIS Energy and the DrillWell centre, are also thanked.

The work has received funding in several rounds; initially by the Research Council of Norway (SIP-OED project number 186917), then by the research centre DrillWell - Drilling and Well Centre for Improved Recovery, a research cooperation between IRIS, NTNU, SINTEF and UiS with the financing partners the Research Council of Norway, AkerBP, ConocoPhillips, Lundin Norway, Repsol (former Talisman), Statoil, Total and Wintershall. And finally, through the currently ongoing project “Geosteering for improved oil recovery” (NFR-Petromaks2 project no. 268122), which is financed by the Research Council of Norway, ENI and Statoil.

The DrillWell technical reference group, that provided recommendations for the research path that resulted in the work presented in this thesis, receive my most sincere gratitude. The group consisted of experts from academia as well as geoscientists from the industry, and was a main driver and motivator during the developments.

Above all, I am grateful for the support from my family: my daughter Julie, who is the sunshine of my life, and my wife Nina, who always stood by my side.

List of papers in Part II

The focus of this thesis is effective earth modelling for geosteering. Four of the papers that the thesis is based on address effective earth modelling, one discusses a proposed workflow for geosteering, and one addresses effective management of real-time LWD logs. To provide context, the main elements of the proposed geosteering workflow are summarized and the theme of each paper is indicated. The workflow is shown in Figure 1.

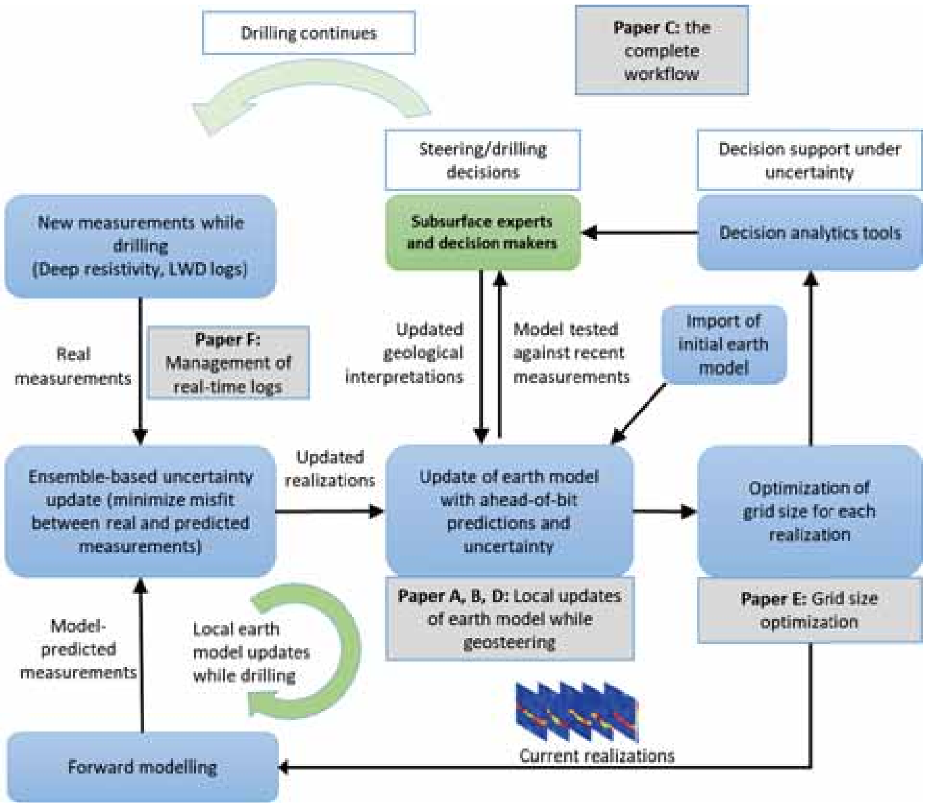

Figure 1. Proposed workflow for real-time geosteering decision support.

First the pre-drill earth model is imported. The initial uncertainty around the planned well has been estimated, and is represented in the form of an ensemble of realizations representing possible geological scenarios around and ahead of the bit. The uncertainties captured by the scenarios include both grid-based properties and geological structures, including the structural topology (connectivity). For each update step while drilling (e.g. every meter), all realizations are automatically updated (**paper C**). The updates are effectively performed, based on the suggested earth modelling technology (**papers A, B, D**). The updates are based on logging-while-drilling (LWD) measurements including Deep EM that are presented to the tool in a consistent manner (**paper F**). Each realization is then optimized in size (**paper E**). Based on a chosen set of decision objectives, tools for decision analytics will calculate an optimal well trajectory based on the currently available information. The earth model and the decision analytics results form a basis for decision support under uncertainty while drilling. The time available for calculations at every step in the workflow is a critical element in the real-time workflow.

The following articles form the basis of the thesis;

Paper A. ***Suter, E.***, Cayeux, E., Vefring, E., Næsheim, L., Friis, H., Escalona, A. and Kårstad, T. (2010) An Efficient Approach for Earth Model Updates. Paper SPE-136319-MS presented at the *SPE Russian Oil and Gas Conference and Exhibition*, Moscow, Russia, 26-28 October. https://dx.doi.org/10.2118/136319-MS.

Paper B. ***Suter, E.***, Cayeux, E., Escalona, A., Kårstad, T. and Vefring, E. (2012) A Strategy for Effective Local Updates of the Geological Structure in an Earth Model during Drilling. Extended abstract presented at the *74th EAGE Conference and Exhibition Incorporating EUROPEC*, Copenhagen, Denmark, 4 June. https://dx.doi.org/10.3997/2214-4609.20148222.

Paper C. Luo, X., Eliasson, P., Alyaev, S., Romdhane, A., ***Suter, E.***, Querendez, E. and Vefring, E. (2015) An Ensemble-Based Framework for Proactive Geosteering. *SPWLA 56th Annual Logging Symposium*, Long Beach, California, USA, 18-22 July.

Paper D. ***Suter, E.***, Cayeux, E., Friis, H., Kårstad, T., Escalona, A. and Vefring, E. (2017a) A Novel Method for Locally Updating an Earth Model While Geosteering, *International Journal of Geosciences* **8**, pp. 237-264. https://doi.org/10.4236/ijg.2017.82010.

Paper E. ***Suter, E.***, Friis, H. A., Vefring, E. H., Kårstad, T. and Escalona, A. (2017b) A novel method for multi-resolution earth model gridding, Paper SPE-182687-MS presented at the *SPE Reservoir Simulation Conference*, 20-22 February, Montgomery, Texas, USA. https://doi.org/10.2118/182687-MS.

Paper F. ***Suter, E.***, Alyaev, S. and Daireaux, (2017c) B. RT-Hub - Next Generation Real-time Data Aggregation While Drilling, Extended abstract presented at the *First EAGE Workshop on Pore Pressure Prediction*, 19-21 March, Pau, France. https://doi.org/10.3997/2214-4609.201700060

I am the main author of all papers except **Paper C**. **Paper D** is peer-reviewed, the others are not.

Paper A describes principles and initial results regarding local updates of the grid when the geological structure is locally modified.

Paper B expands on the initial results by also discussing a coarse framework for a fault operator that allows local insertion, removal and manipulation of a fault.

Paper C describes an ensemble-based framework for geosteering, using an earth model with a simplified geological structure.

Paper D provides a mature insight into the strategy for effective updates of the connectivity of the geological structure in the earth model grid.

Paper E presents a novel strategy for multi-resolution earth modelling where both the structural resolution and the grid resolution can be locally controlled. Also, local management of uncertainties are discussed.

Paper F discusses shortcomings in the current management of real-time measurements. A new approach is presented, particularly designed for automated decision support.

List of presentations

The list includes conferences and seminars, oral and poster presentations.

1. Suter, E. (2010) presentation of paper SPE 136319 at the SPE Russian Oil and Gas Conference and Exhibition, 26-28 October, Moscow, Russia.
2. Suter, E. (2010) presentation of paper SPE 136319 (see above) at the IRIS-GUBKIN joint workshop on “Modelling, Optimization and Process management in the Oil and Gas industry”, 25 October, Moscow, Russia.
3. Suter, E. Cayeux, E., Vefring, E., Næsheim, L.I., Friis, H.A., Escalona, A. and Kårstad, T. (2011) *A gridless earth model enabling effective local modifications of geological structures*, presentation at the Winter conference in Geology in Stavanger, Norway, 11-13 January.
4. Suter, E. Helset, H. M. (2012) *The role of automation in improved decision support for optimal well placement*, presentation at the “Autonomy in the oil and gas industry” conference, Sola strandhotell, Norway, 7-8 March.
5. Suter, E. (2012) presentation of extended abstract *A Strategy for Effective Local Updates of the Geological Structure in an Earth Model during Drilling* at the 74th EAGE Conference and Exhibition in Copenhagen, Denmark, 4-7 June.
6. Suter, E. (2012) *Flexible Earth model*, presented at the SBBU Technical Seminar, Sola, Norway, October 31.

7. Suter, E. (2013) *A novel strategy for updating the fault network locally around the well while drilling*, presented at the SBBU Technical Seminar, Stavanger, Norway, October 3.
8. Suter, E. (2014) *Towards automatic fault network modelling*, presented at the DrillWell Technical Seminar, Stavanger, Norway, September 24.
9. Suter, E. (2015) *Demonstration of complex local updates of earth model structure*, presented at the DrillWell Technical Seminar, Stavanger, Norway, September 22.
10. Suter, E., Alyaev, S., Luo, X., Romdhane, A., Eliasson, P. and Vefring, E., (2016) *Decision Support for Proactive GeoSteering under Uncertainty*, poster and presentation at the SPE/EAGE Geosteering and Well Placement Workshop, Dubai, 8-10 February.
    - I was also Co-chair and member of the Workshop Committee
11. Suter E., Kårstad, T. Escalona, A. and Vefring, E.H. (2016) *A method for locally adaptive gridding and local updates of the geological structure in earth models*, poster at the IOR Norway conference
12. Erich Suter, Sergey Alyaev, Xiaodong Luo, Anouar Romdhane, Peder Eliasson, Erlend Vefring (2017) *Proactive geosteering workflow for enhanced oil recovery*, poster presentation at the 17th Geilo Winter School: Machine learning, deep learning, and data analytics, January 15-20.
13. Suter, E., Friis, H.A., Vefring, E.H., Kårstad, T., Escalona, A. (2017) *A novel method for multi-resolution earth model gridding*, poster presentation of paper SPE-182687-MS presented at the SPE Reservoir Simulation Conference, 20-22 February, Montgomery, Texas, USA.
14. Erich Suter, Sergey Alyaev, Benoit Daireaux, (2017) *RT-Hub: next generation real-time data aggregation while drilling*, poster presentation at the First EAGE Workshop on Pore Pressure Prediction, 19-21 March, Pau, France

In addition, the patent application Suter and Cayeux (2012) was submitted in October 2010. It required a significant effort for co-authoring the application together with the patent attorney.

Thesis structure

The thesis is structured as scientific paper-based and consists of two parts.

Part I

Section 1. Introduction with research topic and the main contributions of the work.

Section 2. Overview of present geosteering methods and their limitations, in particular regarding earth modelling.

Section 3. Overview of present methods for earth modelling and their challenges with respect to geosteering.

Section 4. Proposed method for geosteering, defining requirements for earth modelling support. Described in **papers C and F**.

Section 5. Main method 1, local earth model updates. Detailed in **papers A, B and D**.

Section 6. Main method 2, multi-resolution gridding. Presented in **paper E**.

Section 7. Main method 3, local scale uncertainty management. Discussed in **paper E**.

Section 8. Supporting developments

Section 9. Discussion and future perspectives

Section 10. Summary

Section 11. References

Section 12. Appendix, including 1) an overview of uncertainties in the interpretation of geological structures, 2) a discussion of the handling of subsurface interpretations over multiple scales and frequencies, and 3) a small introduction to topology vs. geometry.

Part II

Contains a compilation of the six **papers A-F** that form the basis of the thesis.

Earth modelling and geosteering are highly multi-disciplinary themes, involving experts from a large variety of backgrounds. Development of new methods and complex software requires long-term efforts. Hence, proper motivation is required. But space in papers is limited. To make the thesis accessible to e.g. geosteering experts without profound knowledge of current earth modelling methodologies, Sections 2 and 3 provide a more complete motivation and background than the papers that this thesis is based on. Moreover, the Appendix provide background information about structural uncertainties and subsurface information at multiple scales and frequencies, and a small discussion about topology vs. geometry. The latter is an essential distinction when handling geological structures in earth models.

Contents

Part I: Overview of methods

1 Introduction

At the Norwegian continental shelf (NCS), the costs of drilling wells are high and hydrocarbons are often located in complex reservoirs. The mature fields on the NCS are moving towards tail end production, and most new discoveries are complex and often marginal. The window for economic success is narrow.

A well is a main tool for realizing the economic values in an asset. Hence, the planning and drilling of new wells is a crucial part of subsurface asset management. The ability to steer the wells optimally in the reservoir by utilizing all available measurements through efficient workflows is important to maximize the recovery from individual wells and to realize future IOR projects and field developments. Optimal exploitation of complex fields can be supported by effective numerical methods for management of massive amounts of subsurface information in the decision loop.

Yet, the steering of a well is today not adequately supported by subsurface modelling tools. Current workflows are dominated by subjective interpretation, simplistic earth models and manual decision making.

1.1 Motivation

The last two decades have seen a growing emphasis on optimal well placement to ensure maximum total asset recovery. Recent technological achievements, such as deep electro-magnetic measurements (Deep EM) and wired drill pipe, open up for new possibilities. Deep EM greatly improves real-time look-around capabilities while the well is being drilled, while the wired drill pipe technology allows transmission of more subsurface information within shorter time. The new information that becomes available while drilling reduces uncertainty and allows revisions of the geological interpretations made prior to the drilling operation.

The new technologies offer possibilities for better well placement and safer drilling at lower cost in complex reservoirs, by improving the understanding of the geology while it is being drilled. Optimal, real-time exploitation of the enormous amounts of available pre-drill and while-drilling measurements and uncertain interpretations requires effective capturing and management in computer-based number-crunching workflows. Future workflows should allow a continuous flow of new information to be effectively interpreted, integrated and utilised for decision support within the timeframe set by the on-going drilling operation. The earlier the predictions are made available, the earlier model-supported proactive decisions can be made. This contributes to better placement of the well, and safer and more cost-effective drilling.

1.2 Problem statement

3D earth models are main tools for support of decision processes for optimal exploitation of subsurface resources. Subsurface models in various forms are used for economic assessments and risk assessments for exploitation of hydrocarbons, mining, CO_2 sequestration and handling of groundwater resources. They are applied by industrial companies, governmental agencies and local authorities.

1.2.1 Ineffective management of structural uncertainties

In most geomodelling methods, the geological structure controls the construction and shape of a grid. The grid represents the distribution of petrophysical properties, e.g. porosity, which is of main importance for optimal well placement. Thus, the interpretation of the geological structure controls where the well should be placed in the reservoir.

Complex uncertainties in the interpretation of the structure is a major class of uncertainties that have largely been neglected in the earth modelling literature, and in earth model based subsurface workflows. It is well known that such uncertainties are often considered more important for decision making than uncertainties captured in the grid-based petrophysical properties. Yet, structural uncertainties cannot be effectively handled in earth model grids. In particular modifications in the structural topology (how the structure is connected) are complex and labour intensive. In addition, the grid must be completely reconstructed and repopulated with properties in a time-consuming workflow. In multi-realization methods, this must be repeated for all regenerated realizations of the grid. This implies that decisive structural uncertainties are not represented in the earth models. Consequently, it is not possible to analyze these uncertainties in highly automatic model-based workflows. In such workflows, only the information that is in fact represented in the model can be considered.

While drilling, new measurements arrive that reduces the uncertainty and allow revision of the pre-drill interpretations. But because of the limited capabilities for effective management of the geological structure, the time needed for updating the model exceeds the time available during drilling operations. This inhibits real-time model-based workflows where structural uncertainties should be considered.

1.2.2 Management of scale and resolution

Effective handling of scale and resolution is important to optimize computer based models that manage large amounts of information, and multi-resolution methods are much used in other scientific disciplines. However, within earth modelling the aim has typically been to optimize workflows that are not performed in real-time. An example is upscaling for flow simulation studies. But for effective interpretation and modelling in real-time, the lacking control of model size is a major bottleneck.

The resolution of the grid controls the computational efficiency when managing the earth model, as well as the computational efficiency for subsequent grid-based modelling and simulation exercises. The model resolution is also tightly linked to the number of parameters for humans to control. The resolution of the grid is selected in a trade-off between multiple objectives. It should be 'as coarse as possible' to avoid too time-consuming computations, while it should still be sufficient to capture the most important uncertainties. The resolution cannot be effectively modified after the model has been established, and local control of the resolution is highly challenging. A severe consequence is that high-frequency and fine scale (subseismic) geological elements cannot be captured and considered for decision making while drilling. Moreover, the subsurface volume that a model covers is 'as small as possible', so that elements outside the model 'box' that are important for interpretation while drilling are left out.

Clearly, interpretations across multiple frequencies, scales and locations are not well handled.

1.2.3 Corner-point grids

Corner-point grids, that are typically used for earth modelling, are inflexible and cannot be used to adequately represent structurally complex reservoirs. When using this type of grid, complex geological structures often cannot be captured with reasonable accuracy without requiring grid refinement. But grid refinement implies a larger grid and therefore more time-consuming management. As a result, such structures are often over-simplified or left out.

1.2.4 Consequences for geosteering

As a consequence of these limitations, it is highly challenging to calibrate geomodels to Deep EM and other LWD measurements for complex formations while drilling when time is limited. Multi-realization strategies for closed-loop management of geological uncertainties are today being incorporated in subsurface workflows such as field development planning. But they cannot be used for geosteering, because they apply present tools for earth modelling. The workflows are time-consuming, and do not capture structural uncertainties that are highly relevant for optimal well placement in complex reservoirs.

For many subsurface decision processes, time is not a main constraint. But for real-time processes such as geosteering, decisions should be taken ‘as quickly as possible’. This contributes to reducing the cost of the drilling operation and to optimize the placement of the well. Moreover, the conditions in the well depend on the formations that are being drilled. Right-time decisions minimize the risk of drilling incidents and potentially hazardous situations. To wait for time-consuming model updates to complete before decisions are taken is generally not an option while drilling. The amount of available time before decisions must be taken depends on the complexity of the geology, on the complexity of the drilling operation, and on the decision to be taken. Some decisions are less time critical, whereas other decisions must be taken within short time. There is always a trade-off between how much time that should be spent on computations to obtain more precise results, and the time available before a decision should be made.

Today there is no effective, transparent, systematic and consistent workflow for quantifying and updating complex geological uncertainties in the geomodel, and considering them when making geosteering decisions. The existing earth modelling technology represent a main bottleneck in a future, highly automated decision support loop.

1.3 Research Objectives

The primary objective of the work presented in this thesis is to improve the real-time support for decision making processes under uncertainty while drilling in complex reservoirs, by development of effective methods for earth model management.

In support of the primary objective, secondary objectives are;

- To develop principles for locally updating the geological structure in a populated grid. When the structural topology is locally modified, e.g. by inserting a new layer or fault, the grid should only require a local modification.
- To develop principles for a multi-resolution representation that provides local control with grid resolution without being constrained by the structural resolution. When the structural resolution (density of fault network and stratigraphy) is locally changed, the grid should only require a local modification.
- To develop principles for effective local scale uncertainty management, including uncertainties in the topology of the geological structure.
- To improve the handling of structurally and geometrically complex geology by application of a more flexible grid type that easier adapt to complex geological structures (without requiring simplifications to the structure).
- To better utilize the computational resources of modern computers via parallel processing.
- To test the principles in a 2D software prototype.

The methods should be applicable within a highly automated geosteering workflow for updating multi-realization models. While the current focus is on geosteering and drilling support, potential future applications could include any earth model based workflow. However, such applications have other requirements that may or may not call for a different approach.

The aim of the developments is to pave the way for real-time workflows where the earth model is always updated with the most recent measurements and interpretations, and is always at an optimal resolution, enabling model-based support for proactive, real-time decision making under uncertainty.

1.4 Main contributions

The first main contribution is the development of principles for locally modifying the geological structure that is incorporated in a populated earth model grid. Such updates also include the structural topology (connectivity), e.g. the insertion of a new fault or a new layer. The geological structure splits the subsurface into a set of regions that are individually discretized. Each region obtains its own ‘subgrid’, and the set of populated subgrids together constitute the earth model grid. When the structural topology is locally updated, only a few of the regions and their subgrids are invalidated and need to be regenerated. Properties are stored in separate property functions, not directly in the grid. The existing properties can then be effectively mapped into the corresponding new subgrids. The rest of the grid is not compromised by the local update and can be retained.

The next main contribution is the development of principles for locally controlling the resolution of a populated grid. It also takes the resolution of the geological structure into account. A novel method for representing the geological structure in a hierarchy supports representation of the regions (with their subgrids) at subsequently finer scales in a nested fashion. Each region, at any scale, is considered to be ‘an earth model on its own’, with its own subgrid, geological structure and properties represented in its interior. Using the principles for local updates of the geological structure, the resolution of the geological structure and the grid can be locally modified by activating subgrids for regions at the desired scale.

Based on the functionalities for local updates and multi-resolution management of the grid, the final main contribution is principles for local scale uncertainty management of the grid. The method allows multi-realization handling of both properties and the geological structure, including the structural topology and geometry. It allows multiple realizations at a local scale in the interior of a large model, e.g. around and ahead of the bit while drilling. As drilling continues, each realization could be locally modified and its resolution be optimized. Moreover, the number of realizations could be locally decreased behind the bit and increased ahead of the bit in a dynamic manner in real-time. By not requiring the inclusion of the complete model in the uncertainty handling, more effective management of the geological uncertainty is achieved. The aim is to focus computational efforts to where it matters for the decision at hand.

A geological environment with faulted layers is considered for development of principles and software prototyping. The principles are demonstrated in a basic 2D software prototype for synthetic cases. The numerical methodology is independent of scale, so the figures presenting the cases do not contain scales.

2 Geosteering decision support

According to Lesso and Kashikar (1996), geosteering refers to an operation where a precise form of directional drilling is used to control the wellbore direction to stay within desired zones, based on real-time geological information gathered while drilling. Geosteering is a series of actions taken to adjust the wellbore direction during the ongoing drilling operation, so it is also referred to as “real-time well placement” or “real-time reservoir navigation” (Kullawan, 2016). The ultimate aim when drilling a new well is to optimize the operation with respect to all considered objectives including e.g. safety while drilling, drilling operational constraints, well maintenance, drilling costs, future production, field planning, and environmental impact.

During the geosteering process, the trajectory of the planned well is adjusted based on measurements obtained from logging tools (LWD) during the ongoing drilling operation. LWD logs provide information about the formation that is penetrated by the wellbore. The new information reduces uncertainty and allows revisions of the geological interpretations made prior to the drilling operation. This requires effective interpretation, integration and utilisation of the new information within the timeframe set by the on-going drilling operation. As for any real-time model-based application, the time spent for model management is a crucial aspect in the attempt to deliver right-time decision support.

2.1 Planning of a new well

The planning of a new well is based on subsurface measurements known prior to drilling, such as surface seismic and offset wells. The interpretation of such information is captured in an earth model that is used to support decision processes before and while drilling. The interpretation of the available measurements is always burdened with uncertainty (see the Appendix, Section

12.1). This is a result e.g. of the processing of measurements (where the parameters used to control the process may not be optimal), derivation of parameters from indirect measurements, and the subjective geological interpretation of the available information. Uncertainties are being propagated throughout the process.

When constructing an earth model, there is always a trade-off between a) how much time that is available for computation before they should provide support for decisions, b) the accuracy that is required for decision support, and c) the volume of the subsurface that should be captured in the model (see Sections 2 and 3). These requirements are closely related to model size, thus depending on the resolution of the grid-based properties and the resolution of the geological structure.

Simulations using a field scale model support the decisions about where to place new wells. A three-dimensional full-field numerical earth model contain large amounts of information. This includes individual structural surfaces that represent interpretations of geological interfaces such as faults and interfaces that represent changes in the stratigraphy, how these surfaces are connected, one or more grids, representation of facies and petrophysical properties in the form of variograms, petrophysical property values distributed in the grid(s), estimations of pressure, results from grid-based fluid flow simulations, and more. First, the manual workflows for managing the model imply that it is slow to construct and update. Second, the model construction is a sequential process. If changes are performed in the first step, the model must be completely regenerated. Third, large amounts of information require much processing time when updating the model. Fourth, modelling and simulation results may often require manual interpretation before decision making can take place. Throughout the whole process, there is a large number of parameters that the interpreters and decision makers must consider.

Briefly and generally stated, the ‘geological model’ (or ‘static model’) is a model at relatively fine scale that allows capturing more geological detail. The ‘simulation model’ (or ‘dynamic model’) is generated from the geological model via upscaling. This is required because the grid in the geological model is too large for conducting flow simulations within reasonable time.

In the planning phase, all available relevant information is examined in detail. Fine scale interpretations of the geology around offset wells are extrapolated to the planned well, guided by coarse scale seismic and knowledge of the geology. The construction of a model at local scale around the planned well (local scale model) may require much manual work. However, the extraction of a local scale 2D model from a large-scale model may take place in a more automatic workflow (see Section 2.2). But large-scale models only carry information at coarser scales, and much information may be left out (see Section 3.3). Furthermore, uncertainties are assessed and possibly included in the local scale model. This depends on the requirements set for the model, the time available for creating the model, as well as on the capabilities of the tool to represent relevant uncertainties. Several tools and models may be involved in the construction of the well scale model, see e.g. Bashir et al. (2016).

2.2 Current geosteering practices

For geosteering, simplified well scale models are constructed. This can take place for example by manually creating a three-dimensional sector model locally around the planned well (see e.g. Arata et al. (2016)). Another approach is to create a two-dimensional model along the path of the planned well, by either automatically intersecting the 3D model or by manual work (see e.g. Pitcher et al. (2010)). Because the 3D model is a coarse scale model, automatic methods do not allow optimal capturing of well scale details. In some geosteering workflows, the 3D model is visualized together with a real-time update of the trajectory of the well being drilled. But the 3D model is not updated, so there is often a mismatch between the real-time logs and the model.

In Kullawan (2016) and Kullawan et al. (2014) an extensive review of current geosteering decision practices is summarized. The summary includes methods for updating the geomodel, such as a) *Model, Compare, Update (MCU)*, b) *Dip interpretation*, and c) *Bed Boundary Mapping*, which are complementary to each other. The *Reservoir Mapping* method, based on Deep EM which brings the interpretation towards a reservoir mapping scale, is the most recent (see also Arata et al. (2016) for a brief review). Less prevalent methods include biosteering, geochemical steering, geomechanics steering and petrophysical steering. Furthermore, the summary pin-points challenges with the current practices and propose a framework for transforming data into insight, providing consistent guidelines for systematic decision making for optimal well placement.

2.2.1 Geosteering example

Figure 2 shows a screen from a software for geosteering decision support. The support is based on real-time interpretation of LWD logs and the updating of a simplified 2D model at the bottom of the screen.

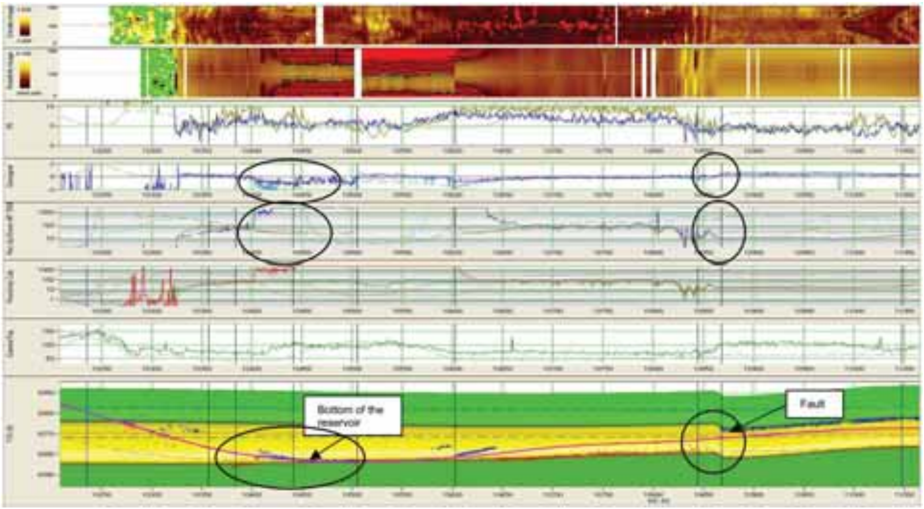

Figure 2. Geosteering decision support software (Source: Pitcher et al. (2010))

Figure 3 depicts how the geological structure in a 2D model is updated while drilling by modifying the depth and thicknesses of the stratigraphic surfaces and inserting vertical faults.

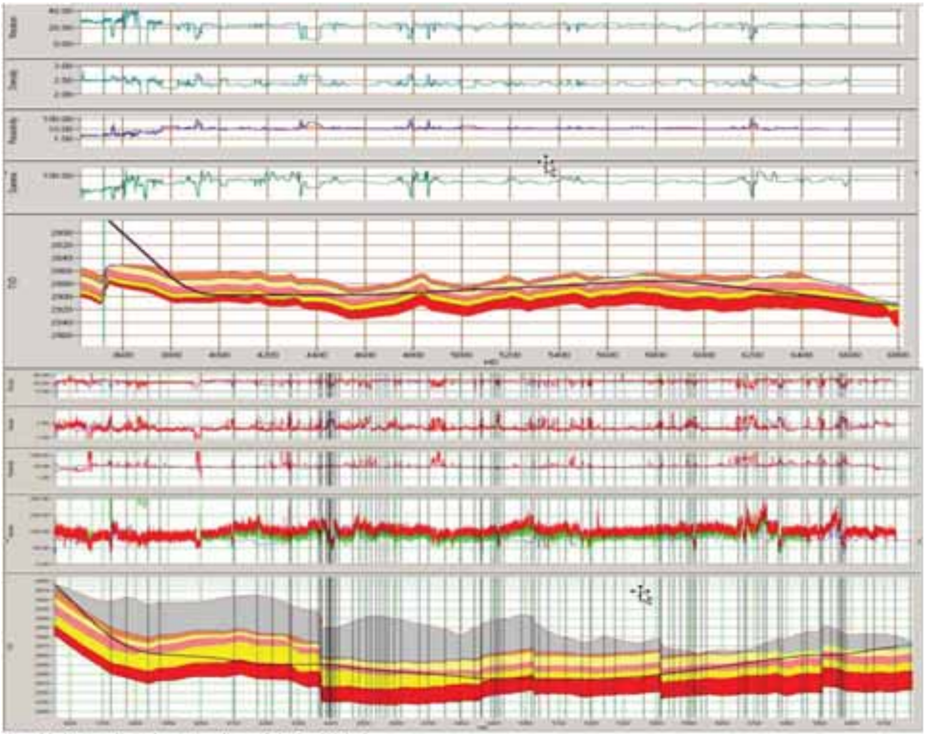

Fig. 11–Pre-well and post-well models for Well A.

Figure 3. Comparison of pre-drill and post-drill 2D models. (Source: Pitcher et al. (2010))

2.3 State-of-the-art geosteering supported by 3D models

2.3.1 Model update shortly after drilling

In Cardola et al. (2017), a geosteering case is detailed. The paper describes a workflow for integrating geosteering outcomes, log interpretation and petrophysical analysis for effectively providing input for field development decision support. The updates described in the paper all took place directly after the drilling operation, in time for amending well completion.

Figure 4.A displays real-time LWD logs (1), Deep EM inversion results (2), together with an updated local scale 2D earth model (3). It is highlighted how the RT resistivity (1) shows low values both in a probable sand and in silt/mudstone. The RT density image helps in reducing the interpretation uncertainty. Figure 4.B indicates how the immediate post-well analysis of the resistivity inversion provided structural and stratigraphic input for the first update of the static model. The depth of the stratigraphic interfaces in the 3D model were updated as part of the workflow. Yet, its structural connectivity remained unchanged. An important conclusion from the paper is that interpretation methodologies, from geosteering to updating the full-field reservoir model, are highly dependent on each other. It is also emphasized in the paper that each of the involved methodologies (geosteering, log interpretation, forward modelling and 3D reservoir modelling) contributed to a better understanding of the other methodologies. Maximum integration of the involved disciplines in a real-time workflow is needed for optimizing production (and drilling efficiency). For example, the workflow discussed in Cardola et al. (2017) allowed a timely choice for well completion. Furthermore, progressive refinement of the results, based on more detailed interpretative tools, allowed for an improved 3D reservoir model at the fine scale.

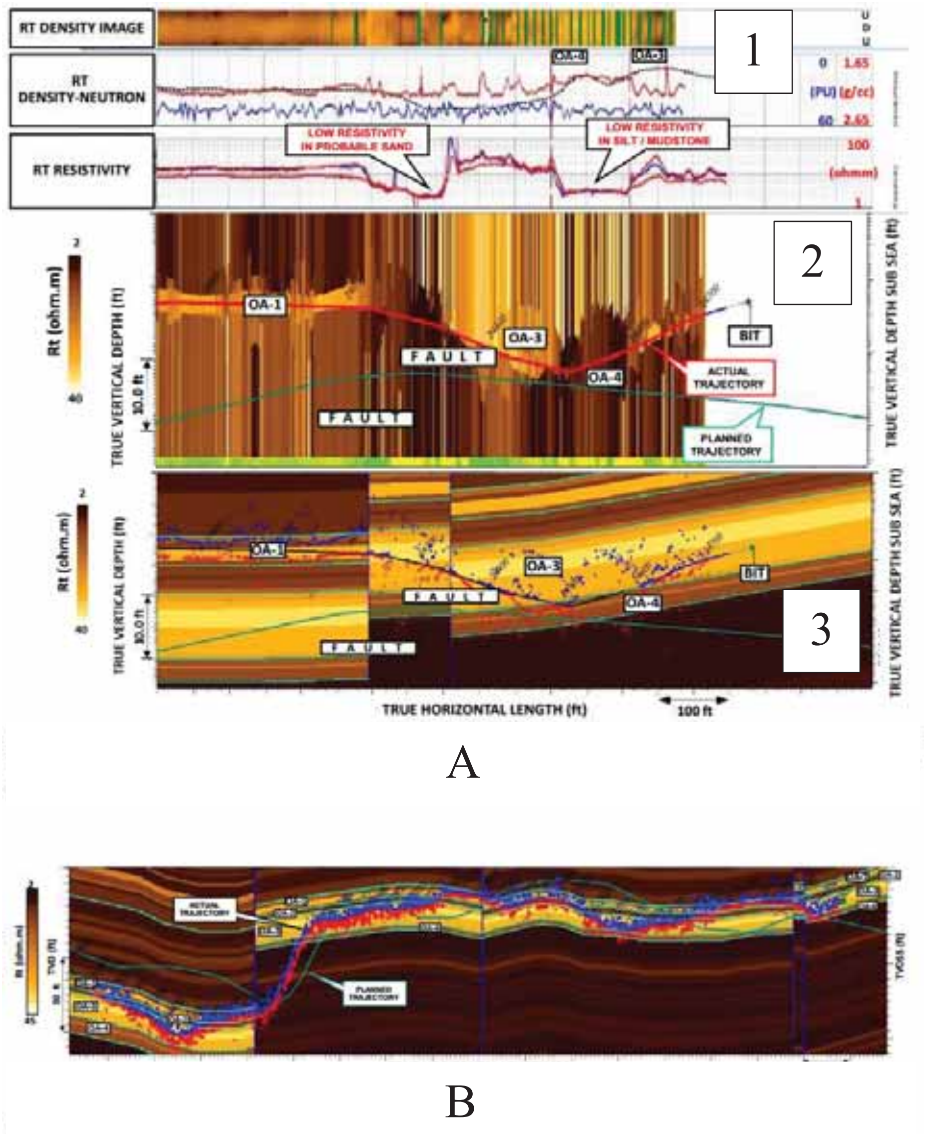

Figure 4. Geosteering case. Modified from Cardola et al. (2017).

In Arata et al. (2016), a workflow for locally updating a seismic-driven multi-realization local scale 3D reservoir model after the drilling of each new well is described. The model updates were based on e.g. Deep EM information from the drilled well, but without a new seismic inversion. In Tarchiani et al. (2017a), a coarse-scale model was updated. In the workflow, the grid-based properties were changed, and small differences in the geological structure could be locally tuned. The latter did not include modifications in the structural topology. The workflow described in the paper for effectively updating the Field Development Plan was important to address subsequent drilling activities. It also provided possibilities for better decision making when appraising and developing the field. It is stated in Arata et al. (2016) that "the ultimate goal is to include the data acquired in horizontal wells in a live reservoir model, updated across the entire cycle of the well placement".

In Hanea et al. (2015), the ensemble-based model is typically updated before the drilling of each new well in a drilling campaign. This allows optimization in the order in which wells are drilled. The geological structure can be updated in depth via modifications in the velocity model. See Suter et al. (2017a) for further discussion about this strategy.

2.3.2 Model update while drilling

In Tarchiani et al. (2017b), a novel workflow for updating the predictions of the geological structure ahead of the bit was outlined. While drilling, the seismic volume and the horizons and faults interpreted from the seismic were adjusted to the depth of the resistivity image generated from Deep EM at a local scale around the well. This took place via a displacement volume that was continuously generated/updated while drilling. No grid was modified in the workflow, and the structural connectivity remained unchanged in this highly automatic procedure. In the paper it is explained that future developments involve "refined management of the uncertainty related to the data and an increasing 3D influence of the geomodel".

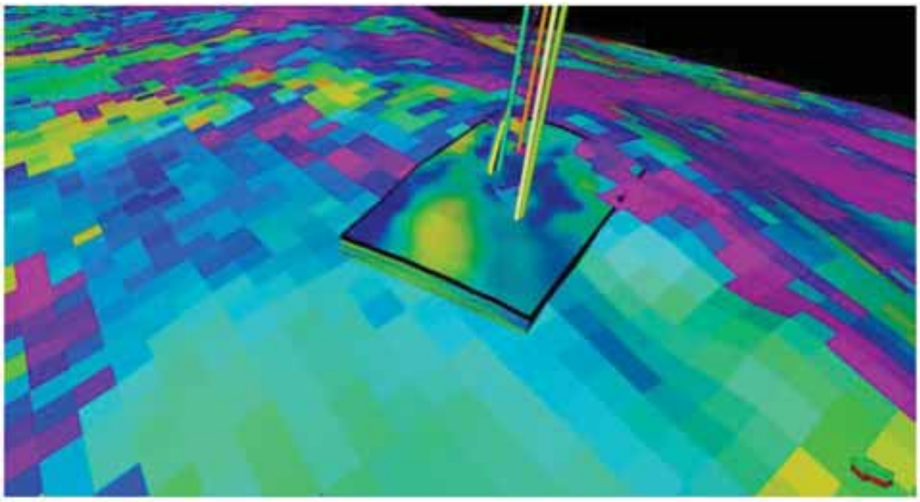

Figure 3—Full field model after data transfer shows well locations sector model and porosity.

Figure 5. Sector model versus large-scale model. (Source: Bashir et al. (2016)).

In Bashir et al. (2016), a methodology where a 3D geocellular sector model is updated while drilling is described. The sector model covered a local volume around the well. Figure 5 shows the relationship between the large-scale model and the sector model in terms of the volumes each of them cover and their grid resolutions. The advantages of maintaining a 3D model rather than a simplistic 2D model are emphasized in the paper; a better understanding of lateral heterogeneity allows improved control when the geological environment favour the well trajectory to be adjusted in three dimensions rather than only up-dip or down-dip in the vertical direction. Bashir et al. (2016) discusses how “The use of a reliable earth model should minimize the need for advanced and expensive LWD tools and their associated services like reservoir boundary mapping”. Moreover, “The trade-off between cost and performance still exists, but the decision to use costly LWD tools can now be based on our confidence in the initial 3D model.” It is also emphasized that the updating of a 3D geocellular model while geosteering shortens the process to update the geological model which feeds the simulation model.

But the same challenges related to the construction of the large-scale model, makes also the construction of sector models around the well challenging. For example, it is explained in Bashir et al. (2016) that the boundaries of the sector model must be carefully selected to honour the influence of adjacent wells. Models covering smaller volumes allow increased horizontal and vertical resolution that approximates the well log resolution without impacting computing time. Just as for large-scale geomodels, there is a trade-off between resolution and time spent for computation. This trade-off must be selected prior to the construction of the sector model, and it cannot be updated once the model has been constructed (see Section 3.3).

During drilling, the formation tops and stratigraphic interfaces in the unfaulted model were adjusted in depth. As the model did not contain faults, it is assumed that the structural connectivity remained unchanged during the model updates. Also, the petrophysical properties were updated. The view of the 3D model was shared among the drilling asset team stakeholders for decision support.

2.4 Technology gaps

Optimal model-based real-time decision support for geosteering and for the drilling operation requires that the model is well calibrated against all measurements and interpretations at all times during drilling, that the relevant uncertainties are quantified in all spatial dimensions, and that decision support is provided at the right time while drilling.

As it has been discussed earlier in Section 2, the current work processes for geosteering suffer from several shortcomings; a) it is highly challenging to calibrate geomodels to EM and LWD measurements for complex formations, b) there is a lack of flexibility in the current geomodelling strategies for support of effective model updates (in particular structural updates) and handling of complex uncertainties while drilling, c) in many workflows, the geological models that are updated are simplified models that cover only a volume locally around the well, and d) there is a lack of an effective, transparent, systematic and consistent workflow for quantifying complex geological uncertainties in the 3D geomodel, and effectively considering them when making geosteering decisions. In the current geosteering practices geological interpretation require a high degree of manual interaction, right up to the extent that the drilling speed must be reduced in critical areas (Antonsen et al. 2015).

In a reactive process, one attempts to resolve challenges and ‘unexpected events’ as they occur. A proactive strategy implies to predict challenges and take actions to minimize the potential effects of these ‘unexpected events’. In a drilling setting, this requires taking all available information, including realistic estimates of all uncertainties, into consideration while still providing decision support within the available time before decisions must be made. In a stressful environment where much is going on at the same time and many experts with different backgrounds, opinions and objectives are involved, this can be highly challenging and lead to poor decisions. Moreover, a documentation of the decision process may be more or less lacking and therefore difficult to evaluate and learn from. In critical situations where all contributing factors intensify, underlying problems become acute and may lead to critically poor decisions with economically unfavourable results and potentially catastrophic outcomes.

2.4.1 Challenges related to the earth model

3D earth modelling tools are today typically used only for strategic decisions, where there is ample time for analysis. However, the requirements for good decision making are the same, independently of how much time that is available (Kullawan, 2016).

Any type of model simplification as discussed in Section 2.2 reduces the amount of information captured in the model. This allows more effective model management and/or to capture more details around the planned well (a trade-off). But simplification also implies that important information may be ignored when constructing the model (see discussion in Section 3), and thus becomes much more difficult to consider for real-time decision-making. If the decision process heavily relies on model-based support, removing potentially critical information from the model is far from optimal. It is well known by subsurface experts, and emphasized in e.g. Bashir et al. (2016), that geological interpretation should take place in three spatial dimensions when providing geosteering decision support. This is particularly important when drilling in heterogeneous depositional environments with large lateral variations in lithology and structure, requiring decision support also when actively steering the well laterally (as opposed to simple vertical changes only). Moreover, it is important that the resolution of the model is fine enough to capture geological features that should be used to control the well path.

When comparing the local scale model to the large-scale model, more details around the planned well are included and information at locations and scales that are assumed to contribute less to the decision making are removed/ignored and not represented in the model. This trade-off is necessary to optimize the model complexity to allow real-time decision support. For 3D sector models, because of their inflexibility in management of information at different scales and frequencies (see Section 3.3), this can only be obtained by ignoring *all* information outside a given box. Clearly, this can have critical consequences for more complex operations. For 2D models, all information outside the vertical plane (the curtain of the planned well) is ignored. If the drilled well deviates laterally from the curtain or the 3D sector model, there is no model representation at all. Obviously, for model-based consideration of interpretation uncertainties while drilling, the uncertainties must be represented in the model. Interpretation uncertainties may have propagated from other scales (importantly, seismic scale) or from distant locations in the subsurface. In such cases, they cannot be properly addressed by considering only a small part around the well.

Depending on the workflow that is applied during drilling, it may for example be that two or more models are considered simultaneously; the large-scale model and a (set of) simplified local-scale model(s) that are updated in real-time. In an environment where time is limited, the extra complexity resulting from considering multiple models is not optimal.

If a conventional 3D geocellular model is used for geosteering support, local updates of the geological structure are highly limited (see Sections 2.4 and 3.3). Moreover, the selection of model resolution take place prior to drilling and cannot be adapted during the operation (see Section 3.3). This inhibits the capturing of high frequency geological features which may be critical to consider at the fine scale that is important to geosteering decision making (see e.g. the discussion in the Appendix, Section 12.2.1). In particular when drilling in heterogeneous environments, such challenges hinder effective model-based decision support.

Field development decision workflows heavily depend on earth models. The use of such models has reduced costs and improved production and safety. In contrast, current workflows for geosteering and drilling operational decision support do not employ models that contain all relevant information about the subsurface, that are continuously updated during the drilling process, and that provide relevant decision information in a timely manner as drilling progresses. This hinders the clear potential that model-based decision support provides, in particular when drilling in more complex and heterogeneous geology.

3 Existing Earth Modelling Approaches

In this section, conventional 3D earth modelling strategies are reviewed. Such methods are typically used for applications where modelling time is not a major limiting constraint; fluid flow modelling, production optimization and field development planning are today not real-time decision processes. In these tools, interpretation uncertainties in the geological structure are not well managed. Consequently, as also discussed in Section 2.2, current geosteering practices do not include updating of the geological structure in 3D models.

In Appendix A.3 in Suter et al. (2017a) and on page 5 in Suter et al. (2017b), it is summarized how the interpretation of the geological structure is often burdened by first-order uncertainties, potentially resulting in dramatic effects on the decision to be taken. The Appendix (Section 12.1) contains a discussion of structural uncertainties.

3.1 Handling of geological uncertainties

A grid-based geological model (geocellular model) contains two 'main parts'; the geological structure (such as stratigraphic interfaces and faults) and the grid-based properties (such as porosity, permeability, saturation, density, etc.). The properties are represented in a grid that conforms to the geological structure (the grid is constrained by and follows the structure, so that the structural elements also exist in the grid). The grid is a necessary input for most types of computer based simulations and predictions. In the model construction workflow, first the structure is constructed, then the grid.

'Geological uncertainties' is a term used to cover a large range of different types of uncertainties when interpreting various types of geological evolution. The existing earth modelling workflows typically have large focus on uncertainties in the grid-based properties. This is not because such uncertainties are generally considered to be more important or dominating compared to uncertainties in the geological structure, but because the existing modelling tools are ineffective and require time consuming manual work to handle structural uncertainties. Uncertainties in the structural and stratigraphic framework are often said to have the highest impact on the results, depending on the complexity of the geology as well as on the type of decision being made. For example, see Branets et al. (2015) regarding modelling of fluid flow, Nasibullin et al. (2016) for estimating gross rock volume (see the sensitivity chart in their Figure 1), and Ahmadi et al. (2013) where a method for managing structural uncertainties for history matching is discussed. The latter article states that much of the past history matching and uncertainty quantification work has neglected structural uncertainties. For example, uncertainties in the reservoir connectivity are crucial when estimating fluid flow. Such uncertainties include e.g. sand-sand connectivity across a major fault known from seismic (see for example Figure 21 in this thesis), or can be related to subseismic faults that are only identified while drilling. Both larger and smaller faults, as well as e.g. subseismic sealing shales, contribute to compartmentalization of the reservoir. Compartmentalization is important to consider when drilling a well. According to Cherpeau et al. (2010), where stochastic simulation of fault networks is discussed, very few methods have been proposed for changing the topology of a structural model once it is established.

Automatic management of grid-based petrophysical properties is much addressed in the literature and there are many algorithms available that support such handling. But there are far fewer algorithms for effectively managing the geological structure and its uncertainties.

3.2 Model construction and management

According to e.g. Mallet (2008), Jackson et al. (2013), Røe et al. (2014) and Howley and Meyer (2015), the construction of a geocellular reservoir model using conventional modelling tools can be summarized as follows;

Table 1. Earth model construction process

1. Decide the conceptual model to be used for the interpretation.
2. Construct the geological structure (e.g. fault surfaces and stratigraphic interfaces).
3. Construct a global corner-point grid that follows (is constrained by) the structure.
4. Populate the grid with properties.

Step (1) in Table 1 is an exercise that takes place in the mind(s) of the subsurface expert(s) that are involved. It is a result of careful studies of all available information. The interpretation exercise is highly subjective and biased by the experience of the expert(s) (see Section 12.1.1 in the Appendix), and may thus introduce 'challenges' or errors that cannot be dealt with without complete reconstruction of the entire model (see e.g. Bond et al. (2007) and Bond (2015)).

Step (2) is the first step in capturing the selected conceptual model in a numerical geomodel. The conceptual model guides in the interpretation of the structural elements observed from seismic, well logs, etc., for example in how the elements should be connected. The structural modelling exercise requires much manual work in the form of picking with the mouse in the set of seismic sections and assuring that the structural elements 'fit together' in a geologically realistic fashion.

Step (3) is a mostly automatic procedure, although it may present challenges so that regridding with different gridding parameters is required.

In steep contrast to Step (2), **Step (4)** is highly automatic. Facies and property modelling over a given grid is based on geological parameters such as e.g. the width, thickness and sinuosity of channels, or other types of property distributions. The use of geological rules, controlled by the geological parameters, enable multiple facies and property realizations to be routinely produced in a fully automatic and geologically sound fashion which approximates the knowledge of the subsurface in an intuitive and effective manner. The results are fully reproducible, and updates in the property models take place by simply modifying the parameters and re-running the algorithms. There is no need for manually modifying e.g. the porosity value in an individual grid cell. The geological parameters also enable effective communication between geoscientists in an intuitive manner.

However, property modelling is typically performed per geological layer. This implies that if the geological structure (in particular its stratigraphy) is modified, the property models may need to be manually changed and re-run to correspond with the new structure. Property modelling is carried out on the same grid for all properties. The result is a populated corner-point grid often referred to as the ‘geological grid’. It forms a basis for e.g. performing fluid flow simulation (typically via upscaling) and other simulation exercises.

The model construction workflow is iterative. Scenarios are generated and tested, before going back and updating if necessary. Clearly, having already passed **Step (4)**, one will typically go back as few steps as possible to save time. The construction of an earth model requires much work, e.g. in the order of several man-years. Depending on internal practices and needs, the model is updated e.g. every 3 or 5 years (ref: private communication). Then all the available and relevant information about the subsurface, including new seismic and logs from new wells, is used as basis for a complete remodelling.

3.3 Technology gaps

In the following, some of the complexity of the modelling process in light of real-time requirements is discussed;

In the construction process in Table 1, each step depends on the previous steps. Assume that a complete model is provided. Then, if the model is locally modified at some step, it implies that all subsequent steps must be performed again. Depending on the model complexity, this may take much time. This is far from optimal for real-time processes.

Step (1), selection of interpretation concept;

There can be multiple conceptual models that fit the available information about the subsurface equally well, both at local and global scales (see the Appendix, Section 12.1). But once a model is generated, the interpretation concept cannot be modified. This is because of the large amount of work involved in the following steps.

Step (2), structural modelling;

For any conceptual model, at any scale, there are many possible geological structures with different topological configurations that fit the available information (uncertainty in the structural interpretation). This issue is detailed in Section 3.3.1.

Because of the applied gridding strategy (see Section 3.4), current tools are limited when attempting to capture and handling more complex geological structures. The corner-point grid with its regular 'IJK'-topology enforces strong limitations on the maximum complexity of the structure. This is explained for example in Mallet (2008), Hocker (2011), Mallet (2014) and Mallison et al. (2014). They emphasize that the geological structure may require modifications by over-simplifying or even ignoring structural elements, to allow a suitable corner-point grid to be constructed. This practice may result in a geologically unrealistic model. In Mallison et al. (2014) it is explained that the process of building a corner-point grid becomes challenging if more than a dozen intersecting faults are included. But there is no further technical reasoning around the nature of the problem. It is also stated in the paper that severe limitations arise if the fault network includes truly 3D features such as Y-faults, where the pillar concept is said to break down entirely and serious compromises must be made. According to the paper, such errors cannot generally be quantified in flow simulation studies. Noteworthy for geosteering applications, it is also claimed that of even greater concern is the fact that these alterations become a major impediment to integrated modelling efforts and interdisciplinary collaboration. Clearly, if the geological structure that is represented in the pre-drill model does not agree with the pre-drill measurements, challenges will arise while geosteering.

The resolution of the geological structure is decided at this early phase in the modelling process, e.g. which faults and layers to include in the model. Moreover, the size of the subsurface volume to represent in the model is selected. These decisions are major constraints for the resolution of the grid to be generated (see Section 12.2 in the Appendix for a discussion of model scale and resolution). The structural resolution must be coarse enough to allow a grid that is coarse enough to avoid spending too much time for computations in later modelling steps. When constructing a model, many geological elements may therefore be left out such as smaller faults (see e.g. Mallet (2008), Mallet (2014), Arata et al. (2016) for further discussions). Then there is no representation of these elements in the model, and they cannot be considered in a highly automatic model-based geosteering process. An example is if there are 500 interpreted faults in a given subsurface volume, but only 100 are represented in the model (ref: private communication). The assumption is that the removed elements play a less important role at the scale that is studied, and for the decision purpose. Moreover, offset wells (and cores) provide high-resolution information which can only be captured at a coarser resolution in the model.

The subsurface volume that a model covers should be ‘as small as possible’, so that elements outside the model ‘box’ that are important for interpretation while drilling may be left out. This also includes local scale interpretations around offset wells. Such interpretations become difficult to reconsider for the interpretation around the well being drilled if the modelled volume doesn’t include the offset well. As a consequence, updates cannot be effectively interpolated from offset wells if required.

All these decisions regarding model scale and resolution are subjective and depend on the bias of the interpreter(s). Depending on the modelling purpose, the trade-off may be severe. Moreover, each model is typically constructed to serve a specific purpose (a specific type of decision). It can thus be challenging or impossible to modify the model to serve another purpose. Each purpose may then require its own model at its own scale and resolution.

To modify the structural resolution (e.g. the density of the fault network or the stratigraphic resolution) once it is established, requires time-consuming manual work. Moreover, such modifications again require the same type of modelling decisions to be made as when the model was initially constructed.

Step (3), grid construction;

Once the grid is constructed, its resolution cannot be locally updated. A new grid must be generated for each required resolution.

Furthermore, the resolution of the corner-point grid is more or less the same throughout the model (although the lateral resolution is typically coarser than the vertical resolution). Dictated by the IJK-topology of the grid (see Section 3.4), all layers extend laterally throughout the model although their thickness may be set to zero when required. The grid adapts to the faults, thus the lateral resolution may to some extent vary with the local fault resolution. But if the fault network is too complex, a grid cannot be generated.

Step (4), property modelling;

A single grid contains all facies and properties; hence all properties are represented at the same resolution independently of the need. It is not possible to represent individual properties at a resolution adapted to the frequency of their variations, even if a modelling exercise would benefit from more details in one property (higher grid resolution) and less detail in others (lower grid resolution). Clearly, also property models are valid for a specific selected scale, namely the same scale as was selected for the structural model. To change the scale requires manual work and possibly re-interpretation.

3.3.1 Managing interpretation uncertainties in the geological structure

In conventional workflows, automatic model updates and uncertainty management are limited to modification of the property values represented in the cells or nodes of an existing grid, e.g. in a History Matching process. This is mainly because a) structural modelling is not an automated process and requires much manual work for proper and geologically realistic handling of the structure, and b) local updates of the geological structure require a time consuming global reconstruction of the populated grid. Thus, the geological structure is typically not included in the uncertainty handling process; only item 4 in Table 1 is subjected to uncertainty modelling.

In more recent methods, one tries to capture uncertainties in the geological structure by geometric perturbation of the base case structural model (see e.g. Mallet (2014), Nasibullin et al. (2015), Hanea et al. (2015) and Caumon (2014)). Geometric perturbation includes to slightly adjust the location and displacement of existing faults (Røe et al., 2014) or adjust the geometry of stratigraphic interfaces (Aarnes et al. 2015). In multi-realization strategies, this perturbation is constrained by an 'uncertainty envelope' where the geometries are perturbed in a continuous manner. If the stratigraphic interface is split by a fault, the uncertainty envelope exists on both sides of the fault. However, the strategy does not allow representation of topological uncertainties such as; "The fault displacement is uncertain. On the right-hand side of the fault, which observed interface is the one that corresponds to a given interface on the left-hand side of the fault?".

Uncertainty management via geometric perturbation is today being implemented in commercially available tools and workflows, see e.g. Nasibullin et al. (2016) and Hanea et al. (2015). Geometric perturbation does not modify the structural topology, and therefore cannot be used to capture uncertainties in how faults are connected, the depositional structure, or uncertainty regarding the existence of faults and stratigraphic elements. Neither does it handle more complex uncertainties involving the geological concept used in the interpretation, such as “is local scale compression taken up by faulting or folding?”. In typical workflows, the grid is globally regenerated even when the structural model is only slightly geometrically perturbed. Thus, multiple realizations are generated in Step (2) in Table 1, and for each realization a separate global grid is constructed. The necessity for globally regenerating the global grid when the structural topology is only locally modified is a result of the grid being a rigid numerical construction where the topological relationship between its cells cannot be modified in a flexible manner (see Section 3.4).

The past few years have seen improvements in addressing more complex fault networks by stairstep (staircase) faults (see e.g. Hoffman et al. (2008)). They allow to maintain the IJK-indexing even across reverse faults. But representing faults in an approximative and inflexible manner via a stairstep approach is not optimal for geosteering. For geosteering, a precise and realistic representation of the geological structure even at well scale is required. The stairstep approach is developed to handle faults in a corner-point grid with its particular challenges regarding cell topology and geometry.

In Table 2, limitations in present earth modelling techniques with respect to geosteering are summarized.

Table 2. Limitations in present earth modelling techniques with respect to geosteering.

1.	Time consuming manual work is required for managing the geological structure, so that uncertainties in the structural connectivity are typically not captured in the model.
2.	Local updates of the geological structure are not possible without global grid reconstruction, so that local management of structural uncertainties is time-consuming also in automatic workflows.
3.	Poor control with grid resolution and size, so that information across multiple scales and frequencies cannot be handled.
4.	Complex geological structures are not properly handled.

Each of these challenges present a serious limitation when drilling in complex reservoirs. Time consuming manual management of the geological structure (item 1 in Table 2) is a challenge that is not directly related to the grid. But the last three items in Table 2 are consequences of using a global corner-point grid (see Section 3.4). If the grid cannot be brought into agreement with the measurements in a geologically sound and realistic manner, there will be a mismatch between the measurements and interpretations, and the model. Such a model has less predictive power, and decision makers will (and should) question its results. In particular when drilling in complex geology, where right-time model support is even more critical, this is far from optimal and may lead to poor decisions. The ability to 'model what you see' and capture the relevant geology in a realistic manner, without being seriously restricted by an inflexible grid, is vital for optimal well placement.

Because of the described limitations for managing structural uncertainties, such uncertainties may easily be underestimated. The lack of tools for effective model updates results in suboptimal decision support for geosteering where structural uncertainties are vital to handle. Moreover, it may also result in underestimating uncertainties regarding e.g. fluid flow or reservoir volume.

In Table 2, challenges in present earth modelling techniques with respect to geosteering were summarized. In Table 3, it is shown how each of the main methods discussed in this thesis relate to these limitations.

Table 3. How the main methods in this thesis address the challenges in using present tools for geosteering.

	Type of limitation	**Addressed by method**
1.	Time consuming manual work is required for managing the geological structure, so that uncertainties in the structural connectivity are typically not captured in the model.	Preliminary work for automatic management of faults (Section 8.1).
2.	Local updates of the geological structure are not possible without global grid reconstruction, so that local management of structural uncertainties is time-consuming in automatic workflows.	Local model updates (Section 5), multi-resolution grid management (Section 6), and local scale uncertainty management (Section 7).
3.	Poor control with grid resolution and size, so that information across multiple scales and frequencies cannot be handled.	Multi-resolution grid management (Section 6). Moreover, local model updates (Section 5) enable local updates of the structural resolution in real-time.
4.	Complex geological structures are not properly handled.	Application of tetrahedral grids (in 2D: triangular grids). Multi-resolution grid management (Section 6).

Control with model resolution and handling of structural uncertainties are important for any earth model based workflow. Local model updates are important for speeding up the earth model management. Moreover, it is explained in Suter et al. (2017a) how the suggested approach can be supported by parallel processing. Processing in parallel aims to speed up the model management by distributing the computational load over multiple processors.

3.4 Globally defined corner-point grid

A main reason for ineffective management (in particular of structural topology) in existing methods for three-dimensional earth modelling is that a three-dimensional corner point grid is an inflexible construction. The topological connections between the cells in a corner-point grid are bound to follow the IJK-regular topology, and the topology cannot be modified in a flexible manner. The grid adapts to (is constrained by) the geological structure (e.g. faults and stratigraphic interfaces). This implies that the geological structure is also represented by a subset of the faces of the grid cells. Also this relationship cannot be easily modified, so geological surfaces (e.g. faults) cannot be moved with respect to the grid topology in a simple manner.

The inflexibility of the globally defined grid implies that the populated grid must be globally regenerated when the structural topology is locally modified.

Moreover, it is highly challenging to adapt the grid to a topologically or geometrically complex geological structure (see Section 3.3). As a simple example, consider two neighbouring faults that can be seen on seismic or interpreted from well logs. Assume that the distance below them are below the resolution of the grid. This implies that they cannot be correctly represented. To allow capturing in the model and enable the creation of grid cells, one fault must be moved away from the other. For flow modelling, such practices may or may not be acceptable. Also note that a typical practice in flow simulation is to have at least two grid cells between faults to avoid too complex grid cell geometries (ref: private communication). But this is a modelling decision, and different interpreters have different habits.

But for automatic decision support while geosteering, such practices are far more challenging. This is because the model cannot be brought into agreement with the well scale measurements. This introduces inconsistencies which in the next step would need to be dealt with algorithmically. Moreover, a suboptimal model results in suboptimal decisions. Furthermore, when drilling in structurally complex environments with more complex geometries and connections, the problem is far more serious. It inhibits to ‘model what you see’ because the grid does not allow it. The consequences for decision making may be severe.

3.5 Emerging technologies

Recent geomodelling research was summarized in Appendix A.4 in Suter et al. (2017a) and on page 6 in Suter et al. (2017b).

In Bentley & Ringrose (2017), future directions in reservoir modelling are discussed. The authors highlight the need for improved uncertainty management, as well as for more effective grid management. Their proposed future strategy for the latter is referred to as a grid-independent world, where grids are disposable and can be generated whenever necessary. This allows fit-for-purpose generation of earth model grids, where the grid resolution is optimal for the task at hand. The generated grid is discarded (archived) once the decision question at hand has been addressed.

Techniques such as those presented in Jackson et al. (2013) and Mallet (2014) are mentioned as methods that may allow improved strategies for reservoir modelling. A conceptual comparison between these two approaches and the method described in this thesis is provided in Appendix A.4 in Suter et al. (2017a) and on page 6 in Suter et al. (2017b). While the strategy in Jackson et al. (2013) allows remeshing in the interior of a region independently of neighbouring regions, in the same manner as in the methods discussed in this thesis, the resolution of the geological structure is not included when considering grid resolution (see Section 6.2.1). In the GeoChron strategy discussed in Mallet (2014), remeshing of individual structural surfaces is applied (see Section 6.2.4). But also here, the structural resolution is not included when the grid resolution is considered. The structural resolution is a major restriction for the grid resolution (see Section 6.2.1). Consequently, both these approaches offer far less control with grid resolution than the method suggested in this thesis.

For reservoir modelling, it has been proposed to use CAD-tools for capturing geological structures in the form of NURBS (non-uniform rational B-splines) surfaces for managing complex geological structures (see Jacquemyn et al. (2016) and Melnikova et al. (2016). Such approaches avoid several of the challenges discussed in Section 3.3. This is because the industrial quality CAD-tools that are used have been refined for management of general and complex geometries as basis for the following grid construction. It is shown how NURBS surfaces representing structurally complex geological environments are created and combined, using an automated stochastic approach based on geological rules.

4 The proposed workflow for geosteering and drilling support

In Figure 1, a proposed workflow for geosteering is shown. The aimed-at functionalities of the workflow determine the requirements set to the earth modelling tool. To better explain the requirements set to the earth modelling methodology presented in this thesis, the geosteering workflow is discussed in more detail.

Ultra-deep directional electro-magnetic (Deep EM) measurements have been used increasingly during the last years to obtain information about the formations around the wellbore while drilling. Deep EM measurements is a technological step change aiming to provide more information about geological structures, fluid contacts and reservoir properties deeper into the formation than traditional Logging While Drilling (LWD) data. The new technology has given the possibility to improve the interpretation of geological formations around the drill bit, resulting in unprecedented opportunities to shift from reactive to proactive geosteering (Bittar and Aki, 2015), and even provide information ahead of the bit (Constable et al., 2016). Depth of penetration depends on many factors. While traditional LWD sensors typically ‘see’ a few centimetres up to a meter or two around the wellbore, Deep EM may extend this range up to e.g. 30 metres. But the range depends on the geology (and the resulting contrasts) that surrounds the wellbore. Moreover, all measurements are subjected to geological interpretation with its uncertainties before they are utilized for decision support (see the Appendix, Section 12.1).

As explained in Antonsen et al. (2015) and Constable et al. (2016), there is an increasing need for better methodologies to evaluate and quantify uncertainties and an improved fundamental understanding of the relationship between the inverted resistivity distributions and the geological structure. In Zhou (2015) and Zhou et al. (2016), strategies to incorporate geological constraints using available information (seismic images, well logs and geological understanding of the reservoir) and their impact on the interpreted models are discussed. As highlighted in Constable et al. (2016), reducing geological uncertainty is a key to minimizing drilling risk, well complexity and non-productive time while drilling.

Optimally, human operators and decision makers should not be burdened with calculations and handling of information at a detailed level. This work should be left to computers that are superior in number-crunching. The main role of humans should be focused on; i) setting objectives for how the handling shall take place (provide model input), and ii) making decisions based on a clearly communicated, model-based prediction of the most likely consequences of the alternative decisions that are presented, including associated risks (exploit model output). To build trust in the modelling results, the models and workflow must be transparent and understandable. Also their limitations must be known and possible to consider.

4.1 Suggested workflow

A key idea behind the proposed geosteering workflow is to continuously update the earth model, represented by an ensemble of possible realizations, by incremental integration of the new measurements acquired during drilling using the Ensemble Kalman Filter (EnKF) methodology.

Prior to drilling, an earth model derived from seismic, offset wells, production measurements and other available information is made available. Its uncertainties are represented in the form of an ensemble of realizations representing possible geological scenarios around and ahead of the bit, aiming to span the space of interpretation uncertainties. The scenarios may differ both in the grid-based properties and the geological structures (including structural connectivity), as well as in grid resolution. The scenarios will be continuously updated during drilling, constrained by while-drilling Deep EM measurements and other LWD logs.

The earth model functionalities limit which type of uncertainties that can be captured and managed in real-time (see Section 3.3). While drilling, each realization in the ensemble is continuously and automatically updated. The model updates are enabled by adapting an ensemble-based method which has previously been implemented for reservoir history-matching and production optimization (see Aanonsen et al. (2009), Skjervheim & Evensen (2011), Skjervheim et al. (2015) and Hanea et al. (2015)).

When new measurements are received during the drilling operation, they are compared to the measurements simulated by the corresponding forward models for each realization. The comparison formulates a stochastic minimization problem for joint inversion of all available measurements. The ensemble-based algorithm updates the realizations to approximate the solution of the problem, and as a result minimizes the misfit between the available measurements and the earth model. The earth model updates are performed by adjusting a set of modelling parameters, implying that the parameterization of the earth model is vital. Optimally, the parameters should enable the model to be automatically managed in a geologically realistic manner that is both intuitive to subsurface experts and that allow capturing of geological uncertainties. Such parameters are referred to as geological parameters.

LWD measurements reduce the pre-drill uncertainties, but the remaining uncertainty is still significant. For example, multiple different geological scenarios may fit the measurements equally well. These scenarios can be topologically different, e.g. in the number of layers and faults at the local scale. It is therefore important that the earth model and the workflow can handle such uncertainties.

Whenever necessary while drilling, experts could be allowed to include more geological knowledge by either constraining the uncertainty using their knowledge of the field or by proposing a new hypothesis of the geology around and ahead of the bit (for example, “is the newly detected contrast below the well an oil-water contact or a shale?”). For each new hypothesis, new realizations must be generated that capture the uncertainties of the hypothesis. As time is a critical factor, the generation of realizations should require as little manual work as possible. This could be achieved by developing suitable geological parameters that ensure effective and intuitive human-system interaction. The new realizations are inserted into the earth model as a local update, and automatically adapted to fit the available measurements using the ensemble-based method. A stochastic algorithm adjusts the probabilities of each hypothesis as drilling continues and new measurements arrive. The calculated probabilities can be used for decision support. Moreover, scenarios with low probability can be removed, hence rejecting the improbable hypotheses.

Allowing humans in the modelling loop introduces subjectivity and bias. However, subjectivity was already introduced in the construction of the model. If humans are not involved, it is up to the algorithms to automatically generate every reasonable geological scenario that may fit with the measurements. But are existing (and future) algorithms sophisticated enough to accomplish this, in particular when drilling in complex geology that may be less well understood?

Based on the predictions of the geology around and ahead of the bit contained in the earth model realizations and the corresponding probabilities, decision analytics algorithms will perform optimization under uncertainty and recommend the optimal well trajectory ahead of the bit with respect to a set of geosteering and drilling objectives. Given the proposal for a trajectory, e.g. geological risks, the cost for drilling the remainder of the well, the cost of performing a side-track, or a rudimentary estimation of future production (with uncertainties) could be estimated in real-time. This forms a basis for decision support while drilling. Such calculations could be performed for the different scenarios of the ahead-of-bit geology.

A distinguishing feature of the workflow is the systematic, transparent and unbiased local updating of the geological uncertainties around and ahead of the bit while drilling. Transparency implies that model parameters can be examined and adjusted in an automatic or manual fashion, and that the effects of the modifications should be understandable to humans. The model updates themselves are unbiased if humans are not involved in the update loop. However, the bias and subjective reasoning from the initial model construction may still be present. Only future research can reveal how this affects the decision support.

The proposed framework aims to allow evaluation of alternative decisions under uncertainty, including predicting the outcome of the decisions, based on the most recent measurements and an always up-to-date earth model that effectively handle all relevant uncertainties in the geological structure, the facies and the petrophysical properties. The aim of the strategy is to contribute to real-time decision support for a) improved drilling safety, b) lower drilling cost, and c) production optimization.

In Figure 6, results from a geosteering prototype software are shown. The figure is similar to Figure 5 in Luo et al. (2015). The prototype applies a simplified earth model where the structural topology is not updated. Prior to drilling, uncertainties in the depths of the top (blue dotted lines) and bottom (green dotted lines) reservoir interfaces and the OWC (red dotted lines) are estimated. The middle lines are the mean estimations, while the upper and lower ones are the estimations $+/-$ one standard deviation (STD) away from the means. The synthetic true model is shown using solid blue and green lines for the top and bottom interfaces, respectively. To the upper left, the drilling has just started (see the location of the drillbit). To the upper right, around 200 m have been drilled. In the image at the bottom, around 400 m have been drilled. The uncertainties in the geological structure and the OWC are reduced as new measurements arrive. The drilled well path is indicated with black curves with plus signs. In this example, the reservoir coverage is good. Luo et al. (2015) contains a more detailed discussion.

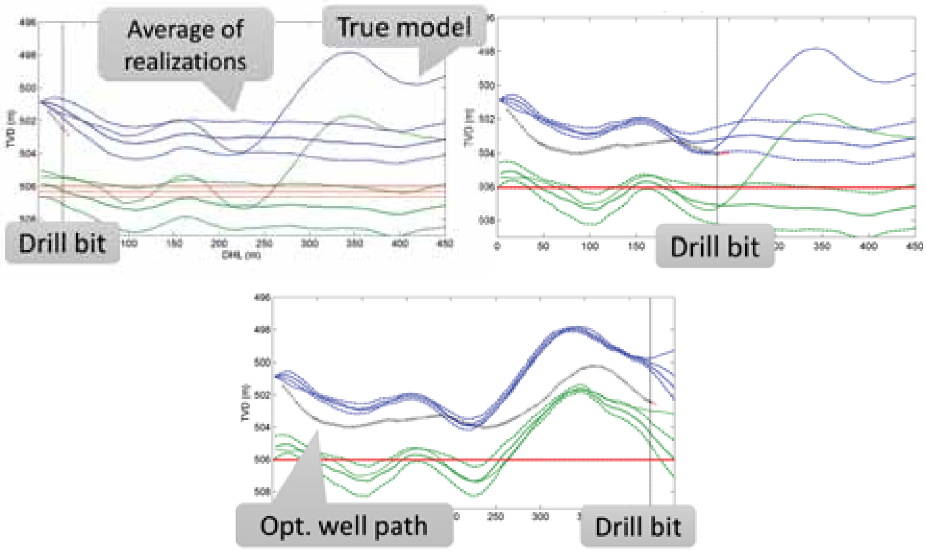

Figure 6. Geosteering workflow applied to a synthetic case.

4.2 Papers describing the methodology

The proposed geosteering methodology is shown in Figure 1. The complete workflow was presented in Luo et al. (2015). It applies an ensemble Kalman filter (EnKF) for managing and updating uncertainties. The updates were constrained by Deep EM measurements.

A decision analytic framework for geosteering is discussed in Kullawan et al. (2014), Kullawan et al. (2016) and Kullawan et al. (2017). The framework is summarized in the PhD dissertation Kullawan (2016). It aims to provide unbiased and consistent decision support under uncertainty for real-time applications. Model updates while drilling is a key element in the approach.

In Suter et al. (2017c), a tool for consistent and automatic management of real-time measurements is proposed. Automatic processing, e.g. the geosteering workflow, requires a certain quality in the measurements. For example, they must be synchronized in time, so that their latencies are equal and preferably close to zero. Another aim is to estimate the uncertainties for each individual measurement. The estimates could then be propagated to the geosteering workflow, allowing them to be appropriately taken into account in the estimation of the interpretation uncertainties.

The main theme of this thesis is the proposal of principles for effective earth modelling while geosteering. A methodology for locally updating the geological structure in a populated earth model grid was presented in Suter et al. (2017a). It was first discussed in Suter et al. (2010) and in Suter et al. (2012). Moreover, a novel technique for multi-resolution grid management was presented in Suter et al. (2017b). This paper also describes a method for management of uncertainties at a local scale within a large model.

The proposed principles for effective earth modelling are discussed in the following sections.

5 Local updates of a populated grid

To address the challenges regarding effective management of the geological structure in an earth model that are discussed in Section 3, principles for locally updating the topology of the geological structure in a populated earth model grid has been developed. It also allows local modification of the grid resolution in the interior of regions bounded by the geological structure. The method was presented in Suter et al. (2017a), and initially discussed in Suter et al. (2010) and in Suter et al. (2012).

5.1 *Principles*

Local updates of the grid when modifying the connectivity of the structural model are obtained by avoiding a global grid. The geological structure and the properties are split and separately managed. The principles are illustrated in Figure 7, which depicts an earth model with two depositional layers (L^1 and L^2) that are split by a fault. The geological structure separates the subsurface into disjoint regions R_i. Each region is individually discretized so that it obtains a subgrid G_i at the required resolution (the grid is not shown in Figure 7). Each region may obtain several subgrids if properties should be handled at different resolutions. Moreover, by refining or coarsening a subgrid, or replacing a subgrid, the grid resolution can be locally altered. The properties are handled in separate property functions Φ^j, e.g. for each depositional layer L^j. The subgrids are populated by interpolation of the appropriate part D_i^j of each property function via a mapping f_i^j. The collection of populated subgrids $\{G_i\}$ for the set of regions $\{R_i\}$ together constitute the earth model.

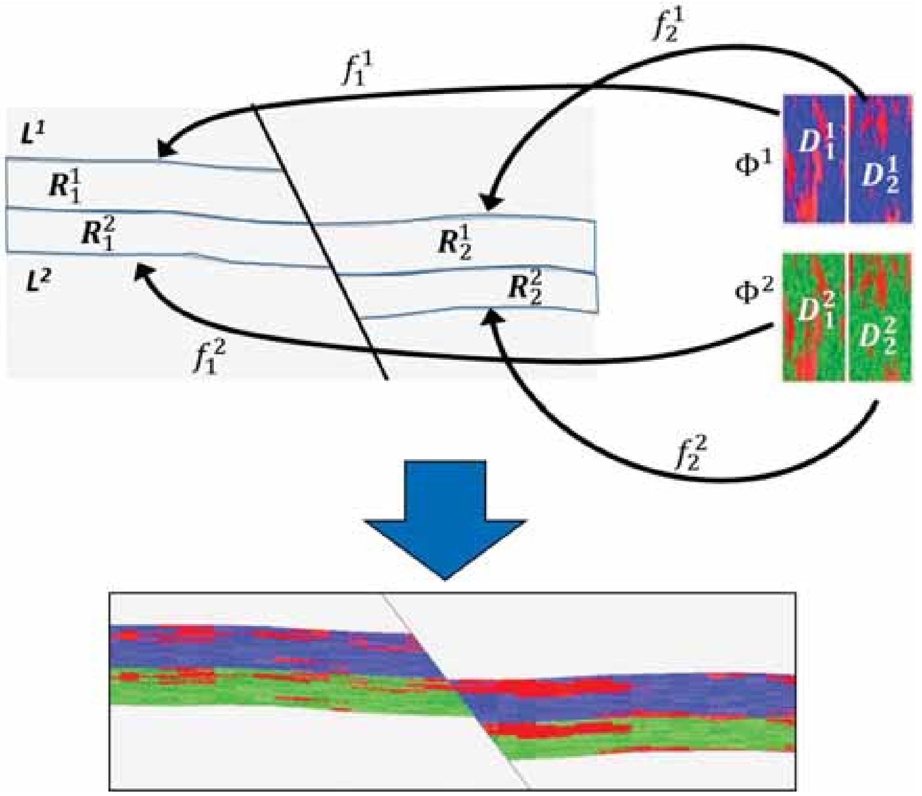

Figure 7. A simple model to illustrate the principles for locally updating a populated earth model grid. The figure can also be found as Figure 2 in Suter et al. (2017a). The colours in the figure indicate property values.

When the geological structure is locally modified, only subgrids in regions that are affected by the structural update (i.e. bounded by a part of a structural element that is modified) must be regenerated and repopulated, whereas the rest of the populated subgrids are kept. In an update of the structural topology, e.g. when inserting a new fault, existing regions may be eliminated and new regions established. Subgrids in the regions that are removed are discarded, while new regions obtain new subgrids that can be effectively populated from the existing property functions. The amount of computations required for a local update is independent of the number of grid cells in the model. For more details, see Sections 2 and 3 in Suter et al. (2017a).

The individual management of each region thus implies that;

- A region does not overlap with other regions except at their common boundaries,
- A region is discretized independently of other regions,
- A region has a dedicated (part of a) property function for each property to be represented in the region,
- A region has a dedicated mapping for transferring property values between the property function(s) and the subgrid(s) in the region.

Individual management of each region enables;

- **Local updates of a populated grid** when the topology (connectivity) of the geological structure is modified.
- **Computational processing in parallel** (subgrid generation, generation of a mapping, property population). Parallel processing effectively utilizes the computational resources in a modern computer, such as multicore CPUs and GPUs, or the resources in a cluster of computers.

The combination of the ability to locally update an existing earth model grid and the capability for parallel processing is expected to dramatically increase the computational efficiency when managing large models.

5.2 Examples

The mapping f allows effective updates of the geological structure without invalidating existing property representations. It is thus important to the discussed methodology when non-trivial complex property distributions are handled. Examples discussing its properties were shown e.g. in the Figures 8-10 in Suter et al. (2010), and in the Figures 1-2 in Suter et al. (2012). Suter et al. (2010, 2012, 2017a, 2017b) all contain multiple examples of mapping properties into the geological structure, both before and after structural updates.

Section 5.3 in Suter et al. (2017a) contains a discussion of the handling of properties.

The properties of f dictate which type of structural configurations that can be handled, while still being able to map values from the property function into the subgrids that are controlled by the geological structure. It thus determines which type of modelling functionalities that can be obtained. Therefore, further figures are shown to indicate how the mapping behaves. They have not been shown in the papers due to space limitations. The example in Figure 8 indicates that f is flexible enough to handle e.g. folded shapes.

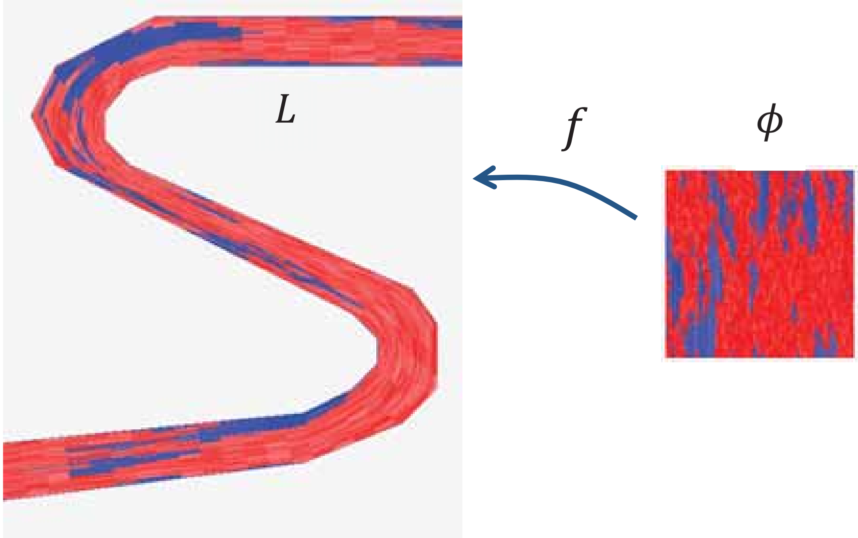

Figure 8. To the left, a simple S-shaped layer L. The layer has been discretized, and properties are interpolated from the property function ϕ to the right and mapped into L using the mapping f. The figure indicates that f is flexible enough to allow population also of folded shapes with existing properties.

Figure 9 contains two shapes S_1 and S_2 that have been discretized. S_1 illustrates an initial shape, while S_2 is a locally updated version of S_1 where three vertices in its polygonal boundary have been moved in correspondence with the movement of the circle in light green which encapsulates all three vertices. No other vertices were moved. The figure indicates how a local deformation of the

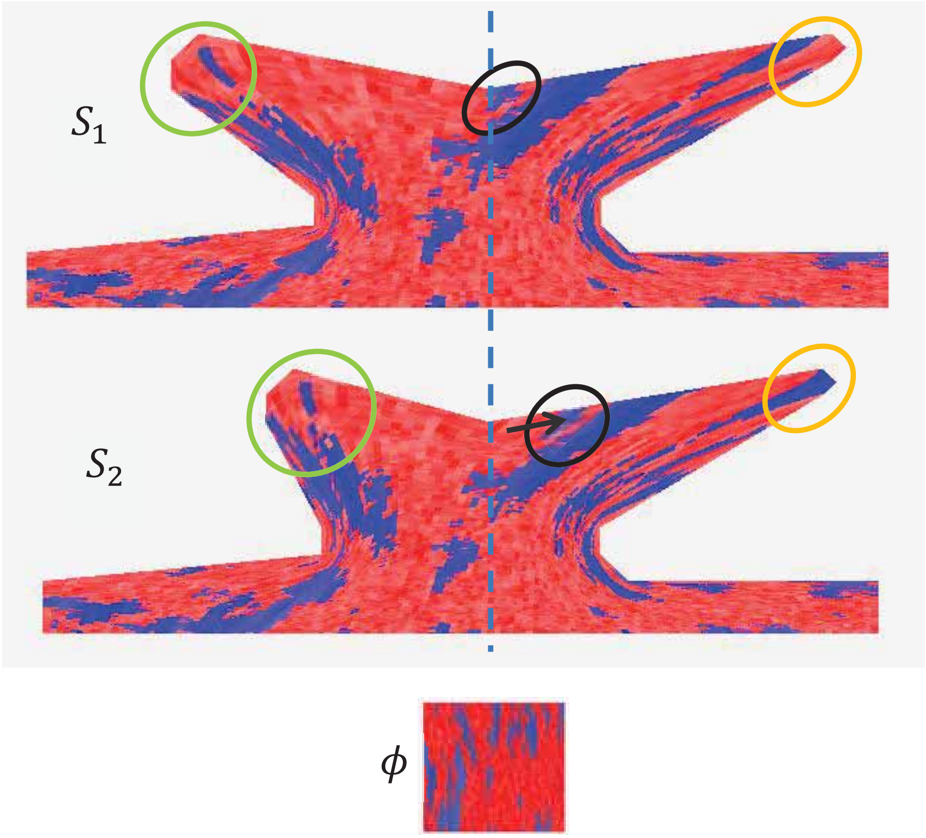

Figure 9. The boundary of S_1 *has been locally deformed into the boundary of* S_2*, as indicated by the green circle (three nodes in the boundary polygon were moved). Values from the property function* ϕ *are mapped into each of the two shapes. It is clear that the local modification of* S_1 *to create* S_2 *has consequences for the mapping and therefore for the property distribution also away from the location of the nodes that were moved. This is seen in the two volumes encircled in black and orange, respectively. The length of the black arrow indicates how much the property distribution has been displaced at this specific location.*

boundary has implications for the mapping f and thus the distribution of properties within the complete volume covered by a single mapping. An example is within the area encircled in black, where it is seen from the pattern in the properties that they have been moved to the right. In the volume encircled in orange (the location of the orange circle is the same for both S_1 and S_2), it is clear how the blue area in the properties has been shifted to the right. The dotted vertical line in blue is for reference, we see that all property values have been 'translated' to the right in a continuous manner. If such deformation becomes problematic, it is possible to subdivide S_1 into a set of smaller regions R_i with a corresponding subdivision of ϕ into smaller regions ϕ_i. Now each region can be handled independently of the others, by ensuring that the local deformation of the boundary of S_1 will only modify the shape of a subset Q_j of the regions R_i. Then the local deformation should only affect the properties in the interior of Q_j. Within the regions with unaltered boundaries, the mapping of the properties will remain unchanged.

5.3 Dependencies between regions

A crucial principle is that the subsurface is split into a set of separate regions that are handled independently; there are no dependencies between the subgrids in any two regions, neither numerically nor when considering storage in the computer memory (the data model).

For practical applications however, there will typically be dependencies between regions (but not between the *subgrids* in two different regions). Dependencies may typically be established e.g. when a set of neighbouring regions are used to represent a faulted stratigraphic layer where properties are interpreted to follow a trend across all regions. In this case it is often reasonable to represent a property for the layer using a single property function that covers all its regions. But it is important to note that this is a modelling choice, it is not a requirement set by the method. If required, each individual region could have its own property function. This is not indicated in Figure 7, but corresponds to letting the property values in D_1^1 and D_2^1 be represented not in a common property function Φ^1 but in two individual functions Φ_1^1 and Φ_2^1. This is useful if the properties on each side of a fault require different handling, e.g. in terms of resolution or if the property values follow different trends. This does not influence the computational efficiency of the method.

A further example is when a stratigraphic interface is displaced by a fault. The interface is represented by two separate geometric elements that are numerically independent. Yet, the elements clearly have a geological connection as they represent the same geological interface. If a property is assigned to the interface instead of being represented in a property function (as is proposed in Jackson et al. (2013)), the property could be used for both geometric elements.

6 Multi-resolution earth model gridding

Management of scale and resolution is much debated in the earth modelling literature (see Sections 3.5 and 6.2 for examples). Next, a novel method for multi-resolution grid management is described, including multi-resolution management of the geological structure (faults and stratigraphic interfaces). Multi-resolution techniques have been successfully applied within other sciences and applications, enabling ordering of information according to scale.

A successfully developed, flexible and general multi-resolution approach for earth modelling would enable effective management of massive amounts of subsurface information (as indicated in Section 12.2 in the Appendix). Multi-resolution management in a geological context is a highly complex theme, and very few methods have been proposed in the literature. Yet, future methods may allow a set of entirely new techniques and model-based workflows where information across multiple scales and frequencies are effectively managed by allowing different resolutions in different parts of the model. Moreover, for real-time applications such as geosteering, local modifications of the model resolution are crucial to optimize the model size. The method was discussed in Suter et al. (2017b).

Rocks are heterogeneous at all scales. The interpretation of the geological evolution at a given scale, say well scale, is constrained by observations and interpretations at both coarser and finer scales (see discussion in Section 12.2). Highly automatic earth model based decision support requires that *all relevant* information is present in the earth model, independently of scale and frequency. If relevant information is *not* present in the model, it is not possible to take it into account in a model-based prediction and decision loop.

But representation of all relevant information typically results in large models;

- Geological interpretation is based on reasoning in terms of multiple scales. Optimally, information over a range of scales should be represented in the model and be ready to be considered for interpretation whenever necessary. But representation of information across a large range of scales increases the model size.
- Frequencies of subsurface heterogeneities are important to consider. If the subsurface change rapidly in a given volume in a manner that matters to decision making, it requires a more detailed representation. But large amounts of details result in a larger model.
- Interpretation uncertainties exist at all scales. Uncertainties can be handled by application of multiple realizations, which again increases the model size.

When geosteering, local scale interpretations around the well must be effectively constrained by and integrated with coarser scale pre-drill interpretations. Real-time model-based interpretation and decision support thus requires integration and management of large amounts of uncertain subsurface information at multiple scales and frequencies in a computationally highly effective manner. To filter out irrelevant information, independently of scale, frequency and location, is important to optimize the model size. Details should be represented when required, and excluded if they do not support decision making. When drilling in complex geology, this is even more vital; computations should focus on the parts of the model that matter for decision making. In conventional earth model construction processes, such filtering is handled manually and depends on the subjective view of the interpreter.

The time available for modelling between new measurements arrive until decision support is required, should optimally be decided by the decision-makers, and not be limited by the capabilities of the modelling tool. Such considerations depend on the operational or steering decision to be made, and may change while drilling. Some decisions require almost immediate support, while for other decisions, more time is available. The decision at hand should control the trade-off between model quality and time available for model management.

The proposed multi-resolution method addresses some of the main challenges pertaining to the control of the model resolution (see discussion in Section 3 regarding shortcomings of existing methods). By combining a) a method for hierarchical representation of the geological structure and the resulting closed regions with b) the method for locally updating the grid described in Section 5, principles for real-time multi-resolution management of the grid are proposed to enable real-time local control with the model resolution.

The strategy has two main aspects for earth model management; a) effective handling of massive amounts of subsurface information, and b) effective modification of the model resolution via local updates. The latter is critical to avoid slow, global model updates.

The aim is to ensure a set of always optimally sized earth model grid realizations for real-time processes such as drilling, by allowing a) different resolutions of the grid in different parts of the model, and b) effective local updates of the resolution of the grid. Optimal control with grid resolution aims to allow optimal control with the trade-off between numerical accuracy and the time needed for computations in the subsequent modelling, simulation and decision processes.

6.1 Principles

In existing approaches for geomodelling, the geological structure splits the subsurface into closed regions (see Section 4.1 in Suter et al. (2017a)). In the proposed multi-resolution approach, by ordering the geological interfaces in a hierarchy, the closed regions also obtain a hierarchical ordering. A hierarchical ordering (e.g. of full-dimensional cells) is the foundation for many existing multi-resolution methods within other sciences.

First the stratigraphy is organized in a hierarchy, following geological principles. An example is a lithological subdivision, where rocks are subdivided into layers at different scales; beds, members, formations, groups and supergroups (layers from fine to coarse scale). But note that given a set of interpreted surfaces, the ordering of the surfaces in a hierarchy is a modelling choice. See Suter et al. (2017b) for details of the ordering according to stratigraphic principles, as well as the Figures 5-8 in that paper.

Faults are associated with the stratigraphic hierarchy, in accordance with the scale of the layer each fault displaces. Simply stated, a small-scale fault typically deforms layers at a fine level of detail, whereas a large-scale fault deforms layers at a coarser level of detail. These coarse-scale layers contain fine-scaled layers and faults, so a large-scale fault will also deform layers and faults at the finer scales. Combining stratigraphic interfaces and faults results in a nested set of closed regions. Each region obtains a populated subgrid as explained in Section 5. Population of properties requires the generation of property functions for layers at any level of detail. The generation of the hierarchy of closed regions is far from trivial, and currently constitutes a major challenge when addressing realistic and irregular geological structures. For example, each fault is associated with the level of detail of the coarsest scale layer it intersects. But clearly, the fault may not terminate exactly in the stratigraphic interfaces that constitute the boundaries of the layer.

As basis for discussing the principles, consider Figure 10. To the middle right it shows a simple, idealized earth model with two layers, split by a fault. There are bounding faults at the left- and right-hand side boundaries, respectively. This second coarsest scale is denoted level-of-detail = 1 ($LOD = 1$). The top layer consists of the two regions B and D, and the bottom layer contains the two regions C and E.

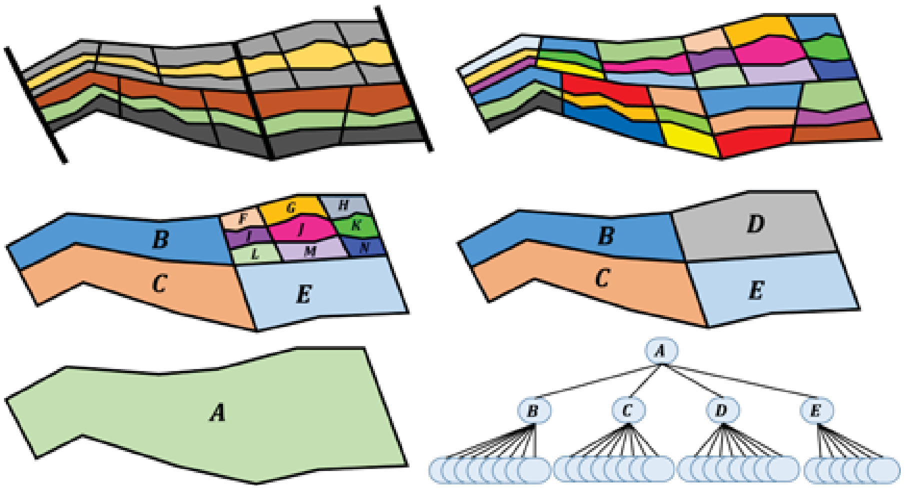

Figure 10. The principles of the multi-resolution earth modelling concepts. At the bottom right is the region tree which captures the hierarchy of nested regions.

Each of the two layers are subdivided into three layers at the next finer scale ($LOD = 2$), see the model to the top right. Each of these layers are split by faults. The two layers in the model to the middle right (at $LOD = 1$) together constitute a single layer called 'A' at the coarser level of detail $LOD = 0$ as indicated in the model to the bottom left.

A fault is associated with the coarsest scale layer it intersects, so that it terminates in the boundaries of this layer or boundaries in the interior of this layer. In the model to the upper left, faults at two different scales ($LOD = 0$ and $LOD = 1$) intersect the layers. In the model in the middle right, the fault in the middle is associated with $LOD = 0$. In the model in the middle left, the faults in the interior of region D (see the model to the middle right) are associated with $LOD = 1$. The tree to the bottom right indicates how the regions are organised in a hierarchy denoted the region tree, the hierarchical representation of regions. Suter et al. (2017b) contains more detail.

6.1.1 A region is an 'earth model on its own'

An important consequence of the methodology is that any given subregion, at any scale, can be considered as being an 'earth model on its own'. This was also discussed on p. 20 in Suter et al. (2017b).

Each region is completely independent of other regions (at any level of detail) that it does not intersect with. Each region R at a specific $LOD = j$ is bounded by structural elements that each belongs to (is associated with) the level of detail j or some coarser level $i < j$. In the interior of R, it can have its own geological structure that belongs to a finer level of detail $k > j$, its own subgrids and its own property functions. This implies that the geological interfaces and properties in the interior of the region can be represented numerically independent of the interfaces and properties in the exterior the region.

As an example, consider the model to the middle right in Figure 10. Region D is 'an earth model on its own'. In the model to the middle left, it is indicated how it contains geological structure in its interior.

Note, however, that in practice one will typically impose dependencies between the geological interfaces and properties in the interior and exterior of the region. For example, a geological interface (say a stratigraphic interface) will generally be used to bound several regions. But the interface could still be modelled as a single geometrical element. This is exemplified in the model to the middle right in Figure 10, where the stratigraphic interface between the two layers bounds multiple regions at different scales. Another example is that a property function will often be used to represent a property for an entire layer, even if the layer is separated by faults into multiple regions. But these dependencies are modelling choices, not requirements set by the method. The numerical framework itself does not require dependencies between the interior and the exterior of a region. For example, when layers in the hangingwall side of a syn-depositional fault have properties that are different from the layers deposited at the same time in the footwall side, this could be represented by using two different property functions. See also Section 5.3 regarding this issue. But in that Section, a region is not considered as being part of a multi-resolution environment. Thus, in its interior, the single-scale region only contains a populated subgrid and no structural interfaces.

Using the already existing geological interfaces as basis for multi-resolution management ensures a smooth transition of level of detail across already existing geological interfaces. For example, a layer that is split by a fault can have different stratigraphic resolution on each side of the fault. On one side of the fault the layer can be represented at its coarsest stratigraphic resolution (e.g. the layer itself), whereas on the other side of the fault the layer can be represented at a finer stratigraphic resolution (so that it is represented by several layers at the next finer scale).

An example is shown in Figure 30 in Suter et al. (2017b), where the regions E_1 and E_2 are represented at different stratigraphic resolutions. This requires that the fault completely intersects the coarse scale layer (the fault cannot start or stop in the middle of this layer). This is also illustrated in the models to the middle right and left in Figure 10.

6.1.2 Local model updates

The principle in Section 6.1.1 establishes that each region at any level of detail in any grid realization is 'an earth model on its own'. This provides a foundation for locally modifying each grid realization in the interior of each such region. Such updates include e.g. the insertion of a new layer or fault in the interior of a region at some scale. The updates can be performed in accordance with the principles for local model updates as outlined in Section 5. However, in this multi-resolution framework the updates can be applied to any region at any level of detail. Such updates would typically affect the hierarchy of geological interfaces and regions at finer scales in the interior of the region.

As a basic example, consider the insertion of a new fault F_1 as shown in Figure 11. Region B is the same as region B in Figure 10, except that here it doesn't contain any interior structure. First, the level of detail of the fault and the smallest region that contains it are identified. The smallest region is region B, which becomes the root of the subtree that is being considered. F_1 is inserted into B, splitting it into two subregions B_1 and B_2. The new subregions are discretized and their subgrids populated, allowing a local update of the global grid realization in the interior of B. The local update takes place by replacing (swapping) the previous geological structure and subgrid(s) in the interior of B with the new geological structure and corresponding subgrids in the two new subregions. The rest of the regions, namely $\{C, D, E\}$ in Figure 10, are retained. This is in correspondence with the principles in Section 5. Furthermore, the region tree must be updated. This amounts to swapping node B in the tree in Figure 10 with the root node B and its subtree as shown to the middle right in Figure 11. Such updates can take place recursively. Each of the new subregions,

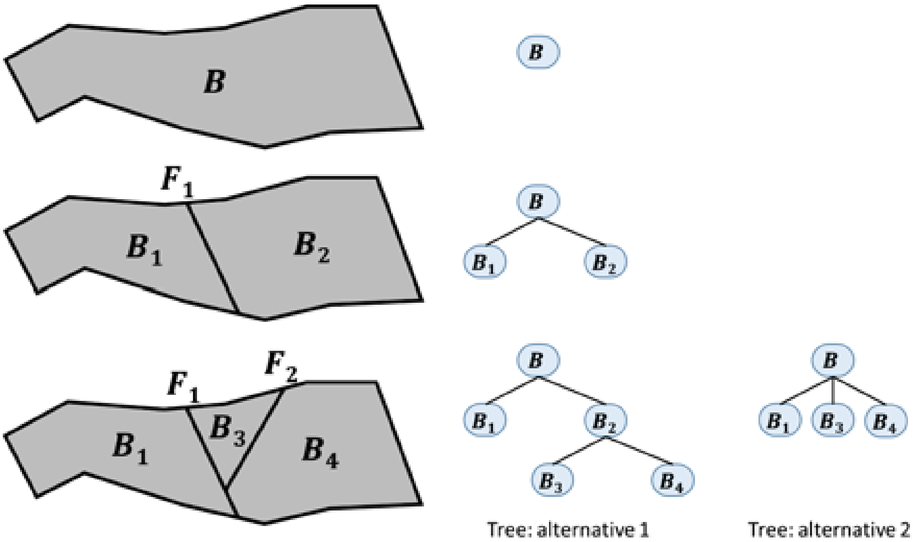

Figure 11. Sequential insertion of two new faults into the region B. B is the same region as region B in Figure 10 (but not including its interior geological structure).

at any scale, is again considered as a 'small earth model on its own' which can be subjected to local updates. This is indicated in the bottom model in Figure 11, where the antithetic fault F_2 is inserted as a local model update as just described.

This example also indicates that different trees can be used in the multi-resolution handling. This is not well explained in Suter et al. (2017b). To the bottom right in Figure 11, two alternative trees having B as their root are shown (alternative 1 and alternative 2, respectively). Both trees include B_1, B_3 and B_4 at the finest level of detail, but only alternative 1 includes B_2 as a separate region. In alternative 2, region B_2 was removed as a separate node and replaced with B_3 and B_4. This corresponds to inserting F_1 and F_2 simultaneously. There is a difference for practical applications in using alternative 1 vs alternative 2. If using alternative 1, an extra level of detail is available. B_2 can then be represented either with or without including F_2 when selecting a specific level of detail (see Section 6.1.3). If alternative 2 is used, one can only choose to include or exclude both faults at the same time when refining the level of detail in the interior of B. But the local model update to insert F_2 can be performed in the interior of B_2 in both cases. Further development is required for consistent handling of these choices of alternatives. Note that the manipulation of trees is computationally cheap, and will be possible to complete in real-time.

Following the same principle as when inserting a new fault in B, it is also possible to update the local scale stratigraphy in the interior of B. As an example, consider the update of B by inserting a new subseismic layer that while drilling is interpreted to be a local pinch-in. An example is shown in Figure 4 in Suter et al. (2017a). In this figure, L_1 corresponds to B while L_3 is the layer that pinches in. Multi-resolution is not considered in that paper. But by application of the principle in Section 6.1.1, it is clear that this update could take place in the interior of some region.

Local model updates in a multi-resolution environment are also exemplified in the Figures 21-24 in Suter et al. (2017b), showing a slightly more complex model. These examples include local updates of both the fault network and the stratigraphy. An example using a software prototype is shown in Figure 29 in Suter et al. (2017b). Several faults are inserted into layer E, which constitutes the root of the local scale region tree. In Figure 30, the interior of E has been locally updated by splitting it into multiple subregions $E_1 - E_6$ by faults that intersect E.

6.1.3 Controlling local scale resolution

A typical use of multi-resolution strategies known from other sciences and applications is that the model resolution can be locally controlled. This can take place by ‘activating’ nodes in a hierarchy represented in a tree. In the suggested approach, these nodes represent regions in the region hierarchy as explained in Suter et al. (2017b). The location of a node in the tree represents its level of detail. An example is the tree at the bottom right in Figure 10.

It is explained in the Sections 3.4 and 6.2.1 that the resolution of the geological interfaces limits how coarse a grid can be. Regions are ‘earth models on their own’ as explained in Section 6.1.1. Each region, at any level of detail, control the resolution of the geological interfaces in its interior. The insertion or removal of interfaces in the interior of a region result in a local modification of the structural topology (see Section 6.1.2). In Section 5, it has been described how the topology of the geological structure can be locally updated within a populated grid. Thus, the suggested framework aims to allow local control with the resolution of populated grid realizations in real-time by enabling insertion and removal of geological interfaces in the interior of regions in a recursive fashion. Control with grid resolution is crucial for the computational efficiency when managing the grid, and also controls the computational efficiency when performing subsequent modelling and simulation exercises.

Next, local coarsening of the grid resolution is discussed. Assume a grid realization where all leaves in the tree of regions are activated so that the realization is at its finest possible resolution. Simply stated, grid coarsening takes place by activating coarser scale subregions. Their populated subgrids replace the subgrids for the subregions at the finer scales as local updates of the grid. An example is shown in Figure 10. Consider the model to the middle left. Region D is activated at its finest level of detail, so that the children of D are activated. In the model to the middle right, D has been activated. The geological interfaces in its interior have been removed and do no longer constrain grid resolution in the interior of D. Local scale grid coarsening is described in the Figures 11-16 in Suter et al. (2017b).

To refine the grid resolution at local scale, corresponds to replacing the subgrid in a parent region with subgrids for the child regions of the parent region. This is the reverse operation of the local scale coarsening described above. Consider the model to the middle right in Figure 10. It will be locally refined in the interior of region D. First, geological interfaces at the next level of detail in the interior of D are activated and used to subdivide D into subregions. If there are no populated subgrids for the subregions, each subregion is discretized and each resulting subgrid G_Z can be populated from a property function that corresponds to the stratigraphic level of detail of each subregion. The set of populated subgrids for these subregions will replace the subgrid used to discretize D. This replacement takes place as a local update of the populated grid, by application of the method in Section 5. All geological interfaces at the next finer level of detail are simultaneously included in the parent region. Only the parts of the interfaces that are in the interior of the parent region are used. A region can be split into an arbitrary number of subregions, depending on the number of geological interfaces at the next finer level of detail. Both refining and coarsening of regions take place in a recursive manner. Local scale grid refinement is indicated in the Figures 11-16 in Suter et al. (2017b), by studying the figures in reverse order.

Already generated subgrids that belong to regions at ‘inactive’ levels of detail can be retained or discarded. If they are discarded, they must be generated and populated when required. If they are kept, the model updates can be more effectively performed. But it comes at the cost of more memory consumption and less adaptivity of the grid (if the gridding objectives have changed and the present subgrids do not satisfy the new objectives).

For each petrophysical property, both the geological structure and correspondingly the grid can have different resolution at different locations within the modelled volume. For example, porosity can be represented at a fine resolution (including both the structure and grid) around and ahead of the bit, while being represented at a coarser resolution away from the bit. Furthermore, for a specific volume of the subsurface, say around the bit, different petrophysical properties (say porosity and saturation) can be represented at different resolutions (including both their structural resolution and grid resolution). This supports individual and effective representation of each property in accordance with the needs for effective modelling.

Figure 9 in Suter et al. (2017b) shows an example where the stratigraphic resolution has been locally refined. In Figures 21-26 in Suter et al. (2017b), it is indicated how local control with grid resolution could be applied while geosteering. In Figures 29-33 in the same paper it is shown using 2D a software prototype how the grid resolution is increased around and ahead of the bit, while it is decreased behind and away from the bit. The 2D prototype is yet too immature to handle more complex geological configurations, so only very regular structural topologies are shown. For example, all faults terminate in the same stratigraphic layer.

Preliminary algorithms for multi-resolution management can be found in Section 6.3.

6.2 Related work

Previous work was summarized on page 6 in Suter et al. (2017b). But there has been performed little work for highly adaptive and flexible multi-resolution management of earth model grids. The most relevant is the method explained in Jackson et al. (2013, 2015), which to a large degree is similar to the method explained in Section 5. Therefore, strategies that may be considered less relevant in light of the suggested approach are also discussed. They may still support the further development of the method.

6.2.1 Local control of grid resolution in the interior of an ‘empty’ region

Within geological modelling, present methods for local control of grid resolution allow the construction of a grid of arbitrary resolution within a closed region. Any such region is at the finest possible scale, and contains no geological interfaces in its interior that should be used to constrain the grid. Methods for locally controlling the resolution within a region include a) locally adaptive gridding (remeshing in the interior of each region) as explained in e.g. Jackson et al. (2013) and Jackson et al. (2015), and b) locally subdividing grid cells in the grid in each region. But in such methods, because the grid is constrained by a static geological structure, the grid resolution will always be finer and cannot be coarser than the structural resolution allows. There will always be some (potentially very large) minimum number of cells in the grid, depending on the resolution of the geological structure (the number of structural surfaces) that the grid must adapt to. The consequence is that even the coarsest possible grid may contain too many cells to allow timely computation of results in a real-time environment.

In Jackson et al. (2013, 2015), geological interfaces are placed in a hierarchy that specify which surfaces that truncate, are truncated by or conform to other surfaces. This is another type of hierarchy than the one suggested in this thesis. Truncation rules control the structural topology and are uncertain.

Traditionally, LGR (Local Grid Refinement) methods are used to subdivide grid cells in corner-point grids, see e.g. Mehl et al. (2006). Corner-point grids are discussed in Section 3.

6.2.2 Binary stratigraphic tree

In Zhang et al. (2015), the use of a binary stratigraphic tree is described. The tree is constructed to allow effective searches in a binary tree. But the tree does not reflect the mindset of subsurface interpreters, where a layer is typically subdivided into sublayers depending on the geological evolution (e.g. as in sequence stratigraphy). The stratigraphic tree proposed in this thesis has an arbitrary number of children for each parent.

6.2.3 Cut-cell grids

In Hocker (2011), a gridding methodology denoted ‘Faulted S-Grid’ is described. The grid is highly regular (orthogonal grid) but individual cells are cut by faults after its initial construction. Cells can be subdivided, allowing different grid resolutions.

Another method using cut-cell grids is described in Mallison et al. (2014). It is an application of the GeoChron model (Mallet, 2014) where cells are cut to allow e.g. more complex fault networks. It is stated that the strategy retains many of the strengths of structured corner-point grids, for example the structured relationship between the coarse-scale simulation grid and the fine-scale geologic grid. Local grid coarsening and refinement is performed, based on nested cells. Structural uncertainties are not particularly addressed in this paper, but it is mentioned that different grids could be generated for each structural realization. Based on this statement, one may assume that a local update of the structural topology requires a global regeneration of the grid.

In Ahmadi (2012) and Ahmadi et al. (2013), a potential approach for modelling of structural uncertainties within the cut-cell grid framework is presented. This work addresses uncertainties in the structural topology of a 2D model with stratigraphic interfaces and faults, but should also be applicable in 3D. Its intended application is history matching, where modelling time is of less importance. Geological interfaces are represented in an order (or hierarchy) that is said to be consistent with the sequence of geological events that created the structure (also see Section 6.2.1, namely the hierarchy mentioned in Jackson et al. (2013) and Jackson et al. (2015)).

6.2.4 Remeshing of structural surfaces

In the construction of a tetrahedral subgrid, the resolution and quality of the grid in particular along its boundary depend on the resolution and quality of the surfaces representing the boundary. Thus, remeshing of surfaces allows better control with the resolution of the grid. This was indicated in the Figures 29-31 in Suter et al. (2017b), where the surfaces representing some of the two-dimensional stratigraphic interfaces were remeshed where less geometric detail was required. Remeshing of surfaces has been discussed in Pellerin et al. (2014) and more recently in Anquez et al. (2017).

6.3 Recursive algorithms for multi-resolution management

Next, a recursive algorithm for generation of a populated earth model grid is proposed (in pseudo-code form). It was not described in Suter et al. (2017b), and is intended to improve the explanation of the proposed method. It generates populated subgrids in parallel. The input is the geological structure, suitable property functions and a region tree (an example of a region tree is shown at the lower right in Figure 10). The starting point is a single region R at some scale, considered to be the local root node. Typically, it could be a region that contains the complete model in its interior. Starting from the root node, the model resolution will be recursively refined in the interior of R to the locally desired resolution. Different subsurface locations can have different resolutions.

Algorithm I (R): Recursively generate populated subgrids for a region R in a grid realization.

```
(1) IF $R$ is an active region (its node in the region tree is active, so that a
    populated subgrid $G_Z$ should be generated at this level of detail), THEN
        a. IF a suitable populated subgrid $G_Z$ for $R$ already exists, THEN
                i. Add $G_Z$ to the set of subgrids $G^\wedge$
           ELSE
                i. Generate a populated subgrid $G_Z$ for $R$ as described in
                   Algorithm 1 in Suter et al. (2017a)
               ii. Add $G_Z$ to the set of subgrids $G^\wedge$
        b. Use $G^\wedge$ to locally update the realization of the global grid
        c. Stop.
(2) ELSE            // $R$ is not an active region
        a. Use the available geological interfaces at the next finer level of
           detail in the interior of the region to create boundaries for its
           subregions $\{r \in R\}$.
        b. parallel for each $r \in R$
                i. Call Algorithm I ($r$).
           end parallel for
(3) ENDIF
```

As can be inferred from **Algorithm 1** in Suter et al. (2017a), **Algorithm I** can be extended to also supporting local updates of the grid resolution and local updates of the grid-based properties.

Next, a recursive algorithm for locally updating the topology (or geometry) of the geological structure in a multi-resolution setting is suggested (in pseudo-code form). It also allows local updates of the resolution of the geological structure and grid in a volume V in the interior of a grid realization. When a geological interface at some level of detail is modified, it may have an effect on all regions at finer levels of detail that are bounded by this interface. The update results in a new set of regions that will replace an old set of regions in the interior of V. The algorithm indicates that not all child regions of a region must be involved in the local grid update. This applies recursively, aiming to minimize the computational efforts for updating a global grid realization.

The starting point is to identify the smallest set of neighbouring regions Q_* that exactly cover V (one or more regions) where the local update of the geological interfaces will take place. The regions Q_* may be at different levels of detail, but Q_* must constitute a volume with no holes. Let P_* be the set of regions in Q_* that are local scale root nodes, so that the rest of the regions in Q_* are children, grandchildren etc. of the nodes in P_*. Outside V, the grid realization remains unaltered.

As a simple example, consider the bottom model in Figure 11 defined by the tree in Alternative 2. This hierarchy implies that B_2 does not exist as a separate region. Therefore, B is the parent region where the local update takes place. Assume that F_2 is being moved. V is the volume covered by B_3 and B_4, as the local update should not include B_1. Thus, Q_* consists of B_3 and B_4, as well as their subregions (if there were any). P_* consists of B_3 and B_4 without their subregions. The aim is to indicate two improvements that both contribute to less computations than if all subregions of B were included; a) when moving F_2, it is not necessary to include B_1 in the local update, and b) if B_3 and B_4 were subdivided at multiple levels of detail, it may be that not all their nested subregions need to be included in the update.

Algorithm II (V): Locally update the topology or geometry of the geological interfaces, or the resolution of the geological structure and grid, in the interior of a volume V.

(1) Modify one or more geological interfaces in the interior of V.

(2) Starting from the regions in P_*, visit all regions Q_* in a recursive manner. For each region, if it has been eliminated or if its boundary has been geometrically modified, add it to Q_*^{Elim}. Let $Q_*^{NotElim}$ be the set of the remaining regions in Q_*.

(3) Discard the subgrids G_Z of all regions in Q_*^{Elim}.

(4) Let Q_{**} be the nested set of new regions that are established using the updated geological structure, and let P_{**} be the regions in Q_{**} that are roots. Let Q_{**} also contain the regions in $Q_*^{NotElim}$ (whose subgrids have not been discarded). P_* and P_{**} both cover V.

(5) Run **Algorithm I** for all $r \in P_{**}$.

Comments to **Algorithm II**:

- The algorithm reflects an aggressive approach aiming to minimize the computational efforts. In Suter et al. (2017a), it is emphasized that a local update of the geological structure implies that only subgrids in regions that are directly affected by the updated structure must be discarded and rebuilt. It is reasonable to assume that a child region, at any finer level of detail, may be retained if its boundary is not geometrically altered in an update of the structure. This is the case if a geological interface at a coarse level of detail is modified, but without affecting interfaces at finer levels of detail. Then the children of fine scale regions with unaltered boundaries may also be recursively retained. This optimization would reduce the number of regions that must be regenerated. A conservative strategy is to remove and regenerate all regions in the interior of the smallest region containing the modified structure. In the example using Figure 11, this corresponds to recursively regenerating everything in the interior of B.
- Step (2) describes a conservative approach; it may not be necessary to discard subgrids belonging to regions whose boundary is only geometrically deformed. Instead, it may be possible to deform the

subgrids in this region. This was discussed in Section 5.3 in Suter et al. (2017a).

Note that neither **Algorithm I** nor **Algorithm II** have been properly implemented and verified in the software prototype, and should be considered as work in progress. It is expected that they can be improved.

In summary, multi-resolution earth model management is a highly complex theme. But multi-resolution analysis has proven to be extremely useful within multiple other sciences and applications. A successful further development of the proposed strategy, in combination with the ability for local grid updates as described in Section 5, has the potential for providing a large range of benefits for earth modelling. This includes enabling generation of realizations that capture large subsurface volumes at a level of detail that is adapted to the purpose of the modelling exercise at hand. The level of detail can vary throughout the grid, and be locally modified during the exercise. In support of such functionalities, the following principles have been proposed;

- **Local control with the earth model resolution**; the model is organized in a set of nested regions that are defined from geological structure that is arranged in a hierarchical manner. The resolution of the geological structure, the grid and the grid-based properties can be locally controlled within each region in a recursive fashion.
- **Local updates of the grid resolution**; in the interior of each region, at any level of detail, the geological structure, grid and properties can be updated without consequence for its exterior.
- **Computational processing in parallel**; the interior of any region at any level of detail can be managed independently of other regions (that do not intersect the region). If there are dependencies between regions (see Section 6.1.1), it may to some extent reduce the potential for parallel processing.

7 Local scale uncertainty modelling

Effective model management is decisive for real-time applications such as geosteering, particularly when aiming at maintaining multiple realizations. Handling of details that do not contribute to decision support will slow down the model management unnecessarily. It is therefore advantageous to focus the uncertainty management to where it is most important for the decisions to be taken; around and ahead of the bit.

Based on the previously discussed methods for local model updates (Section 5) and multi-resolution management (Section 6), it is discussed how local scale uncertainty management e.g. around and ahead of the bit could be supported. The method enables management of both the geological structure (its topology and geometry) and the grid-based properties. The method was discussed on the pages 27-32 in Suter et al. (2017b).

The novelty of the proposed method is that; a) it allows uncertainty management of geological scenarios that differ in their structural topologies, and b) uncertainties can be modelled locally in the interior of grid realizations without requiring regeneration of the complete grid, and c) uncertainties can be modelled at any scale within a large model.

Today, multi-realization models are not suited for real-time applications where time is limited. This is because the update of any realization requires that its populated grid is globally regenerated (see Section 3.3). Moreover, automatic management is limited to geometrically perturbing the base case structural model. Geometric perturbation does not include amendments to the structural topology. This inhibits flexible management of more complex uncertainties.

7.1 Principles

The multi-resolution method in Section 6 provides a method for consistently defining the volume of interest where the local scale uncertainty management should take place; namely in terms of regions in the earth model (that are controlled by the geological structure). Assume there is a single, global realization of the grid. Local scale geological uncertainties can be spanned by a set of realizations of the interior of a region (or a set of regions) in the global scale realization. Each such region is considered to be an 'earth model on its own' (see Section 6.1.1), and is independent of the surrounding regions. This allows representation of uncertainties in both the geological structure and properties. Each realization should respect the constraints set by the surrounding volume (the rest of the grid). Each realization of the interior of the region can be used to locally update the earth model grid as indicated in Figure 12.

Furthermore, the flexibility of the method is indicated. If it is advantageous for the application at hand, it is possible to apply multiple realizations at global scale. Then each such realization could obtain multiple local scale realizations. If required, this principle could also be applied recursively as described next. At some large scale there could be only one realization. Within a portion of the grid at medium scale there could be a set of realizations. And at local scale, each of the medium scale realizations could have a set of realizations. In Figure 12, this amounts to letting e.g. region A_2 or C_3 be represented by multiple realizations. Moreover, specific volumes of the subsurface, say around wells, could be represented by more realizations than elsewhere. This would allow to capture multiple types of geological scenarios with different structural topology.

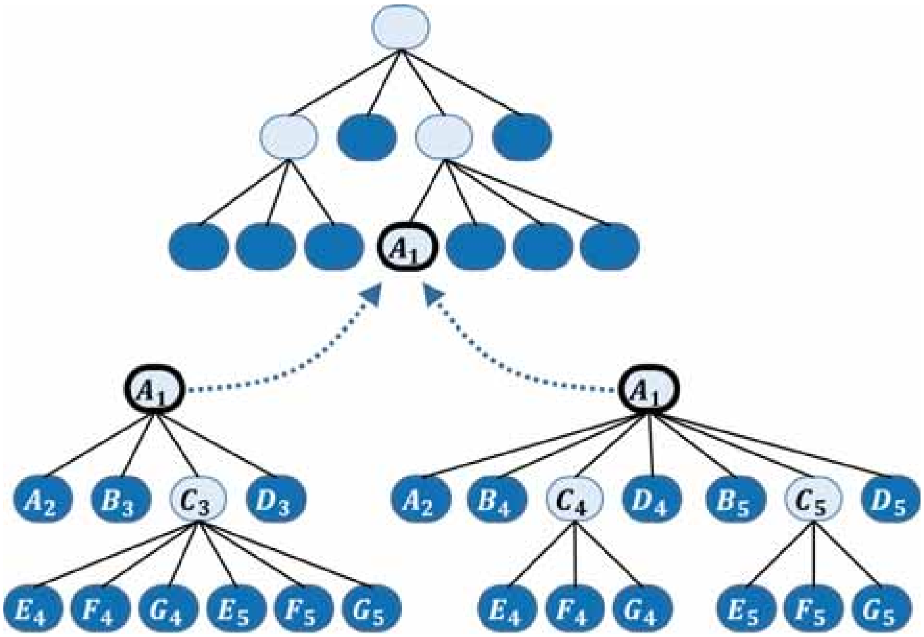

Figure 12. Top: a global tree, representing a global grid realization. Bottom: two subtrees, representing two realizations of the interior of the region A_1 in the global realization. Each of the two subtrees can be swapped into the global tree. The global grid can be correspondingly locally updated with each of the realizations of the interior of A_1. The figure is the same as Figure 28 in Suter et al. (2017b).

7.2 Combining local structural updates, multi-resolution analysis and uncertainty management

Next, the principle in Section 6.1.1 and the nestedness of regions is further explored. Consider the tree in Figure 10, where each region contains multiple regions at finer scale in a recursive manner. Then consider Figure 12, where each region can have multiple realizations of its internal structural topology at the next level of detail. Each realization results in a different configuration of subregions.

Consider any given region in the tree, at any level of detail. In its interior, the proposed method in principle allows multiple realizations of the structural topology (different geological scenarios). This results in multiple realizations of the configuration of children of the region being considered. Each realization is represented in its own subtree as in Figure 12. Each child region in any of these realizations can be further refined in a multi-resolution manner (as in Figure 10), so that it again obtains children (grandchildren of the initially considered region). There can be multiple realizations of the structural topology in the interior of each such child region (as in Figure 12). This applies in a recursive manner.

This principle allows much freedom for modelling. But clearly, the potential for an exponentially growing set of nested regions should not be overused. It is not considered likely that the representation of a large set of structural configurations over a large range of scales will contribute to decision making. But the principle allows that it is possible to have both different grid resolution and a different number of realizations at different subsurface locations. Application of more realizations, independently of scale, allow capturing of more geological scenarios and their uncertainties.

In practice, such capabilities could be used to study the uncertainties in the interior of for example a fault block or a layer at some scale. For each scenario, local scale uncertainties in the interior of finer scale layers or fault blocks of specific interest could be captured and assessed.

Furthermore, in the interior of any region at any level of detail, the proposed method allows local updates of the structural topology or geometry. Such changes are propagated to the finer levels of details in the interior of the region. If the topology is modified, it invalidates many of the existing structural configurations (and thus regions) at the finer scales (see the algorithms in Section 6.3). But when only deforming the boundary of a region, e.g. if a stratigraphic boundary is deformed or a fault operator is applied to deform the geometry in the interior of a region, the changes could possibly be propagated to the finer scales without invalidating the structural topology. This could take place by deforming the geometries also at the finer scales in accordance with the coarse scale deformation. This would allow to retain the present hierarchy of regions.

7.3 Uncertainty management while drilling

The Figures 29-33 in Suter et al. (2017b) shows examples that demonstrate the principles of local scale uncertainty management using a software prototype. The examples include uncertainties in the structural topology.

To capture the uncertainties that are most important for decision support, local scale realizations could be generated in real-time around and ahead of the bit once drilling commences. During the drilling operation, all realizations would be sequentially updated and refined with new information of geological structures and properties at fine resolution around the well as drilling progresses. As a result, the model grows in size. To handle the increase in model size, it is proposed to a) optimize the size of each grid realization, and b) locally control the number of realizations. This is in accordance with the discussion in Section 7.2.

Computationally demanding uncertainty management should focus on the volume of interest for decision support. Therefore, uncertainties around and ahead of the bit could be captured using a high number of local scale realizations, while volumes of less interest for the decision to be taken, say behind the bit, could be represented by a lower number of realizations. The reduction of realizations could take place by removing sets of realizations with the lowest probabilities. The volume of interest will change as the bit progresses, and the number of realizations could be correspondingly updated in a dynamic manner.

Each local scale realization, and also the global scale realization, can be locally updated while drilling as described in Section 6.1.2. Moreover, each local scale realization and the global scale grid can be optimized in size for the application at hand (see Section 6.1.3). By gradually inactivating fine scale regions containing small faults and fine scale stratigraphy, the grid can be gradually coarsened in regions behind and away from the bit as drilling progresses.

It is an important aim to dynamically modify the local model resolution in real-time. Depending on the type of decisions to be supported and the complexity of the geology, the time available for calculations at every step in the geosteering workflow is a critical element. Some decisions must be taken promptly, whereas others allow more time for computations. In general, the decision support should be available ‘as quickly as possible’ (see two examples in Appendix A.1 in Suter et al. (2017a)). Faster results imply a better potential for cost reduction and optimal well placement. Control with model resolution and level of detail is essential for such considerations.

For example, assume that the model just has been updated with new information. A potential approach is to quickly generate a coarse-resolution and approximate ahead-of-bit model that include only the most vital information as input for immediate decision support. At the cost of less accurate predictions, this allows effective computations in the subsequent modelling and decision algorithms so that preliminary decision support is provided as early as possible. Simultaneously, by application of parallel processing, a more accurate model at finer resolution can be generated. The decision support algorithms can be run again to confirm (or reject) the initial estimations from the coarse-resolution model. The fine-resolution model allows improved decision support, but at the cost of more time spent for computations. Moreover, generating and testing local scale scenarios at slightly different resolutions against the measurements in the model update loop in Section 4.1, may contribute to improve the interpretations.

8 Supporting developments

The work described in this thesis focuses on methods for real-time earth modelling. The work described in Sections 5, 6 and 7 focus on effective multi-realization grid management. In support of these principles, other techniques have been briefly visited as part of the developments.

8.1 Fault operator for local scale fault management

Today, management of the structural model typically requires much manual work (see Section 3.3). But multi-realization real-time modelling dictates a highly effective approach. To this end, initial work for automatic management of single faults has been performed. It demonstrates that local structural updates and modelling of structural uncertainties can be done using such an approach.

In Suter et al. (2012), see Figures 3 and 4 in that paper, a basic yet numerically effective fault operator for insertion, manipulation and removal of dipping normal faults in a 2D earth model was suggested. It has later been further developed and in Figure 13 it is indicated how it can be used to adapt and remove the fault in a basic model (this model is the same as shown in Figure 7 in Section 5).

The operator applies the same mapping f as the one used to link a property function with a region in the geological structure (see Section 5). The mapping is used to locally deform the geological structure and populated subgrids in the hangingwall and footwall of the fault in a geologically realistic manner in accordance with e.g. the fault displacement. If an existing fault is modified, so that the structural topology is unaltered, there is often no need to regenerate repopulate the affected subgrids. The hangingwall and footwall regions can have non-trivial shapes, bounded by the geological structure (see p. 11 in Suter et al. (2017b)). The other parameters of the operator can be automatically specified and controlled, e.g. within the EnKF-controlled model update loop in

Section 4.1. This implies that the operator can be set up without manual work, which is a major advantage for automatic local updates and uncertainty management while drilling. Insertion and removal of faults imply that the structural topology is modified. Within the proposed framework, these updates require only a local update of the grid. A fault can be moved by first removing it, then re-inserting it at a different location.

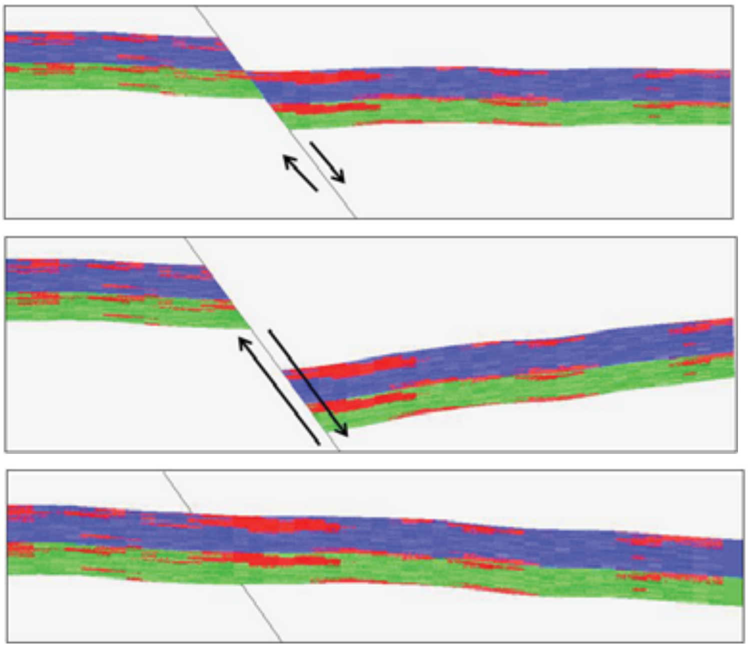

Figure 13. Example of the fault operator, where only the hangingwall side of the fault is modified. Top: a simple faulted model. Middle: the fault displacement has been increased. Bottom: the fault displacement is set to zero and the fault surface can be removed if requested. (The figure is the same as Figure 4 in Suter et al. (2017b).)

The main attractiveness of the proposed operator lies in its simplicity and numerical efficiency. It is particularly aiming to support geosteering, where a high degree of complexity in the operator itself may be in conflict with requirements for multi-realization real-time management. For geosteering, numerical efficiency and realistic management first and foremost of topological and geometrical uncertainties are of major importance to place the well optimally in a structurally complex reservoir.

Because of its simplicity, it should be possible to adapt the fault operator to complex structural topologies and geometries. Moreover, management of more complex fault configurations and geometries such as multiple fault planes, fault drag (see Figure 21) and conjugate faulting could be possible. By sequential application of the operator, even complex events such as fault reactivation and multiple faulting events through geological time may be within reach. Furthermore, in the interior of the hangingwall and footwall of the fault, it should be possible to constrain the stratigraphy and fine scaled faulting by measurements.

8.1.1 Existing strategies

In Section 3.3, it is discussed how current conventional earth modelling tools apply geometric perturbation to each surface in a manually constructed structural base case. The aim is to capture some of the interpretation uncertainties in the depth of the layering within an ‘uncertainty envelope’, and to manage this uncertainty in an automatic workflow. However, the structural topology remains unchanged. In Cherpeau (2010), stochastic simulation of fault networks is discussed. However, but no grid is considered. Several fault operators for automatic management of faults have been suggested in the literature, see for example Georgsen et al. (2012), Laurent et al. (2013), Røe et al. (2014) and Godefroy et al. (2017). They have been developed for reservoir simulation studies, and have not been properly evaluated for use within the suggested geosteering workflow.

Implicit modelling approaches represent a break with the mind set behind manual digitising as basis for model construction. They are promising also for real-time processes, as they aim to allow a highly automatic and fully reproducible workflow to manage the geological structure. See for example

Hjelle et al. (2013) and Laurent et al. (2016) for modelling of folds. The latter approach was expanded in Grose et al. (2017). In Gonçalves et al. (2017), a machine learning approach to implicit modelling was discussed.

8.1.2 Examples

The proposed fault operator is designed for the multi-resolution framework described in this thesis, as it acts in the interior of the regions defined by the geological structure. Yet it needs further development to allow model updates to be constrained within the geosteering workflow explained in Section 4.1.

A more basic version was applied for generation of the models in Figure 5 in Suter et al. (2017a) and in Figures 29-33 in Suter et al. (2017b). This basic version is used to demonstrate local scale uncertainty management in the structural topology in a more complex setting with multiple faults. It does not handle the associated fault related deformation in a realistic fashion, and only handles vertical faults.

Petrophysical properties may have changed in the fault deformation zone due to e.g. fracturation or mineralization. Figure 14 and Figure 15 shows the modification of a simple faulted model. The figures exemplify how the parameters of the fault operator (location and displacement), may also be used to change the properties. Figure 14 shows a fault with a small displacement, whereas in Figure 15 the fault has a larger displacement and a correspondingly larger impact on the surrounding properties. The degree of impact is indicated by the gradual change in ‘darkness’ in the properties; near the fault the properties are very dark (high impact), then the darkness fades away with increasing distance from the fault surface. The degree of darkness is controlled by the fault operator, in this case by calculating the distance to the fault plane. When the properties are mapped into the layers from their respective property functions (see Section 5.1), their values are modified in accordance with the distance to the fault plane. The fault can be automatically moved using the fault operator, and the impact on the petrophysical properties would move with it. These two examples only indicate how properties can be automatically changed depending on the geological structure; it has not yet been addressed how this could take place in a geologically realistic manner.

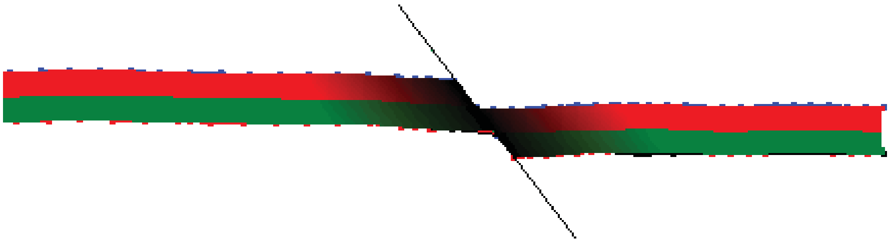

Figure 14. Impact of faulting on petrophysical properties. Here the impact depends on the distance from the fault and the fault displacement, and is indicated by darkening the layers. Dark means high impact.

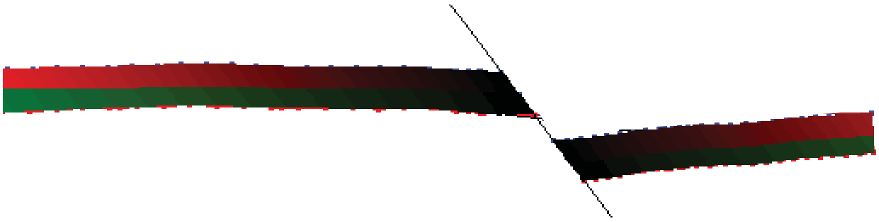

Figure 15. The fault displacement is larger than in Figure 14, and the petrophysical properties are modified in a correspondingly larger volume around the fault.

8.2 Multi-resolution management of grid-based properties

It was briefly mentioned in Section 4.2 in Suter et al. (2017a) how grid-based properties could be managed, using a multi-resolution property function. Preliminary results are shown next, to indicate the future potential.

Figure 16 depicts the results of subjecting a realization of porosity from a stochastically modelled scenario to multi-resolution analysis using Haar wavelets. The analysis was not constrained by physics. An advantage of the principles discussed in Section 5 is that property functions can be represented over a domain suitable for e.g. multi-resolution analysis. In this example the domain is a square, in correspondence with the other examples discussed in this thesis. Figure 16 indicates how details below a given threshold were removed in a global manner (namely for the entire property function), while main features were kept. For each image in the figure, the amount of information that was removed is shown.

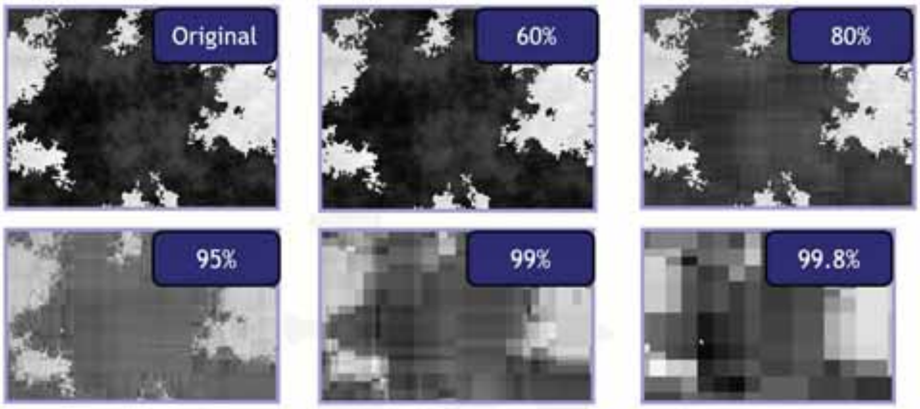

Figure 16. Multi-resolution analysis of porosity in two facies types, shale and sand. For each image, the removed amount of information is shown.

In Figure 17 it is shown how a property subjected to multi-resolution analysis was interpolated and mapped (using the mapping f as discussed in Section 5) into a geological structure with two layers. The difference between the property in the top layer and the bottom layer is in resolution only. The top layer represents the property at a much coarser resolution than the bottom layer. The property distributions are visually comparable as the shape of the two layers are very similar. The resolution of the two subgrids in the two layers should be adapted to the resolution of the property that is interpolated.

In Sahni and Horne (2005), an application of Haar wavelets for History Matching under uncertainty is described. Multi-resolution management of properties will depend on the application of the model, e.g. geosteering dictates different requirements than flow simulation.

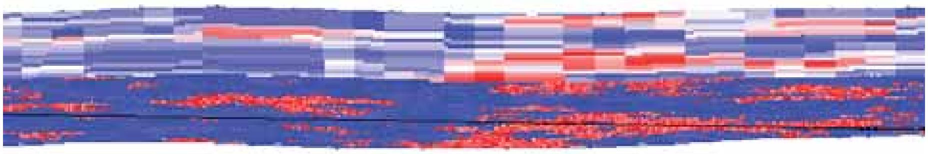

Figure 17. The same property function at two different resolutions is interpolated into a layer-cake model with two layers. The resolution in the bottom layer is much finer than the resolution in the top layer.

9 Discussion and future perspectives

The development of the proposed earth modelling strategy is still in an early phase, and there are many open questions. Multiple principles have been discussed, they need to be combined into a strategy that fully demonstrates the targeted functionalities.

The figures shown in Suter et al. (2017a) and Suter et al. (2017b) are generated from a software prototype which is not yet mature enough to handle more sophisticated cases. To demonstrate the potential of the principles that are discussed in this thesis, they should be verified using more realistic 2D sections. The sections should represent more complex structural configurations over a larger range of scales. They should allow verification of local scale management of structural uncertainties, control with the model resolution over multiple levels of detail (both stratigraphically and in the fault network), and local updates of both uncertainties and the grid resolution.

9.1 Adaptation to 3D

The initial developments have taken place in 2D to demonstrate principles. The principles that have been developed so far should also be applicable in 3D. But the complexity of a three-dimensional strategy is significant, given the topological irregularities and uncertainties in a realistic interpretation. 3D functionalities are far from being just simple extensions of functionalities in 2D. The challenges pertain e.g. to geometric modelling (modelling of surfaces is more complex than modelling of curves so that both topological uncertainties and multi-resolution become more complex to handle), as well as to geological modelling (capturing of complex, heterogeneous geology with its interpretation uncertainties in three dimensions, development of operators and geological parameters that act also in 3D).

9.2 Including the earth model in the geosteering workflow

Effective interaction between the earth model and the ensemble-based update tool (see Section 4) is critical. The update tool updates each realization based on a set of parameters. For addressing complex geological configurations in an effective, automatic and realistic manner, geological parameters should be developed to control the earth model. Such parameters represent geological knowledge and are consistent with geological rules. They should also allow automatic control with related uncertainties. The earth model must be capable of 'modelling what you see' and to realistically represent events such as a faulting, erosion, deposition in various environments, fault re-activation, and other relevant types of geological evolution. If relevant parameters cannot be developed, realistic prediction ahead of the bit in a timely manner may not be possible or becomes highly challenging. Moreover, the parameters must also be intuitive to the subsurface experts that manage the model.

Examples can be found in Graham et al. (2015a) and Graham et al. (2015b), where a set of geological parameters for controlling clinoforms was used. Moreover, the developments discussed in Section 8.1 rely on such parameters.

9.3 Support of drilling operational decisions

Drilling operational decisions depend on the formations being drilled. An always updated model could be used for support of real-time decisions, and to aid in the prediction of potential well control incidents that may even affect the safety of the drilling operation. This requires extremely effective modelling capabilities, as some decisions are taken within very short time.

Current 3D earth modelling tools are developed to support reservoir engineering and other disciplines where time is not an important issue, and the interpretation of the modelling results requires expert skills. But for drilling operational support where time can be critical, it is important to develop methods that effectively communicate the modelling results and decision suggestions in a manner that are adapted to the drilling environment. Visualization and manual inspection of a 3D model may not be optimal.

The driller and his crew are located on a rig, not in an integrated operations centre. The data transmission between the rig and the operation centre may be unstable. Future developments should address also such scenarios.

9.4 Management of realistic structural topologies in a multi-resolution environment

In traditional multi-resolution strategies within other sciences, e.g. for effective visualization, one typically takes advantage of a very regular topology between cells to define a hierarchy of nested cells. But in geomodelling, topological connections between regions are consequences of structural heterogeneities. To allow realistic modelling, complex topology and its uncertainties must be handled within the proposed multi-resolution framework.

One of the most challenging issues is thus that the described methods currently only handle structural configurations with a high degree of regularity. Examples are shown Figure 5 in Suter et al. (2017a) and the Figures 30-33 in Suter et al. (2017b), where all faults start in the same stratigraphic interface and end in the same stratigraphic interface. But structural heterogeneity results in ‘irregularities’ in the connectivity between stratigraphic interfaces and in the topology of a fault network. For example, in the figures in Suter et al. (2017a, 2017b) it should not be a requirement that all faults intersect the exact same layers. This requires improvements in the multi-resolution method.

Note that multi-resolution analysis is designed for applying approximations where details are removed. Details in the structural topology could be included in this methodology. This is briefly discussed in the last section of the Appendix in Suter et al. (2017b).

When developing more complex multi-resolution functionalities, it is important to keep in mind that the gain of sacrificing accuracy is computational efficiency, targeting real-time decision support. While geosteering, structural details will be added around and ahead of the bit and removed once the bit has passed. But structural connections such as fault terminations are difficult to identify away from the well based on local scale LWD measurements (fault surfaces may extend e.g. ten times the maximum fault displacement). It may thus be advisable to approximate the structural topology while drilling, so that it becomes more regular. After the well has been drilled, such simplifications can be improved by also considering seismic.

9.5 Formalization of the multi-resolution framework

Multi-resolution methods are much used within many sciences and applications, including image processing, signal processing, geometric modelling, visualization and rendering of animated movies. In these sciences, there is a formalized mathematical/numerical framework that supports the understanding of existing methods and provides a basis for further developments. In this thesis, however, only a few basic rules for multi-resolution management have been described (see Suter et al. (2017b)). Thus, the framework for multi-resolution handling of the geological structure, regions and subgrids should be improved and formalized. Management of local updates and uncertainty should also be addressed within such a formalization. Moreover, criteria deciding the resolution of the geological structure and petrophysical properties according to the decisions at hand should be developed. The aim is to allow effective, consistent and transparent management of model resolution.

9.6 Non-unique region hierarchies

The hierarchy of regions originating from a multi-resolution structural model with given topology is not unique, see the lower model in Figure 11 with two alternative hierarchies.

Consider the model to the middle right in Figure 10. The four child regions of the parent region can be organized in the following three trees; a) by subdividing the parent using all geological interfaces in its interior (results in four children), or b) by first subdividing using the stratigraphic interface, which results in two layers, then each of the two layers are split by the fault (results in two children of the parent, then each of the two children have two children), or c) by first subdividing using the fault, which results in two fault blocks, then each of the fault blocks can be subdivided using the stratigraphic interface (results in two children of the parent, then each of the two children have two children).

These subregions are a result of the given structural topology, yet they can be represented using several different hierarchies. The hierarchy has consequences for how to handle the resolution of the structural model and thus the grid. It also affects the subsurface volume that is included in a local update or in local scale uncertainty management. The options provide modelling flexibility. For example, should a parent region contain a set of layers that are subdivided by faults, or should it contain a fault block that is subdivided by the layers? Note that tree structures used to represent different hierarchies could be easily modified in real-time. This may allow a flexible approach where the hierarchy of regions depends on the modelling question at hand. Multiple different hierarchies could be established to optimize for different modelling tasks.

9.7 Control with grid resolution supports interpretation while geosteering

Improved control with grid resolution aims to support real-time modelling capabilities. For example, the grid resolution around and ahead of the bit where more details are required could be very fine (e.g. log-scale if required), and be gradually coarsened away from the bit (to seismic scale and coarser). As drilling progresses, the resolution ahead of the bit would be refined, whereas the resolution behind the bit is coarsened.

But such improved control could also be used for new functionalities. Offset wells could be present in the model, but with little detail while the focus is on the well being drilled. During drilling one could effectively zoom in on an offset well and revise details in its interpretation. The updates could be extrapolated and have an immediate effect on the interpretation of the well currently being drilled. Such functionalities are not possible using a local scale sector model where offset wells are not represented.

9.8 Multi-scale earth model management

Current subsurface interpretation workflows are often based on extracting local scale sector models from the geological model, say for geosteering support or for investigating dynamic behaviour in a particularly challenging part of the subsurface. Properly developed multi-resolution techniques may in the future be employed to avoid the need to construct separate models, instead the volumes of interest could be generated from the geological model at a suitable resolution. Modifications would then happen directly in the geological model, without requiring a manual transfer of results from a separate sector model.

9.9 Grid-supported interpretation

Improved control with model resolution may allow improved capabilities for seismic interpretation while drilling. Seismic interpretation typically takes place on a coarser scale. Considering seismic while drilling requires that the model is capable of handling information across a range of scales.

Future methods for locally updating the geological structure, for real-time optimization of the grid resolution and for local scale uncertainty management may become essential parts of interpretation workflows that are not run in real-time. For construction of an initial model based on for example seismic and well logs, an ensemble of populated grid realizations could be generated. During seismic interpretation, newly interpreted surfaces could be used to locally update the realizations. Optimization of grid resolution could enable temporary focus on and enable local updates in particularly challenging parts of the subsurface.

For flow modelling, management of scale and resolution is an important challenge that is much debated in the literature (see e.g. Section 3.5). Moreover, effective management of structural uncertainties is currently a major challenge. But a potential future application of the proposed methods for flow simulation has not been investigated in this thesis. Many challenges pertaining to such an application have not yet been addressed.

9.10 Model-based collaboration over computer networks

Even today, experts support geosteering from various geographic locations such as their offices, the rig or an IO-centre. The proposed multi-resolution strategy may provide a foundation for effective collaboration between multiple users at different geographic locations. Each user could have access to the complete model, either passively (visualization of the results) or actively (updating local parts of it). The updated parts could then be submitted via a computer network and be used to update the corresponding parts in the models of the other users (or in a shared model) in real-time. The aim is to allow experts to work together on the same model, sharing their knowledge and alternative interpretations, and discussing decisions, even from different locations.

Though it may sound attractive, there will be challenges pertaining to the subjective interpretations of each user. If care is not taken in the numerical methodology to consistently handle a range of different interpretations, sharing of a model may easily lead to inconsistencies. On the other hand, it is assumed that today's practitioners face similar challenges when working together to construct a model.

10 Summary

In this thesis, a set of principles that address major challenges for effective management of uncertainties in geomodels has been described.

The first main development is a method enabling local updates of the topology of the geological structure in a grid. The second main development is a method for multi-resolution representation of the grid, based on multi-resolution management of the geological structure. The combination of these two methods aim to enable unprecedented control with the grid resolution in real-time. This is important to allow real-time efficiency when managing complex interpretation uncertainties over multiple scales and frequencies.

The third main development is a method for local scale uncertainty management, including the structural topology. It is based on the first two main methods, and aims to enable effective sequential updates of the uncertainty around and ahead of the bit as drilling progresses.

Simplex-based grids are employed (triangulations in 2D, tetrahedralizations in 3D). This allows management of complex geological structures that cannot be properly handled using a corner-point grid.

The principles have been discussed and demonstrated in a basic 2D software prototype. But many open questions remain. The developments have been aimed at pointing out a path for future research on effective 3D earth modelling.

The ultimate aim is to enable an always updated multi-realization 3D geomodel at optimal resolution while drilling, suitable for real-time decision support under uncertainty.

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12 Appendix

Earth modelling and geosteering are highly multi-disciplinary themes, applying knowledge from different fields of science. To make the thesis better accessible to non-experts, the Appendix provide background information about structural uncertainties (Section 12.1), about subsurface information at multiple scales and frequencies (Section 12.2), and a small discussion about topology vs. geometry (Section 12.3).

12.1 Interpretation uncertainty

Geological configurations such as complex depositional environments, erosion, faulting and folding can be highly challenging to interpret. Fracturing and mineralization affect the flow in the reservoir, which is important for optimal well placement. E.g salt movements and sand injectites may provide excellent hydrocarbon traps, but the precise locations of the traps can be difficult to identify from seismic.

Poor measurements, such as poor seismic below salt or basalt, imply more interpretation uncertainties. Successful exploitation of subsurface resources in such environments thus depend on effective interpretation while drilling. If a model-based decision loop is employed while geosteering under challenging conditions, it is vital that the model can in fact capture complex geological configurations and that it can be effectively updated while drilling.

Interpretation uncertainties are a result of a) lack of measurements at all scales and imprecision in the measurements, b) uncertainty in the interpolation between and extrapolation from known data points, and c) uncertainty in the interpretation concept and incomplete knowledge of relevant geological behaviour by the interpreter. Therefore, any geological interpretation is uncertain. Some uncertainties can be captured in a model, and some cannot.

The range of uncertainties that can be captured and effectively managed in a realistic manner depends on the capabilities of the modelling tool. The modelling of interpretation uncertainties is extensively discussed in the geological literature, e.g. in Bond et al. (2007), Bond (2015), Caers (2011), Caumon (2014), Hesthammer et al. (2001), Linde et al. (2015), Mallet (2008), Mallet (2014) and numerous other articles within geology and geological interpretation. Moreover, interpretation of the subsurface generally depends much on interpretation of visual information. In Schetinger et al. (2017), the conclusion from an extensive user study was that humans are easily fooled by digital images. In the attempt to evaluate if an image had been edited or not, the performance of humans was superior to random guessing, but poor compared to results achieved by computational techniques.

Optimal placement of the well while geosteering depends much on the geological structures in the reservoir, e.g. when following a thin, faulted layer (Kullawan et al., 2017). Next, different types of interpretation uncertainties, with a particular focus on structural uncertainties, are illustrated in a series of figures from the existing literature. Note the scales in the figures, uncertainties in the structural interpretation can be large. Moreover, these types of uncertainties exist at all scales, including scales relevant to drilling and geosteering.

In Figure 18 it is indicated how a set of data can be interpreted in different manners.

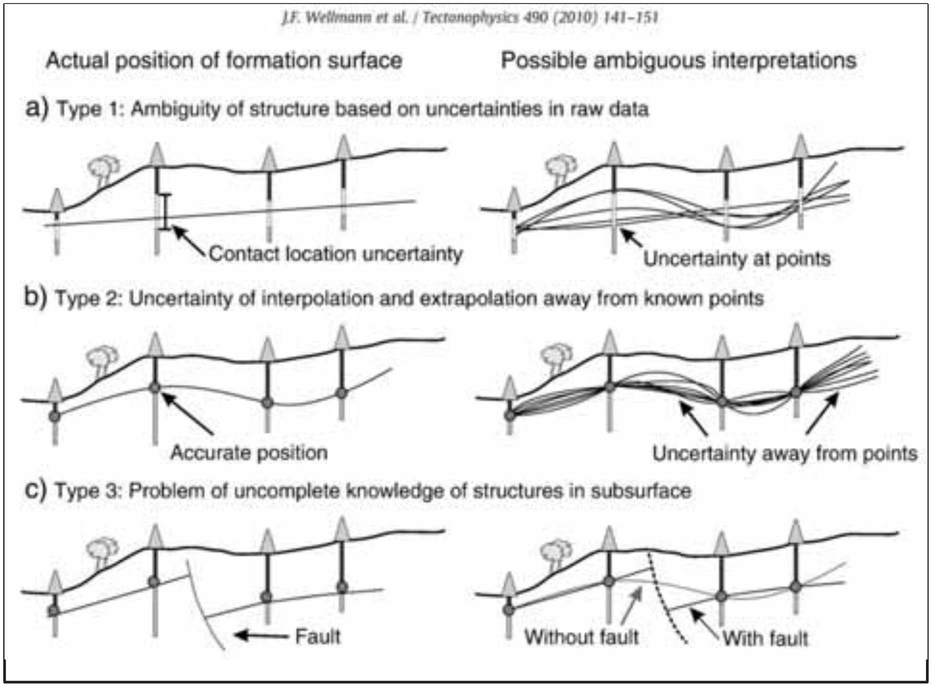

Figure 18. Modified from Wellmann et al. (2010). Original figure caption: "Fig. 2. Adapting the classifications of Mann (1993) to the uncertainties in structural modelling; (a) interpretation of a geological formation boundary based on ill-defined input data points (i.e. where the contact position itself is uncertain) and resulting uncertainty in the interpreted boundary, (b) uncertainty of interpolation between and extrapolation away from known data points, (c) incomplete knowledge of structures in the subsurface, e.g. does a fault exist or not."

In particular type 3 indicates a type of uncertainty that in existing earth model strategies cannot be managed without globally reconstructing the grid if changing from the case with a fault to the case without a fault. Such a change implies to modify the topology (connectivity) of the structural model, which requires a global regeneration of the entire grid (see the discussion in Section 3).

In Figure 19 it is shown how a given set of field observations can result in very different interpretations of the geological evolution; a set of outcrop observations can be interpreted as a fold (B.i), a compressional fault (B.ii) or an extensional fault (B.iii).

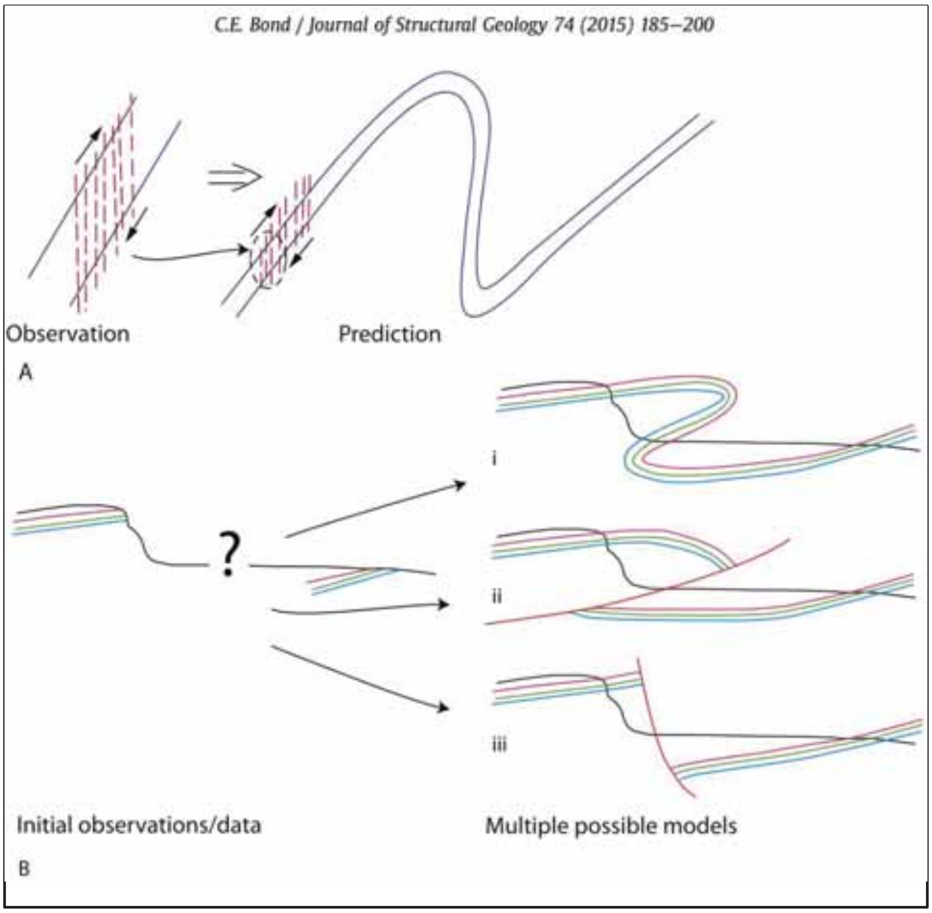

Figure 19. Modified from Bond (2015). Original figure caption: "Fig. 4. Making observations and predictions to construct and test model(s). A) Simple field observations, such as bedding cleavage relationships can be used to make predictions of what you would expect to see walking across strike. The scale and geometry of the folds, and other complications (e.g. faults) can be determined by further observation, but a reasonable prediction of the overall structural model can be made from the initial observation. B) A set of initial data or observations allows multiple models to be created that fit the data, there is not a unique solution."

A conceptual model is the basis for any geological interpretation as it defines the geological rule set to be used for the interpretation. Depending on the region at hand, some models may be discarded. In Figure 20 it is shown how the choice of a conceptual model results in different interpretations of fault location and connectivity. The selected conceptual model has severe consequences for the interpretation of the depth of a horizon in the structurally complex area. The seismic profile in the figure covers around ten kilometres in lateral direction.

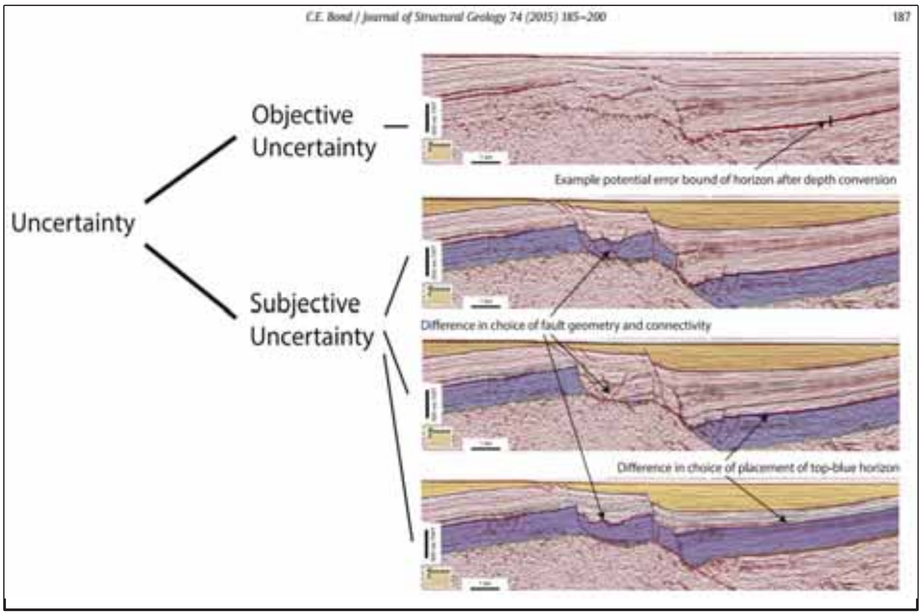

Figure 20. Modified from Bond (2015). Original figure caption: "Fig. 2. A tree diagram used to define different classifications of uncertainty, after Tannert et al. (2007). Uncertainty is divided into objective and subjective components. Objective uncertainties may be dealt with through the use of error bounds. For example in the seismic image a chosen velocity model could be used for depth conversion, an assessment of the possible range of velocity models could be employed to assigned errors or uncertainties to the depth of different horizons. Decisions can be made in a quasi-rational knowledge guided way and the uncertainties assessed. For subjective uncertainty the different interpretations of the seimsic image represent the subjective uncertainty in geological interpretation - creating error bounds is not so easy when different conceptual models are applied in an interpretation e.g. for fault placement and connectivity. Subjective uncertainties may be through of as intution or rule guided. Seimsic imagery from the Virtual Seismic Atlas (www.seismicatlas.org), interpretations by Rob Butler and Clare Bond."

The geological structure is important for the reservoir connectivity and the conditions for the flow of fluids, and hence for optimal well placement. But its interpretation is burdened with large uncertainties. For example, internal geometries in the damage zone of a fault are often difficult to interpret from seismic even for large faults. This results in uncertainty regarding interpretation of traps, and the flow pattern during production (is the fault sealing or not?). For subseismic faults there is even less information available at a suitable scale.

In Figure 21 is an example describing challenges pertaining to the interpretation of fault geometries and displaced stratigraphic layers. In (a), it is indicated how the seismic resolution is too low to distinguish between three possible conceptual interpretations of the fault damage zone; the top interpretation shows a single fault plane with no reservoir connectivity across the fault, the interpretation in the middle is for a fault where the deformation has been taken up by multiple parallel fault planes that results in reservoir connectivity across the fault, whereas the bottom interpretation indicates that parts of the deformation has been taken up by normal drag also resulting in reservoir connectivity across the fault. These interpretations may result in very different flow and migration patterns around the fault.

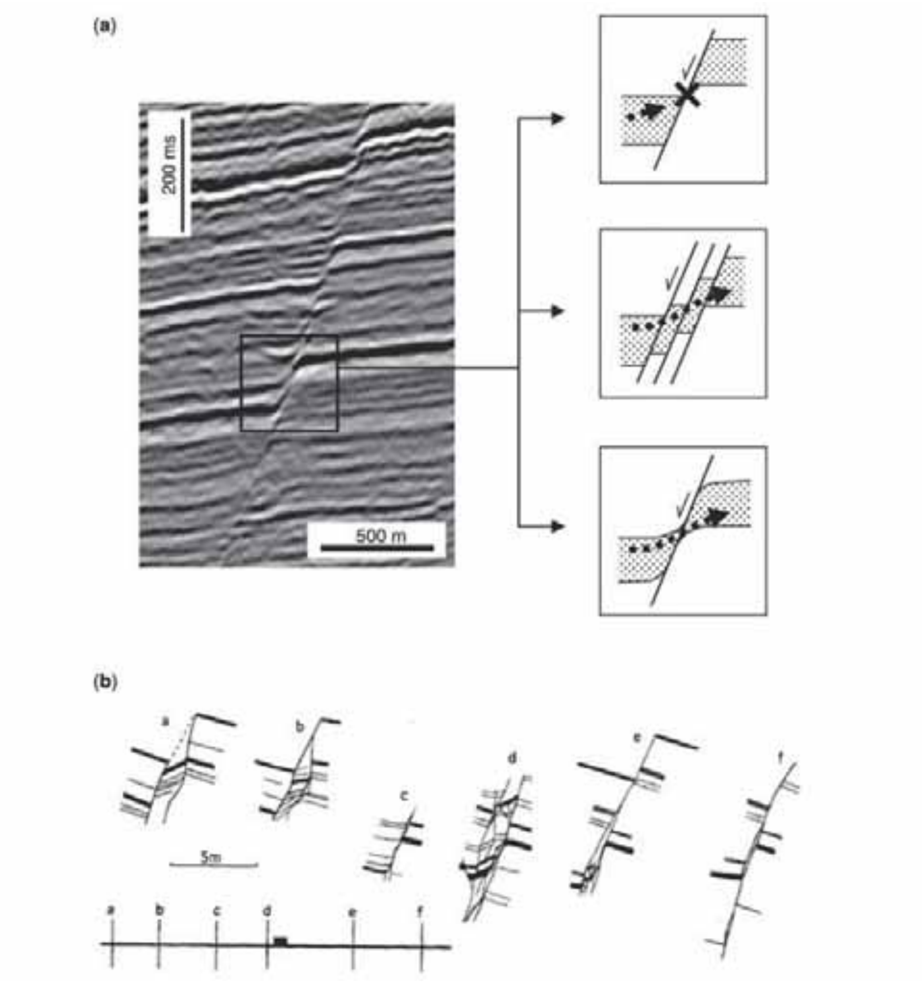

*Figure 21. Modified from Wibberley et al (2008). Original figure caption: "Fig. 5. The problem of resolution from seismically imaged faults and impact on across-fault reservoir connectivity and possible fluid flow pathways. **(a)** Fault zones more complicated than a single slip plane will have reservoir-reservoir connectivities and the potential for fluid migration (bold dashed arrows), which are difficult to predict, as a function of multiple slip planes and/or normal drag. **(b)** An example of along-strike changes in fault zone structure (from Childs et al. 1996)."*

In a geosteering situation, new information constrains the uncertainty. This could affect the placement of a well which is currently being drilled, depending on e.g. the fault displacement and whether it is sealing or not. Moreover, the pressure regime may be different on each side of the fault, potentially leading to serious drilling problems. An always updated model may be used to support decisions both for placing the well optimally with respect to later production, and for aiding in addressing drilling problems. In particular the latter will require very effective earth model updates. In (b) in Figure 21, potential models of the structural geometries in the fault damage zone are shown.

In Figure 22 a complex geological structure is discussed. A seismic data set from 1992 was interpreted as shown at the bottom in the Figure. A later data set from 1996 of far better quality allowed a new interpretation, depicted at the top of the figure. Without going into details, the interpretation of the geological structure is very different. The drilling of a well confirmed the interpretation from 1996. The scales on the left-hand side in the Figure show that the seismic profiles cover around 500 ms TWT.

Structural uncertainties are complex to handle in earth models. They do not only include uncertainties in the shape of the geological bodies, but also if the bodies exist and their location with respect to other bodies of interest. Moreover, many uncertainties should be handled at a local scale as they don’t have significant impact on coarser scale interpretations or the interpretations at other locations. Uncertainties in the interpretation of geological structures have a profound impact on drilling risks, the cost of the drilling operation and the estimated future production, as well as completion, maintenance and decommissioning of wells, and field planning including placement of future wells.

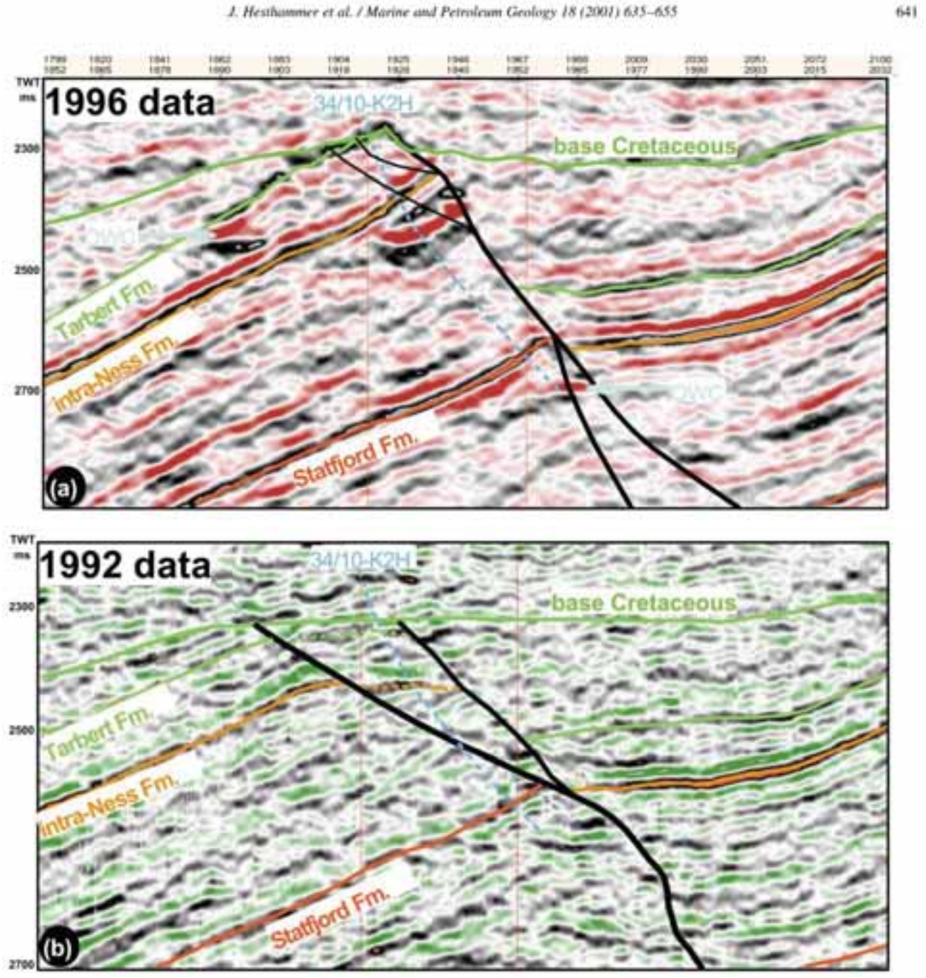

Figure 22. Modified from Hesthammer (2001). Original figure caption: "Fig. 6. Seismic profiles along the 34/10-K2H well on Gullveig. (a) Seismic interpretation based on the 1996 survey. (b) Seismic interpretation based on the 1992 seismic survey. Drilling of the well verified the interpretation shown in (a). The oil-water contact is clearly observed within the Brent group and Statfjord Formation in the 1996 survey, but is absent in the 1992 seismic data set."

When drilling in complex geology, 'unexpected events' that were not properly considered prior to drilling may occur. A valuable contribution to decision support would be tools that allow real-time updates of the model and of the estimates of the risks, costs and production for a set of alternative drilling and well placement scenarios. An example is to provide an answer to the following question while drilling; "should the well be drilled to the primary target (an option that just got worse) or the secondary target (an option that is currently interpreted to be more promising than expected)?". A successful outcome of the drilling operation and predictions of the future cost/income may depend much on the ability to effectively handle more complex geological configurations and events. In particular when exploiting resources in more complex geology in already depleted fields (tail production), where the economical margins are narrower.

While geosteering, it will often not be sufficient to update the model only locally around the bit. The new interpretation at local scale may not agree with any of the pre-drill models at the coarser scale, see Figure 22. Such agreement can then only be achieved by updating also at a coarser scale. Clearly, this is an even more complex challenge for real-time modelling.

12.1.1 Uncertainties in the conceptual model

The geological concept (the fundamental assumptions/hypotheses about the geological evolution) used in the interpretation constrains the possible outcomes of the exercise. But as indicated in Figure 20, the selection of (range of) concept(s) is also burdened by uncertainties. In Bond (2015) it is argued that 'experimental evidence suggests that minimising interpretation error through the use of geological reasoning and rules can help decrease interpretation uncertainty'. On the other hand, use of geological reasoning to constrain the possible range of interpretations implies that the bias of the interpreter may lead to that other possible interpretations are ignored and not captured. If a range of possible interpretations are not captured in the model, the model will have less prediction power. In Bond et al. (2007) it is investigated how the background and experience (bias) of the interpreter may result in different geological concepts being used for interpretation. It was demonstrated in a thought-provoking manner how a single seismic profile was interpreted using highly different concepts, resulting in very different outcomes. Further literature on the subject includes Refsgaard et al. (2012), Cavero et al. (2016) and Bentley & Ringrose (2017).

Existing earth modelling strategies require much manual work for handling the geological structure. As indicated above, uncertainties in the geological concept used for interpretation generally involves also uncertainties in the geological structure. The strategy discussed in this thesis aims at effective management of both the structure and the properties by enabling local model updates. It may thus form a basis for a future modelling approach where also uncertainties in the geological concept used for interpretation at a local scale can be effectively handled.

12.2 Subsurface information at multiple scales and frequencies

Rocks are heterogeneous at all scales, as demonstrated in the Figures following next.

In Figure 23, a seismic line covering several kilometers laterally and in depth is interpreted as a region subjected to extension, resulting in domino style rotated fault blocks.

Figure 24 shows an outcrop at the scale of 10's of meters together with an interpretation of the main extensional faults (in black) in the fault network, and some stratigraphic interfaces (various colours). In the interior of each fault block, some fault surfaces in white are indicated.

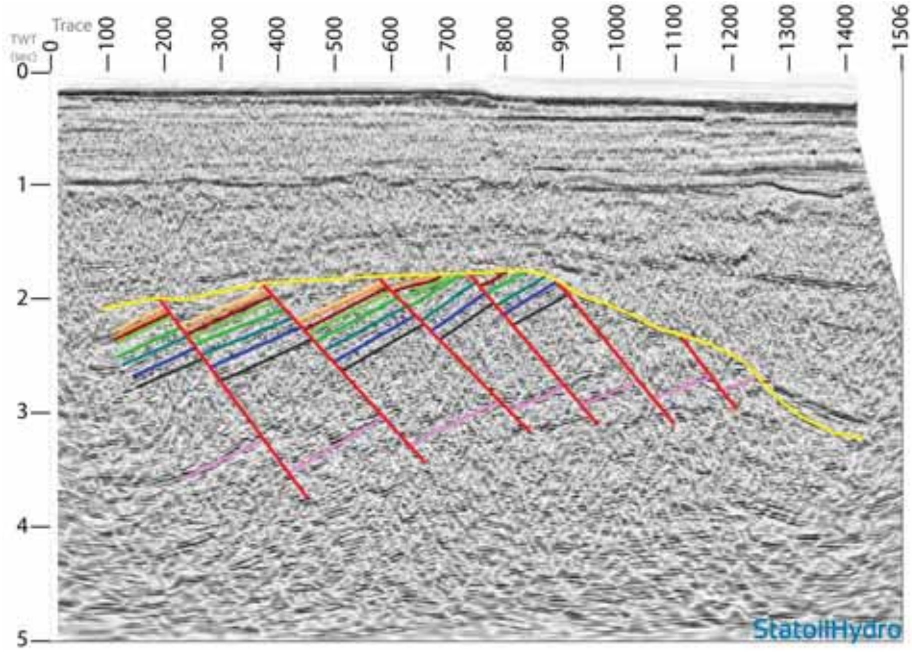

Figure 23. An interpreted seismic line from Gullfaks. (Source: http://www.seismicatlas.org, Gullfaks: ST8511r92 Inline 394 Interpretation, by Mike Sizer).

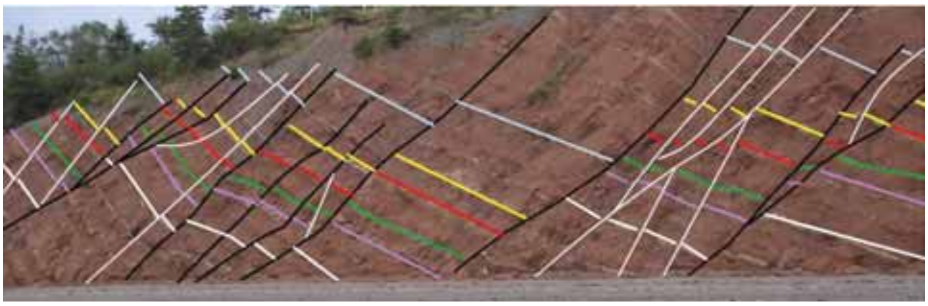

Figure 24. An outcrop showing an array of extensional faults cutting Triassic to Lower Jurassic Blomidon Formation rocks, near Clarke Head, Minas Basin North Shore, Nova Scotia. See trees in the background for scale. On top of the original image, a more detailed structural interpretation is drawn. (Source: Mikenorton (https://commons.wikimedia.org/wiki/File:Extensional_fault_array_Clarke_Head.png), "Extensional fault array Clarke Head", https://creativecommons.org/licenses/by-sa/3.0/legalcode)).

Figure 25 shows outcrops at cm-scale. Lamination and fracturing at mm to cm scale may exhibit noticeable contrast in properties. Such effects at this fine scale are usually not captured in any detail when constructing an earth model, even if there is a need and suitable information is available e.g. from cores and outcrops.

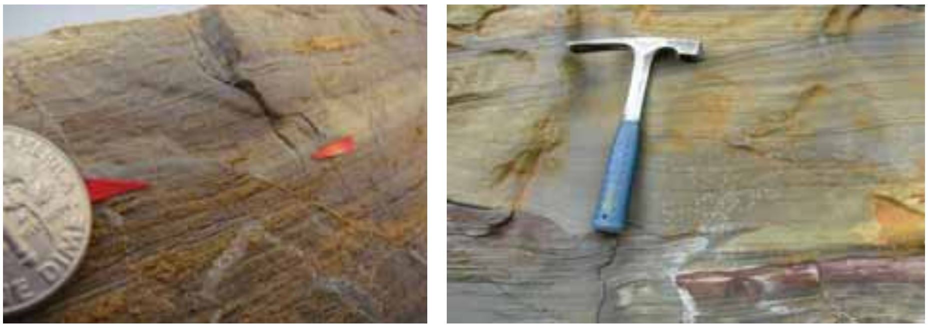

Figure 25. Two images depicting geological structures at cm-scale. Left: Microfault in a sedimentary rock, US dime for scale. Red arrows show amount of offset (Source: Qfl247 (https://commons.wikimedia.org/wiki/File:Microfault.jpg), "Microfault", https://creativecommons.org/licenses/by-sa/3.0/legalcode). Right: Cross-bedding and scour in the Logan Formation (Mississippian) of Jackson County, Ohio, hammer for scale (source: https://commons.wikimedia.org/wiki/File:Logan_Formation_Cross_Bedding_Scour.jpg).

Now assume there is a strong need for representing and interpolating such local scale details, including their main uncertainties, in a model covering also coarser scales. But when using conventional tools, capturing across a large range of scales is not possible. A major reason is the poor control with the grid resolution.

12.2.1 A geosteering example

In Figure 26, a model is shown at two different scales. In (a), the model expresses fault blocks with folded stratigraphic layers at a coarse scale. In (b), one of the fault blocks in the model from (a) is shown at a finer scale. It is indicated how fine scale (subseismic) faulting was filtered out from the model in (a). But the figure also demonstrates different deformation styles at the two scales. In (a), a ductile deformation style at the coarse scale is indicated, and each layer in the interior of each fault block is represented in a geometrically continuous manner.

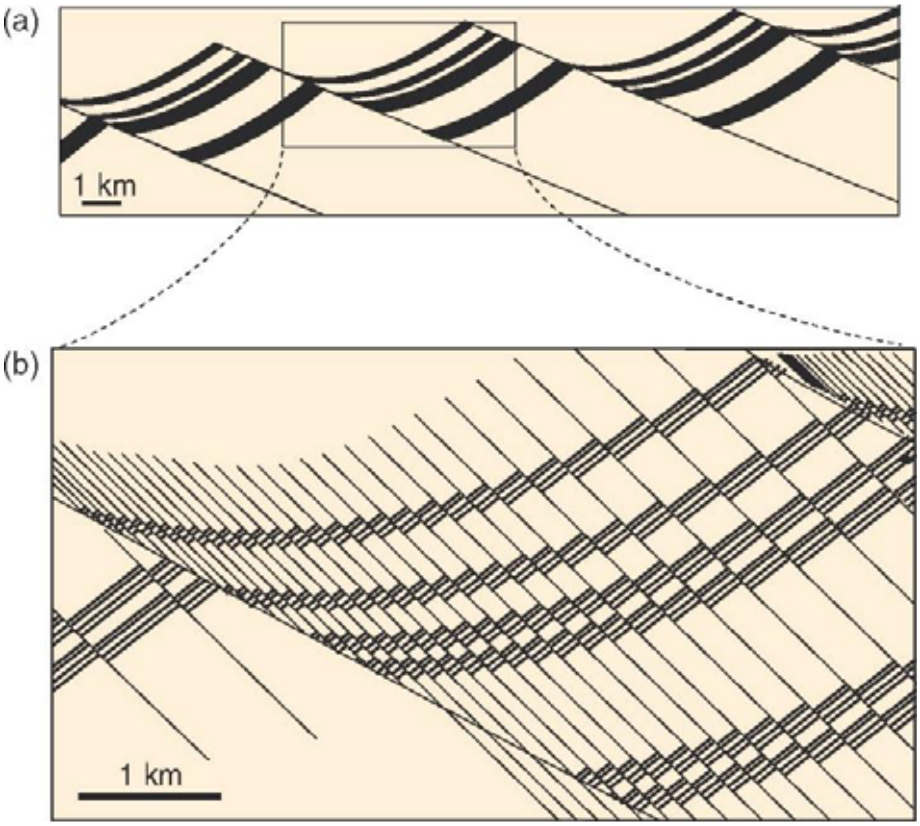

Figure 26. View of geological structure at (a) coarse scale, and (b) fine scale. (Source: Fossen (2010)).

However, when details are added in (b), it is demonstrated how the deformation at the finer scale appears as brittle, resulting in the series of small (subseismic) faults that displaces each layer (here in a very regular manner). Moreover, the finer scale stratigraphy in (b) shows how each layer from (a) is divided into finer scale units. At a yet finer scale, it is reasonable to assume that even more details in the fault network and stratigraphy could be represented.

To indicate challenges for geosteering, let us assume that a geosteering operation was planned in the section in Figure 26. It was interpreted from offset wells that several of the layers are good reservoir rocks. Let us further assume that the geological structure was more variable than indicated, and that seismic interpretation was challenging. In fact, assume we are left with an interpretation more or less as in Figure 26 (a), but with large associated uncertainties. This uncertainty includes details in the stratigraphy and fault network that was interpolated from offset wells. One possible fine-scale scenario is the one shown in Figure 26 (b), with a brittle deformation style at the fine scale. Another possible fine-scale scenario is that the reservoir rocks are less consolidated, resulting in a more ductile deformation style also at the fine scale.

The geometries of the reservoir rocks are highly uncertain; are they displaced by subseismic faults or not? The structural uncertainties could include fault locations and displacements, resulting in different trap geometries. Other uncertainties may include if the subseismic faults are sealing or not, and possibly uncertainties in the oil-water contacts (if there was already a production history). Pre-drill fluid flow predictions may have resulted in very different flow models for the two fine-scale scenarios. Now, let us assume that the well was planned to follow one of the black layers shown in Figure 26 (a). Moreover, it should be steered in the best possible manner according to the new information that arrives while drilling (using the workflow discussed in Section 4). Such steering includes the possibility for changing the target layer while drilling.

The outlined geosteering scenario emphasizes the importance of a) representing information about the reservoir architecture at various scales in an effective manner, b) pre-drill capturing of the uncertainty regarding brittle or ductile deformation style at the fine scale, and c) local updates of the geological scenarios around and ahead of the bit while drilling.

In summary, interpretation at a fine scale is understood in light of, and is constrained by, the interpretation of the geological evolution at coarser scales. The typical strategy is to first interpret the coarse scale geological evolution before considering details around planned wells. But information at fine scale from well logs is used to constrain the interpretation also at coarser scales. When updating the interpretation at the coarser scales, it affects the interpretation at finer scales. Ideally, all information that is available for decision support should be reflected in the always updated earth model, independently of scale.

12.3 Topology versus geometry

12.3.1 Mathematics

In mathematics, topology is the study of the properties that are preserved through continuous deformations, twistings and stretchings of objects, see e.g. Weisstein (2017b) and numerous textbooks. Tearing or gluing, however, is not allowed. A circle is topologically equivalent to an ellipse (the circle can be deformed into an ellipse by stretching) and a sphere is equivalent to an ellipsoid. A much-used example is the following; ‘A coffee cup is topologically equivalent to a doughnut, they both have exactly one hole’.

Geometry is the study of figures in a space of a given number of dimensions, of a given type and with a certain shape. Examples are plane geometry (dealing with objects in a plane such as points, lines, circles, triangles, polygons) and solid geometry (where objects such as points, lines, spheres, surfaces, cubes, cylinders and polyhedra, all in three-dimensional space, are discussed). See e.g. Weisstein (2017a) and numerous textbooks.

12.3.2 In geological modelling

In geological interpretation and modelling, a geobody is a volume with relatively homogenous properties in its interior, being for example the result of a depositional event where conditions did not change much over some geological period of time. Its boundaries are described with surfaces. The topology (connectivity) of the structural model describes how the different (parts of) geobodies are connected, or, correspondingly, how the surfaces in the structural model are connected. For example, if a new fault or a new layer is included in the model, both the model topology and geometry is modified. If the shape of a surface is slightly changed, e.g. by modifying a couple of its vertices, only the structural geometry is altered while the topology is retained (assuming that the updated surface does not introduce new intersections with other surfaces). The structural topology is a major control when predicting the flow of fluids, for example by capturing if two sand bodies are connected across a fault.

The different conceptual models (see Section 12.1.1 in the Appendix) that are used for interpreting the subsurface geology will often have different structural topologies. In general, structural topology is more complex to handle in numerical models than structural geometry (see Section 3).

Part II: Compilation of papers

Paper A

Suter, E., Cayeux, E., Vefring, E., Næsheim, L., Friis, H., Escalona, A. and Kårstad, T. (2010) An Efficient Approach for Earth Model Updates. Paper SPE-136319-MS Presented at the *SPE Russian Oil and Gas Conference and Exhibition*, Moscow, Russia, 26-28 October. https://dx.doi.org/10.2118/136319-MS.

Not available in Brage.

Paper B

Suter, E., Cayeux, E., Escalona, A., Kårstad, T. and Vefring, E. (2012) A Strategy for Effective Local Updates of the Geological Structure in an Earth Model during Drilling. Extended Abstract Presented at the *74th EAGE Conference and Exhibition Incorporating EUROPEC*, Copenhagen, Denmark, 4 June. https://dx.doi.org/10.3997/2214-4609.20148222.

Not available in Brage.

Paper C

Luo, X., Eliasson, P., Alyaev, S., Romdhane, A., ***Suter, E.***, Querendez, E. and Vefring, E. (2015) An Ensemble Based Framework for Proactive Geosteering. *SPWLA 56th Annual Logging Symposium*, Long Beach, California, USA, 18-22 July.

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Paper D

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A Novel Method for Locally Updating an Earth Model While Geosteering

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Abstract

Earth models are important tools for support of decision making processes for optimal exploitation of subsurface resources. For geosteering and other real-time processes where time is a major constraint, effective model management is decisive for optimal decision support. During drilling, subsurface information is received which should optimally be used to modify the 3D earth model. Today this model is typically not altered during the operation. We discuss the principles of a novel method that enables a populated earth model grid to be locally modified when the topology (connectivity) of the geological structure is locally altered. The method also allows local updates of the grid resolution. The modelled volume is split into closed regions by the structural model. Each region is individually discretized and obtains its own subgrid. Properties are stored in separate functions, e.g. for each layer, and transferred into each subgrid via a mapping. A local update of the geological structure implies that only subgrids in regions that are directly affected by the updated structure must be discarded and rebuilt, and the rest of the populated earth model grid is retained. Our focus is on decision support for optimal well placement while geosteering. The proposed method aims to manage multiple model realizations that are never fixed and always locally updated with the most recent measurements and interpretations in real-time, and where each realization is always kept at an optimal resolution.

Keywords

Geosteering, Optimal Well Placement, Earth Modelling, Local Update, Geological Structure, Connectivity, Uncertainty

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1. Introduction

The planning of a new well is based on information known prior to drilling such as surface seismic and offset wells. The interpretation of the information is captured in an earth model that is used to support decision processes while drilling. Due to incomplete knowledge of the subsurface, the interpretation is always burdened with uncertainty. During the geosteering process, the trajectory of the planned well is adjusted based on measurements obtained from logging tools during the ongoing drilling operation. The new information reduces uncertainty and allows revisions of the geological interpretations made prior to the drilling operation. This requires effective interpretation, integration and utilisation of the new information within the timeframe set by the on-going drilling operation.

However, commercially available three-dimensional earth modelling tools have limited capabilities for real-time updates. Model modifications are complex and labour intensive (see Section A.3 in the Appendix for details), and the time needed for updating the model exceeds the time available during drilling operations. This results in sub-optimal utilization of the measurements obtained while drilling, and is a large drawback for decision making processes that require the most current and precise information.

In Section A.1 in the Appendix, two examples of how a more effective decision loop can contribute to safer and more effective drilling and geosteering are discussed. In Section A.2 in the Appendix, a potential future workflow for effective decision support is indicated. It aims to support decisions for safer and faster drilling, increased future production and reduced drilling costs. The aim of the method suggested in this paper is to enable effective local updates of the earth model grid and local scale uncertainty management around and ahead of the bit, including uncertainties in the topology (connectivity) of the geological structure. Effective earth model management is essential to shorten the geosteering decision loop.

1.1. Current Methods for Geosteering

The recently developed ultra-deep directional electro-magnetic (deep EM) technology is sensitive to resistivity contrasts up to tens of meters around the wellbore (see e.g. [1] [2] [3]). Deep EM measurements is a technological step change that gives more information about geological structures, fluid contacts and reservoir properties deeper into the formation than traditional Logging While Drilling (LWD) measurements, even ahead of the bit [4]. The technology contributes to closing the gap between seismic scale measurements and well scale measurements. Next, we briefly review two current workflows for updating an earth model in real-time, and how the model is used for decision support for optimal well placement.

In [2], it is explained that the full-field 3D model typically ignores or blends small-scale features such as faults and facies changes that can impact drilling. For drilling support, the full-field model can be refined around the well or a separate sector model on a fine scale around the well can be constructed. The detailed model is used to extract a 2D section along the planned well path, containing geological structure and properties, which is used for drilling support. During the drilling process, four different interpretation methods are used for local scale structural interpretation, such as dip interpretation and remote boundary detection. Moreover, the results of the inversion of the deep EM measurements acquired while drilling are visualized together with and compared with the seismic. After drilling is completed the 2D well-scale structural model and petrophysical model are modified, as basis for the following update of the 3D full-field model.

In the geosteering workflow discussed in [3], a 3D sector model around the planned well is generated prior to drilling. The volumetrically smaller model allows an increase in the horizontal and vertical resolution, and the high-resolution model is populated based on full-field petrophysical properties. It is emphasized that 3D modelling enables geologists to envision the result also of lateral changes in the well trajectory, as opposed to the simple vertical changes that 2D models allow, and thus to mitigate misinterpretations in the imaging of facies models. During drilling, the geometries of conformable layers can be updated to locally adjust their depths. Also properties are updated. Geosteering decisions are supported by sharing the continuously updated 3D view among the members of the decision making tea m.

In the mind of the interpreters, geological modelling is a process that takes place in three-dimensional space. If a 2D model is used as the main tool for supporting decisions, important information may be ignored. 3D sector models based on the standard tools used in the industry today do not allow effective updates of more complex geological structures within the short time available during drilling (see discussion in Section A.3 in the Appendix). In particular when drilling in complex geology, effective handling of complex structural uncertainties can be decisive for the outcome of the geosteering operation.

1.2. Main Contributions of This Paper

In the tools and methods for earth modelling that are today standard in the industry, a global grid is used to capture both properties and structure. This technique implies that the entire grid is invalidated even by small changes in the geological structure (see Section A.3 in the Appendix).

In the suggested approach, we use the geological structure to split the modelled volume into a set of regions. Each region is individually handled and discretized without reference to other regions. Moreover, properties are not handled in a single grid but in individual property functions that each represents only a small part of the subsurface. Each property function is handled separately without reference to other property functions. A region and a property function are linked via a mapping. All mappings are also handled separately, without reference to other mappings. As a result, local updates of the geometries and topology of the geological structures that are captured in the earth model grid, as well as local updates of the grid resolution, can be performed locally within a time frame independent of the size of the grid.

When using conventional earth modelling tools, local updates of the structural topology, e.g. insertion or removal of a subseismic fault or layer, require the grid to be globally regenerated and populated. Enabling local updates of the grid when the structural topology is locally modified aims to drastically shorten the time required for such updates. Local control with grid resolution (for each individual rock property) aims at improving the control with the trade-off between numerical accuracy and the time required for handling the grid(s). Moreover, local updates aim to enable effective, local scale uncertainty handling. When uncertainties are handled locally, less time is required for updating the grid. Furthermore, separate handling of each region opens up for parallel computer implementations. Such developments are important to speed up and streamline the earth modelling process when targeting real-time workflows. Rudimentary discussions of the strategy were presented in [5] [6].

It is emphasized that the proposed method is at an early stage of development, yet too immature to handle complex geological configurations and uncertainties. Therefore, our aim in this article is not to describe a complete method for geosteering support, but to discuss principles for how a populated earth model grid can be effectively modified when the topology (connectivity) of the geological structure is locally altered. Structural modelling can be a complex task, and could e.g. be handled in combination with the methodology described in [7] (see Section A.2 in the Appendix). The principles of the suggested method are demonstrated in 2D using a simplified geological structure.

We start by providing an overview of the proposed method in Section 2. In Section 3, we show how the strategy is applied in a geological setting containing layers and faults. Next, the required input for the grid construction process is discussed in Section 4. In Section 5, the construction of a populated grid is described, including pseudo code. In Section 6, the procedure for locally updating the grid is discussed, and in Section 7 examples are provided. In Section 8, the mapping is discussed in more detail. Section 9 summarizes the paper. In the Appendix, two examples that highlight the need and potential benefits of improved workflows for drilling are presented in Section A.1. In Section A.2, we indicate a potential future geosteering workflow. The conventional 3D earth modelling methodology used in the industry today is reviewed in Section A.3. In Section A.4, more recent technological developments within 3D earth modelling are discussed. Finally, in Section A.5, various strategies for gridding of the earth model and their implications for model management are discussed.

2. Overview of the Proposed Method

A main component of our strategy is to separate the modelled volume into disjoint regions that are individually handled. The regions are defined using the geological interfaces in the structural model (see Section 4.1). Each region R gets its own grid, or even a set of grids if different properties should be discretized at different resolutions. A grid for a particular region is called a subgrid G_Z, and it should be generated at the resolution and quality decided by the application of the model. The subscript Z indicates the properties of each specific subgrid, e.g. its resolution. The resolution of each subgrid is in general independent of the other subgrids for this region and of subgrids for neighbouring regions. However, if two subgrids in neighbouring regions are connected by the sharing of faces along their common boundary, dependencies between the two neighbouring subgrids are introduced. Typically, the subgrid is an unstructured grid.

The properties are not represented in a single global grid, but in a set of individual property functions (see Section 4.2). Each property function represents a specific property, e.g. porosity, for a geologically defined small rock volume, e.g. a depositional layer. A property, say porosity, can be represented at multiple resolutions by application of multiple functions (or a multi-resolution function). Control with resolution of both the subgrid and the property function provides a large degree of flexibility for locally controlling the earth model resolution. A given property could be represented at varying resolution depending on the location in the model, and different properties can be represented at different resolutions within the same region.

A mapping links a region with the corresponding part of a property function, and allows population of the subgrid with properties from the property function. For example, if a layer is split by faults into multiple regions, a set of mappings link each region with the corresponding part of a property function. (Note that a "function" and a "mapping" is the same in the mathematical terminology. In this article we let a "function" represent values of a rock property. A "mapping" is used to link a subgrid with a property function.)

When the geological structure is modified, only the regions and subgrids that are in direct contact with the modified parts of the structure must be discarded and rebuilt (see Section 6). The rest of the existing subgrids are retained. Moreover, a local update of the grid resolution implies that only the subgrids in the affected regions are discarded and that new subgrids are established for these regions. Again, the rest of the existing subgrids are kept. An update of a property function only implies that a small set of the existing subgrids must be repopulated. The method is independent of the particular strategy used for structural modelling as long as a structural model (see Section 4.1) can be extracted.

To update the populated grid as a fully local operation requires that all involved data structures can be locally updated. In our strategy, the grid, the mappings and the property functions are data structures that represent information for only a small part of the subsurface. Local updates of the populated grid are thus achieved by avoiding the use of any globally defined data structure that cannot be locally updated. In this paper, simple examples of local updates of the fault network and the stratigraphy are shown.

In the proposed method, each individual region is assigned its own mapping that links a subgrid for the region with a property function for a stratigraphic layer. First, this individual handling of each layer aims to enable more flexibility for controlling and locally altering the interpretation of the stratigraphic record. Second, a region has a relatively simple shape and does not contain any geological interfaces in its interior. As a result, the mapping can be kept simple without the complexity of taking interior geometries into consideration. A particularly attractive choice of mapping is therefore one that only requires knowledge of the geometric boundaries of the region and the geometric boundaries of the corresponding parameter domain of the property function (see Section 5.2) for its construction. Such mappings have been developed, verified, optimized and documented elsewhere in the scientific community, see Section 8. The use of general purpose mappings also allows us to capitalize from future developments within the field. Moreover, also gridding strategies for the discretization of each region may benefit when regions do not contain any interior geometries that the grid must honour. Gridding strategies are discussed in more detail in Section A.5 in the Appendix.

3. Application of Method to Layered Media with Faults

Next, we exemplify the approach for a geological setting comprising layered depositions with faults. A region is then assumed to be a part of a layer within a fault block (note, however, that a region could also be defined differently within the proposed framework). In this setting, a layer therefore consists of a set of regions separated by faults. Each property is handled in a separate property function Φ that represents a property for a layer L. But more flexible designs are also possible using the proposed framework. For example, a single property function could cover a set of layers, a specific fault block, or some other geologically defined volume of rock.

When a structural element such as a fault or another geological interface is updated, *i.e.* geometrically perturbed, removed, inserted, or its connectivity with other structural elements is modified, only the regions whose boundaries are affected by the structural update are involved in the update of the grid. The principle is indicated in **Figure 1**, where the insertion of faults in the interior of the fault block denoted "A" only affects the subgrids in this particular fault block.

In **Figure 2**, the population of an earth model grid is explained. The top layer L^1 is split into two regions R_1^1 and R_2^1 by the fault, and similarly for the bottom layer L^2. Each of the four regions is individually discretized and we obtain four subgrids. Two properties, represented by the two property functions Φ^1 and Φ^2 for the two layers L^1 and L^2 respectively, are linked with each region using four corresponding mappings $\left\{f_1^1, f_2^1, f_1^2, f_2^2\right\}$. Each mapping links a region with the corresponding part of the parameter domain of the property function. For example, the subgrid in R_1^1 is linked with the part D_1^1 of the parameter domain of Φ^1 via f_1^1. Informally, we can say that the mapping deforms the interior of D_1^1 into the shape of R_1^1. This allows the subgrid to be populated by sampling values from Φ^1. This deformation is further explained in Section 5. The effect of deforming e.g. D_1^1 into the shape of R_1^1 is that it is elongated in horizontal direction and squeezed together in vertical direction. The white near-vertical

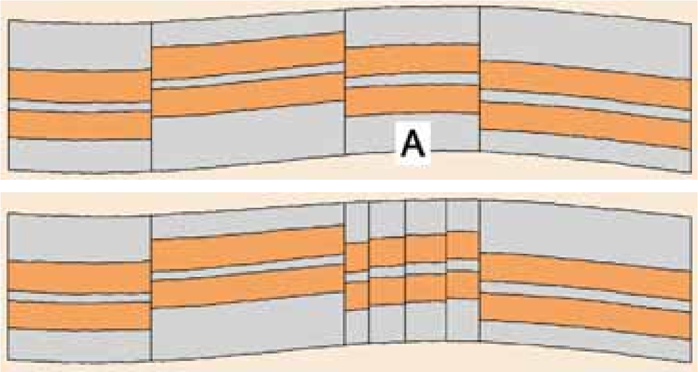

Figure 1. At the top is a model representing a faulted reservoir with alternating sands and shales. At the bottom the initial model is locally updated by inserting three new vertical faults in fault block A.

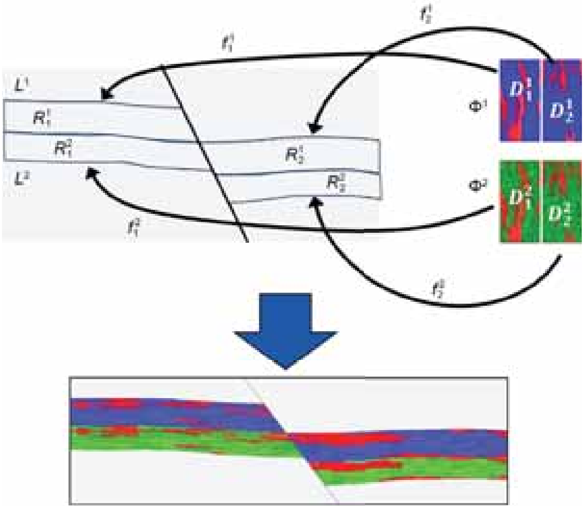

Figure 2. A structural model with two depositional layers (L^1 and L^2) split by a fault contains four regions R that are individually gridded. Property values are interpolated from the property functions Φ^1 and Φ^2 to the right and transferred into the grid in each region by the use of mappings (f). The result is a populated grid as shown at the bottom. The colors in the figure indicate property values.

line that splits Φ^1 into D_1^1 and D_2^1 is the image of a part of the fault, correspondingly for Φ^2. Note that the direction of the arrows in the figure indicates how property values evaluated from the property functions are transferred to the subgrids. The mappings are in fact directed in the opposite direction (see Section 5.2). Also note that we have zoomed in on the fault so that only parts of the layers are shown, they extend further both to the right and the left. As a result, only the corresponding parts of the properties around the fault are shown in the populated earth model at the bottom of the figure.

In the simple example in **Figure 2**, created using a rudimentary software prototype, the property functions used to populate each layer are identical. Clearly, for realistic modelling, separate property functions will exist for each layer.

4. Input for Earth Model Construction

The required input for generating a populated earth model grid is a structural model and associated property functions.

4.1. The Structural Model

The structural model $\mathcal{M}^S$ captures an interpretation of the geological structure at a specific resolution. The geometries in the structural model create a partition of space into disjoint polytopic regions $\mathcal{R}$ (polygons in 2D). The boundary Ω_R of each region $R \in \mathcal{R}$ is represented by a set of geometric patches, where each patch is a part of a geological interface. For example, a region can be a layer in a fault block and be bounded by parts of fault geometries and stratigraphic interfaces. Each region is a continuous closed volume, and it is the smallest volumetric object in the partition of space as it cannot be subdivided by any other geometric patch in $\mathcal{M}^S$. Geometric patches do not cross, and each patch stop into another patch (including patches representing the model boundary). A layer can e.g. be locally split in two as a result of hiatus or erosion so that it has zero thickness. Then the two parts are handled as two separate regions. The part of the layer with zero thickness is not represented by a region and is therefore not part of the earth model grid. Neither faults nor layers are required to cross the entire model. The described structural model is similar to the sealed structural model described in 3D in e.g. [8] [9] [10] [11].

In the initial strategy described in this paper there are no geological interfaces in the interior of a region. This implies that faults must terminate into other geological interfaces. To enable faults to terminate in the interior of a layer, adjustments are required when mapping properties to subgrids. Furthermore, when discretizing a region, this part of the fault must be taken into consideration.

An important future target is to allow integration of the proposed method with conventional tools for 3D earth modelling. The rules for the described structural model allow us to import from and possibly integrate with the standard tools used in the industry today. Potentially, the rules could also be adapted to other earth modelling approaches.

4.2. Property Functions

For each layer L we have at least one property function Φ. The function represents a physical property, say porosity, density, velocity or saturation. A bivariate scalar property function is defined by $\Phi:(v,w)\rightarrow\phi$ over a parameter domain D^Φ, for example the unit square.

Each property function is independent of the other property functions, and can be managed at its own resolution. For example, porosity could be represented at a finer resolution than saturation. The same property can be represented by property functions at different resolutions. Property functions can be defined over parameter domains D^{Φ} of different shapes. This may be useful for more optimal handling of facies and property distributions of more complex geological shapes. Different functions, typically over the same parameter domain and with the same resolution, can be used to represent multiple realizations of the same property.

A set of functions can be constructed from the property representation of existing earth models. Each function is then handled separately, which provides flexibility e.g. for locally updating the stratigraphic record and for handling each property at its own resolution. However, to modify existing properties in a geologically reasonable manner to match an updated interpretation of stratigraphic interfaces is not straight-forward. Property functions are mathematical constructions without the burdening requirement of carrying direct geological meaning. Geological meaning is only assumed after the functions have been used to populate the grid. This provides an extra degree of freedom such that the functions can be set up in ways that are mathematically convenient. On the other hand, it requires that the mapping of properties from the functions to the grid ensures that the geological meaning is restored when the grid is populated from the property functions. This issue is discussed in Section 5.3.

The property functions can be set up in ways that are mathematically convenient. Φ could in principle be any type of function, as long as it can be evaluated everywhere within D^{Φ}. Potential strategies include that the function is represented over a grid, or is a uniform value as in [12]. The function could also be a complex analytical function, or a multi-resolution function as suggested in [5] [13] [14]. A property function can be constructed from grid-based property distributions that are imported from external tools. It could also be derived from the interpretation of well logs in real-time.

In the example in **Figure 2**, the geological structure is imported from Petrel and the property functions are generated from an imported Petrel grid. Currently, the construction of the property functions take place in a simple manner and is only intended for demonstrating principles; by identifying a layer in an imported corner-point grid, the value in each cell in the grid is simply transferred into a regular grid with the same topology as the corner-point grid (*i.e.* the same number of cells in all directions). The populated regular grid then constitutes a property function. But in this manner, e.g. collapsed cells are not properly handled. An improved procedure would sample the properties from the geological space where the corner-point grid has been adapted to the geological structure.

5. Construction of a Populated Grid

The construction of a populated grid takes place by first identifying the closed regions $\mathcal{R}$ in $\mathcal{M}^S$ to populate. Each region R is handled independently of the other regions. Each region can contain multiple subgrids at different resolutions and with different numerical qualities, allowing each property within each region to be handled separately at its own resolution. There are three main steps required for populating a region R with a property, namely 1) construction of a grid in the region with a resolution and quality adapted to the property in question, 2) construction of a mapping to link the region with the corresponding domain of a property function, and 3) populating the grid by transferring values interpolated from the property function using the mapping. Once a boundary polygon for R has been created, step 1) and 2) are independent and could be completed in parallel.

Next, a procedure for populating a subgrid with a property is described. The procedure is repeated for all subgrids within all required regions and for all required properties.

5.1. Construction of Boundary Polygon and Subgrid

A polygon P_R representing the boundary Ω_R of the region R is required both for gridding and for construction of the mapping. P_R is constructed by extracting and joining the geometric patches in $\mathcal{M}^S$ that together constitute the boundary of R. Details for its construction are discussed in Section 5.2. The resolution of P_R controls the resolution of the subgrid as well as the computational efficiency of the evaluation of the mapping. Once P_R is constructed, a subgrid G_Z at an appropriate resolution and quality to discretize the interior of R can be constructed using a suitable grid generator. If such a subgrid already exists, it may be reused.

5.2. Construction of the Mapping and Population of the Subgrid

For linking the property function Φ for a layer with the region R, we apply a mapping f. First, let us assume that we have an unfaulted layer L, represented by a single region R. The exact shape of L is a matter of geological interpretation, so we assume that we have arrived at an alternative we call L^1. An informal and intuitive way to understand the mapping of properties from a property function to a layer is to imagine that the shape of Φ is deformed into the shape of L^1 as shown in **Figure 3**. Then the mapping ensures that the interior follows. If the geological structure is modified from L^1 to L^2, a new mapping f^2 is generated to deform Φ to fit within L^2 as shown in the figure. The nodes of the polygonal boundaries of D^Φ, L^1 and L^2 are also indicated. Note that the direction of the arrows also in this figure indicates how property values are transferred from the property function to the layer.

Next, we describe a preliminary strategy for handling faults. The approach demonstrates how property functions are used to populate faulted layers, but further developments are required for proper handling of updates in the geological structure when addressing realistic model alterations while drilling (see discussion in Section 5.3). Φ represents the property function for the complete layer L, and we assume that $n-1$ faults separate L into n regions R_i, $i = 1, \cdots, n$.

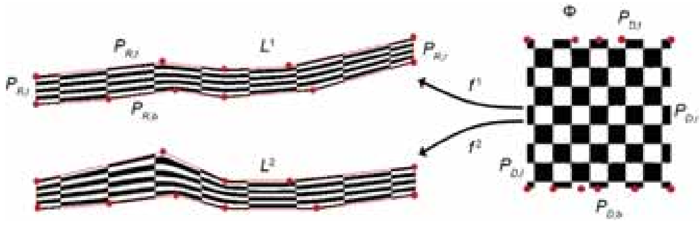

Figure 3. Two mappings f^1 and f^2 can informally be said to deform the property function Φ to the right to fit within any of the two alternative interpretations L^1 and L^2 of the shape of a sedimentary layer L. $P_{R,t}$ is the geometric patch representing the top stratigraphic boundary of L^1, whereas $P_{D,t}$ is the geometric patch representing the top boundary of the parameter domain D^Φ of Φ. The other parts of the boundaries of L^1 and D^Φ are correspondingly marked.

A fault may displace multiple layers, but here we only consider the part of a fault that affects the layer that is currently being populated. The parameter domain D^Φ of Φ must then be correspondingly split into n subdomains $D_i \subset D^\Phi$, for $i = 1, \cdots, n$. Now each R_i in L can be associated with each corresponding D_i. As an example, consider Figure 2 where L^1 is split into two regions R_1^1 and R_2^1 by the fault. The parameter domain of the property function Φ^1 is then split into two subdomains D_1^1 and D_2^1 by a curve which is the image in D^Φ of the part of the fault that splits the layer. In the example the curve is an almost vertical line, but it can also have a more complex geometry.

The mapping is on the form $f: \Omega_S \to \Omega_T$ from a source polygon Ω_S to a target polygon Ω_T. In the described strategy, Ω_S is the polygonal boundary P_R of R and Ω_T is the polygonal boundary P_D of D, for any $R = R_i$ and corresponding $D = D_i$. We call the mapping f_{P_R,P_D}, and it links any pair R and D so that properties represented by property functions can be used to populate subgrids in R.

The mapping we use (see Section 8) requires that the source polygon P_R and the target polygon P_D are topologically equivalent, so that P_R can be deformed into P_D. Here, topological equivalence means that the two polygons have the same number of nodes and that the nodes have the same ordering. Next, a recipe to construct P_R and P_D is discussed.

In the same manner as P_R was constructed (see Section 5.1), P_D is constructed by joining the geometric patches that constitute the boundary of D. We let the patches constituting P_R and P_D be pairwise associated; the top boundary of R is associated with the top boundary of D, the right hand side part of the boundary of R is associated with the right hand side part of the boundary of D, and so on. Each geometric patch in the pairwise association must be topologically equivalent. This is obtained by inserting new nodes into either of the two patches, but typically into the patch being part of the boundary of P_D. This is because P_D generally has the lowest geometric resolution, as a result of the simple quadratic shape of D^Φ. As an example, consider Figure 3 where R is the entire L^1 and correspondingly, D is the domain D^Φ of the entire property function. For this example, L^1 is thus considered to be the part of a layer in the interior of a fault block. $P_{R,t}$ is the top stratigraphic interface of R, $P_{R,l}$ is the left hand side boundary of R, $P_{R,b}$ is its bottom stratigraphic interface, whereas $P_{R,r}$ is the right hand side boundary of R. Correspondingly, $P_{D,t}$ is the top boundary of D, $P_{D,l}$ is its left hand side boundary, $P_{D,b}$ is its bottom boundary, whereas $P_{D,r}$ is the right hand side boundary of D. $P_{D,t}$ is associated with $P_{R,t}$, $P_{D,l}$ is associated with $P_{R,l}$, $P_{D,b}$ is associated with $P_{R,b}$, and $P_{D,r}$ is associated with $P_{R,r}$. Note that $P_{R,t}$ and $P_{R,b}$ can have a different number of nodes, and there are no constraints regarding the placement of these nodes. Thus, the top and bottom boundaries of a layer can have different geometric resolutions.

In **Figure 3**, we see that $P_{R,t}$ contains five nodes. D is a square, so $P_{D,t}$ is a straight line represented only by its two end points at the upper left corner and upper right corner of the square. To ensure that $P_{R,t}$ and $P_{D,t}$ are topologically equivalent, $P_{D,t}$ is refined by inserting new nodes (see **Figure 3**). We let $P_{R,t}$ and $P_{D,t}$ be parameterized by normalized arc length. The three new nodes in $P_{D,t}$ are inserted at the same parameter values s_i, for $i = 1, 2, 3$, as where $P_{R,t}$ has interior nodes. A similar refinement is applied to $P_{D,b}$ with respect to its counterpart $P_{R,b}$. Neither $P_{R,l}$ nor $P_{R,r}$ have interior nodes, so neither $P_{D,l}$ nor $P_{D,r}$ need further refinement. Now that all pairwise associated geometric patches are topologically equivalent, we join $\{P_{D,t}, P_{D,l}, P_{D,b}, P_{D,r}\}$ to form P_D. Each of the patches must be oriented so that a valid polygon is formed, and P_D must be have the same orientation (clockwise or anticlockwise) as P_R. Now P_R and P_D are topologically equivalent.

f_{P_R,P_D} can be constructed from the source and target polygons P_R and P_D, respectively (see Section 8, where a particular type of mapping is discussed). The mapping allows any point $\boldsymbol{x} \in R$ to be mapped to its corresponding point $\boldsymbol{x}' \in D$, as $\boldsymbol{x}' = f(\boldsymbol{x})$. A property value $\Phi(\boldsymbol{x}')$ can then be evaluated by interpolation of Φ, and the value can be used to populate the subgrid G_Z that covers R. Typically, all nodes or cell centres in G_Z are given values in this manner. The procedure is called "backward mapping" and is well known from image warping, see e.g. [15]. Note that for handling of more complex fault networks, e.g. where a fault terminates into another fault, the strategy must be generalized to handle more complex topological relationships in the geological structure.

Pseudo code for grid construction is provided in **Algorithm 1**. The input is a list of regions in $\mathcal{M}^S$ where subgrids should be constructed, together with associated property functions. The output is a populated subgrid for each region. The algorithm handles each region independently of the other regions.

5.3. Handling of Properties When the Structure Is Locally Modified

Existing properties are the results of modelling prior to drilling, or of predictions made earlier during the drilling process. But property predictions are burdened by uncertainties, and predictions of the geological structures and properties that are constrained by the most recent measurements and interpretations obtained during the ongoing drilling process are important to support the geosteering decision process.

Algorithm 1. Part 1: Generation of subgrids for a set of regions.

```
Initialization:
    Let $\mathcal{M}^s$ be a structural model
    Let $\mathcal{R}$ be the regions from $\mathcal{M}^s$ to be gridded and populated
    Let $\bar{\Phi}$ be the property functions $\Phi$ for each $L$ containing an $R$ in $\mathcal{R}$
    Let $\mathcal{G}$ be a set of grids $G_Z$
    $\mathcal{G} \leftarrow \varnothing$
    Let $\mathcal{F}$ be a set of mappings $f$
    $\mathcal{F} \leftarrow \varnothing$
    Let $\mathcal{A}$ be a set of arrays $a$ for storing grid-based property values
    $\mathcal{A} \leftarrow \varnothing$
parallel for each $R \in \mathcal{R}$ do
    Select a property function $\Phi \in \bar{\Phi}$
    $P_R \leftarrow$ Construct the polygonal boundary of $R$ from $\mathcal{M}^s$
        ▷ Retrieval of $G_Z$ and $f_{P_R,P_D}$ are independent processes
    Select $Z$ (subgrid resolution and quality)
    $G_Z \leftarrow \text{RetrieveSubgrid}(P_R, Z)$ (An existing $G_Z$ may be reused)
    $\mathcal{G} \leftarrow \mathcal{G} \cup \{G_Z\}$
    $f_{P_R,P_D} \leftarrow \text{RetrieveMapping}(P_R, \Phi)$
    $\mathcal{F} \leftarrow \mathcal{F} \cup \{f_{P_R,P_D}\}$
    $a \leftarrow \text{PopulateSubGrid}(G_Z, f_{P_R,P_D}, \Phi)$
    $\mathcal{A} \leftarrow \mathcal{A} \cup \{a\}$
end parallel for
return $\{\mathcal{G}, \mathcal{A}\}$
```

Algorithm 1. Part 2.

```
function RetrieveMapping$(P_R, \Phi)$
    if $f_{P_R,P_D} \in \mathcal{F}$ then
            ▷ If a subgrid in $R$ has been populated, $f_{P_R,P_D}$ already exists
        Select $f_{P_R,P_D}$ from $\mathcal{F}$
    else
        $P_D \leftarrow$ Construct the boundary of $D$
        $f_{P_R,P_D} \leftarrow$ Construct $f: P_R \rightarrow P_D$
    end if
    return $f_{P_R,P_D}$
end function
```

Algorithm 1. Part 3.

```
function PopulateSubGrid$(G_Z, f_{P_R,P_D}, \Phi)$
        ▷ Array containing property values
    $a \leftarrow \varnothing$
    parallel for each node or cell in $G_Z$ do
        $\boldsymbol{x} \leftarrow$ Either grid node or cell barycentre
            ▷ Map point in $R$ to point in $D$
        $\boldsymbol{x}' \leftarrow f(\boldsymbol{x})$
            ▷ Interpolate $\Phi$ in $\boldsymbol{x}'$
        $\phi \leftarrow \Phi(\boldsymbol{x}')$
        $a \leftarrow \phi$
    end parallel for
    return $a$
end function
```

More complex property distributions are time consuming to generate for the entire grid. Therefore, to reduce the time for locally modifying the structural model, existing properties represented in property functions should be reused if possible. In a property distribution captured in a grid, e.g. facies objects are implicitly represented. The sizes of the objects and the distances between the objects carry geological meaning, and the property distribution is matched to the shape of the layer it originally populated. In the parts of the model where there is no alteration of the geological structure during a local model update, which is typically a very large portion of the model, existing properties could be reused because their geological meaning is not altered. But when a property function is used to populate a subgrid that is adapted to a locally updated geological structure, care must be taken to ensure that the original geological meaning is (approximately) restored so that the updated model is geologically reasonable. This depends on the complexity of the property function, as well as on the complexity of the structural update, e.g. the amount of deformation of an existing layer. A major revision of the structure at local scale may render existing complex property representations locally inapplicable, so that new properties that respect the new measurements should be generated at the local scale. This depends on the application of the model. Such issues have not yet been properly addressed. More basic property representations, such as constant-valued representations, are easier to handle. In the method described in [7], the aim is to allow automatic modification of both properties and the geological structure.

While drilling, when time is limited and an updated model is urgently needed for decision support, methods that provide approximate solutions within short time are typically preferred to methods that provide more exact solutions long after a decision has been made and the drilling operation has progressed. Therefore, careful consideration with respect to the modelling requirements set by the decision process is required. The time needed to generate a model-based decision recommendation must be weighed against the desired quality of the recommendation.

Finally, it is important to note that the current focus of the proposed strategy is on local updates to support decisions for the well being drilled, not on updating the model globally during the drilling process. In [16], a novel strategy for multi-resolution earth model gridding is described. It is based on the methodology described in this paper, and one of its objectives is to aid in the localization of the updates by arranging the regions in $\mathcal{M}^S$ in a hierarchical manner. Outside a region at any level of detail in the hierarchy, the model will not be modified. Moreover, the approach in [16] aims to increase the modelling efficiency while drilling by locally controlling the resolution of the geological structure and the grid.

6. Local Updates of the Earth Model Grid

With **Algorithm 1** in mind, we explain the general method to locally update the geological structure in a populated grid. Let $\mathcal{M}_\star^S$ be the pre-update structural model, while the corresponding post-update structural model is denoted $\mathcal{M}^s_{\star\star}$. $\mathcal{M}^s_{\star\star}$ is obtained by locally updating the structural connectivity and/or geometry in $\mathcal{M}^s_{\star}$. $\mathcal{R}_{\star}$ is the set of regions in $\mathcal{M}^s_{\star}$ that are affected by the local structural update, whereas $\mathcal{R}_{\star\star}$ is the set of regions in $\mathcal{M}^s_{\star\star}$ that are established or deformed in the update.

Thus, a local update of $\mathcal{M}^s_{\star}$ implies that one or more regions $\mathcal{R}_{\star}$ in $\mathcal{M}^s_{\star}$ are affected; they are either deformed or new regions have taken their place. In both cases, $\mathcal{R}_{\star\star}$ is the set of regions in $\mathcal{M}^s_{\star\star}$ that must be attended. The rest of the regions in $\mathcal{M}^s_{\star\star}$ already exist in $\mathcal{M}^s_{\star}$. The general method is to first remove the subgrids for the regions in $\mathcal{R}_{\star}$. To reestablish the global earth model grid, **Algorithm 1** is run to generate populated subgrids only for the regions in $\mathcal{R}_{\star\star}$. If a region is only slightly deformed during the structural update, it could be possible to deform its existing populated subgrids.

Structural modelling can be challenging, and the particular technique to locally updating $\mathcal{M}^s_{\star}$ is not considered here. For example, such updates could be controlled in combination with an external process where multiple model realizations are constrained by new measurements obtained while drilling as discussed in [7]. In this article we focus on how the populated global grid can be locally (rather than globally) modified when a local update of the structural model is performed.

7. Examples of Local Updates of an Earth Model Grid

Next, some basic examples are shown that demonstrate the principles of how the grid is locally modified when the structural topology is locally altered. Such local updates cannot be performed using the methodologies on which the commercially available earth modelling tools are based. It requires further developments to handle more realistic geological configurations and uncertainties than those shown in the examples.

In **Figure 4**, a new layer is inserted as a local model update. The $\mathcal{M}^s_{\star}$ at the top has two layers L_1 and L_2, and a fault splits the layers into totally four regions

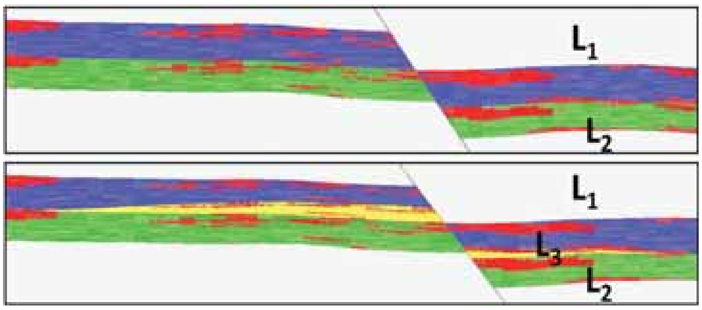

Figure 4. An example of a local stratigraphic update. Top: an initial model with two layers L_1 and L_2 split by a fault. Bottom: a pinch-out in yellow marked L_3 is inserted. The update affects only the two regions that together constitute L_1, the subgrids in the two regions for L_2 are retained. The colors in the figure indicate property values.

that are separately gridded and populated with properties. In the updated $\mathcal{M}^{S}_{\star\star}$ at the bottom of the figure, the volume formerly covered by the top layer L_1 is now occupied by L_1 and the pinch-out L_3 in yellow. $\mathcal{R}_{\star}$ consists of the two regions representing L_1. The subgrids for $\mathcal{R}_{\star}$ were discarded while the subgrids for L_2 were kept. $\mathcal{R}_{\star\star}$ consists of the two updated regions for L_1 as well as the two new regions for L_3. A new property function for L_3 was generated before $\mathcal{R}_{\star\star}$ was sent for gridding using **Algorithm 1**.

In the example in **Figure 4** the property functions used to populate each layer are identical just as in **Figure 2**, so that the effect of a local structural update can be examined. The procedure for populating the subgrid in any R using properties represented in the corresponding D is based on deformation of the boundary polygon of R into the shape of the boundary polygon of D (see Section 5.2). In **Figure 4**, the thickness of the layer L_1 is locally decreased in the local update. The figure shows that the polygon deformation implies that the property representation in the interior of L_1 is correspondingly deformed, so that the vertical distances between the objects that are implicitly represented in the grid are decreased. See Section 5.3 for further discussion.

In **Figure 5**, an example is shown where the grid resolution and the fault network are locally modified within two separate fault blocks. The synthetic model consists of alternating sands (in orange) and shales (in gray), and all faults are vertical. The five layers in the middle of the model contain the faulted reservoir rocks. The two layers at the top and the two layers at the bottom of the model do not contain faults. Let us assume that these four boundary layers are of less interest for the modelling purpose at hand. Their boundary geometries were originally at the same resolution as the geometries closer to the reservoir, but they were coarsened to allow coarser subgrids. A coarser subgrid requires less computational time for its generation and population, but comes at the expense that fewer details can be captured in the grid. The grid resolution is generally finer within the sand layers than within the shale layers. This is useful if variations in the rock heterogeneity should be captured at different levels of detail for the two facies.

At the top is the initial model, it has finer grid resolution within the fault block denoted "A". The middle and the bottom models in the figure were obtained by locally updating the model at the top. First, the grid resolution in the interior of fault block "A" was coarsened as a local model update. Then, for each of the two models, fault block "B" was modified in a local update by inserting new vertical faults with small displacements (a local update of the structural topology). The subgrids for all new regions within the fault block were constructed at a fine resolution. In fault block "B", the number of new faults and their respective displacements are different for each of the two updated models. The assumption is that the two updated models both represent possible realizations of the fault network, but with significant differences in the reservoir connectivity and with corresponding consequences for the resulting flow patterns. Within the fault block, parameters such as number of faults, fault location and fault

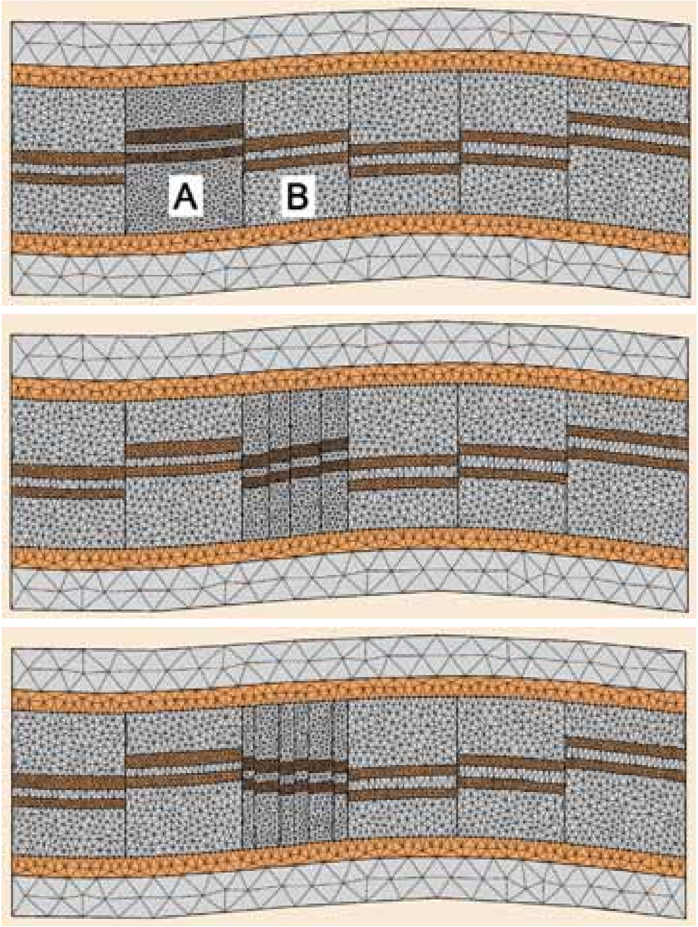

Figure 5. Top: an initial model with faulted reservoir rocks. The grid resolution varies across the model. Middle and bottom: the fault network and the grid resolution were locally updated within fault blocks A and B. Gray indicates shale, orange indicates sand rocks.

displacement were used to automatically update the fault network in the interior of the fault block. The vertical faults were inserted using a simple fault operator that locally moved the stratigraphic interfaces vertically up or down. All model updates were accomplished in a fully automatic fashion that also supports uncertainty modelling.

8. The Selected Mapping

Mapping between polytopes (in 2D they are planar polygonal domains) is a well known problem in computer graphics and geometric modelling. Numerous mappings with various numerical properties exist in the literature. One group of mappings is based on barycentric coordinates. Barycentric coordinates are frequently used to represent a point in the interior of a polygon as an affine combination of the nodes of the polygon. The coordinates are unique for triangles and tetrahedra, but for arbitrary simple polygons there are many generalizations that each has a different set of numerical properties. The examples shown in this paper are generated using a mapping based on mean value coordinates (MVC). It was first described in [17], while pseudo-code can be found in [15]. It has also been extended to 3D, see [18]. In [19], a 2D mesh that conforms to the geological interfaces is used for seismic restoration. When the structure is deformed in the restoration process, the MVC-based mapping ensures that the positions of the nodes in the interior of the triangulated mesh follow the restored interfaces. Then the properties stored in the grid are always available during restoration.

The general procedure to populate a subgrid with values from a property function was described in Section 5.2. As shown there, the mapping from a source polygon to a target polygon takes the form f_{P_R,P_D}. When using the MVC-based mapping, barycentric coordinates for a given source point $\boldsymbol{x} \in R$ with respect to P_R are calculated (see [15] for details). Then the coordinates are kept fixed while P_R is deformed into P_D. The target point $\boldsymbol{x}' \in D$ can then be evaluated by applying the barycentric coordinates with respect to P_D.

The MVC-based mapping has many favourable properties. One of the most prominent is its computational efficiency; it has a closed form and it can easily be parallellized, allowing multiple property values to be interpolated simultaneously. It is not based on a grid and thus independent of the resolution of such a grid. However, the mapping discussed in [15] [17] is not bijective. A bijective mapping that also enable the application of source and target polygons of any shape may allow e.g. to address facies distributions of complex shapes in an easier manner. In [20], smooth and bijective mappings that also extend to 3D are discussed.

9. Conclusions

Decision making to optimize the exploitation of subsurface resources is challenging in particular when targeting more complex fields and reservoirs. Three-dimensional grid based earth models are routinely used for decision support in workflows where time is not a major constraint. In geosteering operations, new measurements received while drilling should be used to modify the pre-drill interpretation captured in the earth model and support right-time decision making based on the most recent measurements and interpretations. But today's methods fall short in the attempt to update the model in a timely manner.

We have described a novel method that aims to enable real-time local updates of the topology of the geological structure and the grid resolution in a 3D earth model while drilling. The main principles for locally updating the populated grid when the geological structure is modified have been discussed, but the developments have not yet come far enough to address more realistic geological problems. Examples have been shown for basic cases. If the method can be further developed to handle realistic geology, it would offer a number of advantages for increased grid handling efficiency:

- The grid can be locally modified when the topology (connectivity) or geometry of the structural model is updated.
- The grid resolution can be locally updated.
- Each property can be handled at its own resolution.
- Grid handling can be parallellized to further reduce the computational time required for managing the model.
- Uncertainties in the structure and properties can be handled at a local scale while the rest of the model is kept unaltered.

The method is described in 2D. The mapping described in Section 8 has a three-dimensional counterpart. Therefore the basic principles for locally updating the grid as discussed in this article, applied to a simplified geological structure, should be possible to extend to 3D. Future work should first and foremost focus on management of more complex and realistic geology. The potential for improved modelling efficiency provided by local model updates, control with model resolution and parallel processing should be further explored. Moreover, modelling for real-time applications could be achieved by a high degree of automation so that the need for time-consuming manual work is minimized. Automation should be addressed by algorithms that update the model, both structure and properties, in a geologically realistic manner. Such algorithms should be controlled by geological parameters that are also intuitive to geoscience experts, to allow capturing of the geological reasoning behind the interpretation directly in the model.

Modelling efficiency is important to support optimal well placement while geosteering. The suggested approach could potentially form an essential part of a methodology for effective uncertainty modelling where an ensemble of three-dimensional earth model realizations is always kept up-to-date with the most recent measurements, interpretations and uncertainty estimates, and is always at an optimal resolution, even during real-time workflows.

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Appendix

A.1. Two Geosteering/Operational Challenges

Example 1: Effective updates of the geological uncertainty while drilling aim to offer support for improved geosteering workflows. Today, drilling speed (ROP, rate of penetration) is often reduced to allow time for geological interpretation and decision making while geosteering (see [22]), with the consequence that the drilling performance decreases. But with longer drilling durations there is an increased probability for hole collapse before the production liner is set, in particular when drilling long horizontal sections. With high speed bidirectional telemetry like wired drill-pipe it is possible to quickly reprogram the rotary steerable system to new settings, and therefore it is possible to shorten the directional update loop considerably. This allows higher ROP so that the probability for drilling problems is reduced, but implies that less time is available for geological interpretation and steering decisions. A more effective decision loop will thus contribute to safe and effective drilling, and minimize the time spent in the open hole section.

Example 2: Geological interpretation is uncertain. Assume that measurements indicate that the drill bit may have penetrated a fault or the roof of the reservoir and drilled into a formation associated with high risk for drilling problems. The longer the drilling continues in this formation, the higher is the risk of encountering problems. However, it is important to stay in the pay zone to maximize future production. The decision to be taken is if 1) a side-track should be drilled to reduce the risk of serious drilling problems, 2) retain the strategy and continue along the currently planned trajectory, or 3) continue drilling to collect more information and continuously re-evaluate the decision to side-track. In the latter case, when more information is available it may already be too late to avoid drilling problems. Also the uncertainty in the well trajectory should be considered. To support decision making, the geosteering decision support tool indicated in Section A.2 could be applied to continuously monitor the operation and provide real-time model-based recommendations.

A.2. A Potential Future Geosteering Workflow

In [7], a novel workflow is discussed where a set of earth model realizations are used to capture uncertainties in the locations and displacements of faults, in the shapes of stratigraphic interfaces and in water saturation. In the workflow the realizations are automatically conditioned to deep electromagnetic (EM) measurements while drilling. To minimize the time spent for managing multiple realizations representing complex geology in real-time, the ability to effectively update both structure and properties is crucial.

A decision analytic framework for geosteering is discussed in [23] [24] [25]. It aims to provide unbiased and consistent decision support under uncertainty by optimization with respect to multiple weighed geosteering and drilling objectives. Such objectives may include e.g. to minimize the probability of drilling into formations associated with drilling problems, maximize reservoir exposure and future production, minimize dogleg severity, minimize the cost of drilling, etc. Local earth model updates in real-time is a key element in the approach.

A possible highly automated future workflow for real-time geosteering and drilling decision support is to 1) if required, generate new realizations of the geology around and ahead of bit by locally updating the earth model, 2) locally condition all realizations by the recently received measurements as described in [7], and 3) employ decision analytics methods to provide decision support under uncertainty. This process should be run in a continuous loop to assess the current risks and aid the optimization of the drilling operation. For support of the workflow excellent control with the geological structure and grid is paramount, which is the theme addressed in this paper. The faster the situation can be analyzed, the uncertainties and probabilities can be calculated, and a decision recommendation can be produced, the faster the modelling results can be applied by the drilling/geosteering team. This will contribute to safer and faster drilling, increased future production and reduced drilling costs.

A.3. Current Methods for Earth Modelling

The interpretation of the geological structure is frequently burdened by first order uncertainties, see e.g. [10] [13] [26] [27] [28] [29]. Poor assessment of structural uncertainties can thus have dramatic effects on the decisions to be taken, in particular when drilling in more complex geology. Uncertainty in the topology (connectivity) of the geological structure includes how geological interfaces, e.g. stratigraphic and fault surfaces, are connected. Topological uncertainty also includes if particular faults and layers exist or not, the lateral magnitude and depth of an erosional event (which layers that are eroded), complex fault patterns around a salt dome, if fault segments are linked or not, stratigraphic correlation between wells (e.g. if layers pinch out or not), if there is communication between layers across a fault or not, and so on. For example, when geosteering in seismically obscured areas, such as below salt or gas, interpretation uncertainties are often higher and the measurements and interpretations obtained while drilling become more important to guide the steering of the well.

Numerous numerical methods require a grid for their discretization algorithms. A grid is by nature a rigid numerical construction where the topological relationship between its cells cannot be modified in a flexible manner, and grid construction is an area of active research.

In today's 3D earth modelling methodologies, implemented in software tools such as Petrel and IRAP RMS, a globally defined corner-point grid at a specific resolution is constructed early in the modelling process [12] [27] [30]. The grid construction is based on a deterministic representation of the geological structure, often denoted a base case or reference model. Rock properties are then distributed in this grid. The grid thus represents both structure and properties. The strategy implies that modifications in the topology of the geological structure cannot be effectively transferred to the earth model without invalidating the existing grid [12] [27] [30]. The updated structure is incompatible with the connectivity between the cells in the grid, and the cell connectivity cannot be modified in a general manner. Therefore, for each such update, a new grid based on the updated structure must be constructed. Moreover, all properties must be recomputed over the new grid. The reconstruction of the grid and distribution of properties may require much computational time, depending on the size of the model. In addition, much manual work is typically required to handle more complex updates of the geological structure.

As a result of the slow and complicated management, a crucial class of geological uncertainties may be underestimated or overlooked. Today, structural uncertainties are normally addressed by perturbing the geometry of a grid while the topology remains unaltered (see e.g. [31]).

In [30], a framework for modelling uncertainties in fault location and fault geometry in a structural model is presented. Here it is explained that if the base case structural model is updated, there are two possible procedures to construct a grid that match the new structure. In general, the grid must be entirely rebuilt and the new grid must be populated with properties as explained above. The second alternative is to deform the grid so that it matches the updated structure. This is an attractive option because the grid is not invalidated and the properties stored in the grid remain intact. In [32] [33] it is demonstrated how alterations in the displacement of a fault can be accommodated by grid deformation. But this only works for grids with simple fault geometries and when there are no changes to the topology of the geological structure [30] [32].

Recently, a system for closed-loop reservoir modelling has been developed [33] [34] [35] [36]. In the history-matching workflow a set of model realizations that are used for capturing geological uncertainty, including geometric uncertainties in the geological structures, are updated. A main advantage of the workflow is that multiple model realizations can be automatically generated in batch and in parallel, in a fully reproducible manner. In [34] it is discussed how the geometry and depth of a stack of stratigraphic interfaces can be modified in a geologically realistic manner. In [33] it is explained that for each realization of the earth model grid, all individual modelling steps are still performed as in the conventional modelling process. Whenever the structural model is updated, each realization of the grid is constructed from scratch.

A.4. Recent Earth Modelling Methods

In the approach described in [13] [27], the structure is split from the property representation and all properties are stored in a globally defined rectilinear grid. A single globally defined mapping, called the *uvt*-transformation, links the property grid (in a parametric *uvt*-space) with a geological grid (in the geological *xyz*-space) that conforms to the geological structure. The mapping enables population of the geological grid with values from the property grid. However, structural uncertainty modelling is performed by geometric perturbation of the base case structural model [13] [37]. Geometric perturbation does not include modifications in the topology of the fault network or layering.

In [14] [38], a strategy for seismic interpretation based on capturing the geological evolution in the model is presented. The evolution is described as a sequence of geological processes that take place through geological time. For each step in geological time, a structural model can be constructed over a computational grid. The computational grid is a regular grid with the same resolution everywhere. In [14] it is explained that the properties are handled in a parameter space, separate from the structure. A globally defined bijective mapping links the existing properties with the restored structure, and the properties can be mapped into the computational grid where the structure resides. The strategy permits local updates of faulting by the application of a fault operator that is used to insert and remove faults by locally updating the mapping.

Earth modelling strategies where the structure and the properties are separated and connected via a mapping introduce a new level of flexibility for updating the earth model. When the structure is modified, the existing properties can be reused without the need for a full reconstruction of the properties. However, the numerical characteristics of the mapping determine e.g. its computational efficiency and its ability to handle local updates in the structure. In the two methods explained in [13] [14], properties are represented in a globally defined grid and linked to the structure via a single mapping. Our approach is similar in that the structure and the properties are handled separately. However, we do not apply a global strategy.

In [12] [39], a surface-based method for adaptive gridding during fluid flow simulation is presented. Here the modelled volume is split into separate rock volumes by surfaces that represent geological interfaces to capture e.g. stratigraphic and diagenetic heterogeneities. Aiming to avoid upscaling, each property within each volume is uniform. Each rock volume is separately gridded, and the grid resolution can be locally updated within each volume. A characteristic aspect of the approach is that it avoids the complexity of handling property representations captured in a global grid. Numerically, the strategy suggested in this paper enables the same functionalities. But it also offers an additional level of flexibility as it allows capturing non-uniform property distributions within each rock volume. This provides an alternative when capturing e.g. gradational changes in different directions, or more complex trends and distributions.

A.5. Gridding Strategy

Geological heterogeneities have complex geometries. It is emphasized e.g. in [12] that using strictly rectangular (Cartesian) grids, approximately rectangular (corner-point) grids or PEBI grids of a given spatial resolution often provide a poor representation of geological heterogeneity. Local updates and uncertainty handling of complex geological structures and other heterogeneities at well scale are main motivations behind the suggested strategy. A simplex-based subgrid (triangulation in 2D, tetrahedralization in 3D) typically offers better flexibility to adapt to complex structural geometries, and enables local control with grid resolution and quality. To optimize the grid to its application, it should be possible to use different constraints in the gridding algorithm to obtain subgrids of different qualities. Different quality parameters such as shape and orientation of grid cells, grid resolution and how well the grid can be adapted to complex geological structures are important for many numerical schemes.

The geometry and topology of the structural model has severe consequences for the construction of the grid. In [12] [27] it is discussed how a corner-point grid may fail to capture complex structural architectures. A complex structural model may result in a grid of too poor quality to support various simulations, or even inhibit the generation of a grid. Moreover, in the trade-off between numerical accuracy and the time spent for computations, grid resolution is a main factor. But the structural resolution dictates the resolution of the grid because the size of the grid cells cannot be coarser than the distance between individual elements in the geological structure. The requirements to the grid size may therefore dictate a coarse structural resolution that fails to capture important structural features. Furthermore, in [12], it is discussed how the resolution of the grid cannot be modified in a flexible manner. In [27], it is emphasized that a normal procedure to reduce the complexity and size of the grid is to simplify or leave out known structural elements such as faults (as exemplified in [2]). For drilling in complex geology, where structural accuracy in the model around and ahead of bit is of particular importance, such limitations and practices are far from optimal. Optimally, the model capturing the geological interpretation should not be obstructed by limitations in the modelling method.

Gridding of complex geological structures is well known to be problematic. In the proposed strategy each region is individually discretized, potentially with different subgrids for each property. The subgrids in **Figure 5** are generally not matching across their shared boundaries. For many applications, this is not a problem. For visualization, even small gaps between regions are acceptable. However, many numerical schemes require that the faces of neighbouring subgrids match across their shared boundaries. In [12] [39] it is discussed how grid resolution is independently controlled for each rock volume, and how grids for separate regions are linked together. When more constraints are used in the gridding process to obtain high quality grids, more computation time is generally required. For optimal performance in a real-time environment, it could be important to carefully tune the input parameters of the grid generator to the application of the grid. Moreover, similar to the method in [39], our method allows populated subgrids to be generated in parallel. It may thus benefit from approaches for domain partitioning, see e.g. [40], to further streamline the gridding process.

Flow modelling is not our primary concern. Yet, we believe that also such applications could potentially benefit from the proposed strategy when effective assessment of more complex structural uncertainties is required. In [39], the generation of unstructured grids for use in the next generation of unstructured-mesh fluid flow simulators is discussed. Unstructured grids allow the capabilities of such simulators to be fully utilized in the modelling of complex reservoir architectures. In [41], different workflows for construction of tetrahedral grids for simulations on complex structures are evaluated.

Paper E

Suter, E., Friis, H.A., Vefring, E.H., Kårstad, T. and Escalona, A. (2017) A novel method for multi-resolution earth model gridding, Paper SPE-182687-MS presented at the *SPE Reservoir Simulation Conference*, 20-22 February, Montgomery, Texas, USA. https://doi.org/10.2118/182687-MS.

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Paper F

Suter, E., Alyaev, S. and Daireaux, B. (2017) RT-Hub - Next Generation Real-time Data Aggregation While Drilling, Extented abstract presented at the *First EAGE Workshop on Pore Pressure Prediction*, 19-21 March, Pau, France. https://doi.org/10.3997/2214-4609.201700060

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