3D stochastic modelling of fault zones in siliciclastic reservoirs

Implications for reservoir description and fluid flow modelling

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Scientific environment

This dissertation was submitted as partial fulfilment for the degree philosophiae doctor (PhD) to the University of Bergen (UiB), Norway. The research presented in this dissertation was carried out within the framework of a three-year scholarship funded by the University of Bergen. The majority of the work was conducted at the Uni Centre for Integrated Petroleum Research (Uni CIPR) as part of the Fault Facies Project. The general aim of the Fault Facies Project has been to produce a practical method for incorporating realistic fault zone features into standard industrial reservoir models. Specifically, the project has been a concerted effort to provide a potential solution to a number of identified shortcomings in present industrial fault modelling techniques. The project is a multi-disciplinary collaboration involving Uni CIPR, the Departments of Earth Science and Mathematics at the University of Bergen, the Norwegian Computing Centre, and Roxar Software Solutions. The Research Council of Norway, Uni CIPR, Statoil, and ConocoPhillips provided financial support for this project from 2005 to 2008.

The research project presented in this dissertation is contractual and it came into an agreement between the author and the Faculty of Mathematics and Natural Sciences at the University of Bergen in November 2006. The original title of the project was “3D modelling of fault zones”. The intention of the project was to address issues relating to the implementation of structural field data into 3D geomodels, upscaling of fault rock properties, and fluid flow simulation. Dr. Jan Tveranger (Uni CIPR) has acted as principle supervisor for the work, while Professor William Helland-Hansen (Department of Earth Science, University of Bergen) has acted as co-supervisor.

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Many people had a hand in forming this dissertation one way or another, either by direct contribution, giving input into the research, or keeping me motivated to finish the work.

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I thank the co-authors of the papers in this dissertation: Alvar Braathen, Nestor Cardozo, Atle Rotevatn, Sylvie Schueller, Per Røe, and Øystein Pettersen. Our collaborations to combine many perspectives in single output papers have given me firm understandings on other scientific fields outside my core competence.

I would like to thank my colleagues and friends in the Fault Facies project, Uni CIPR, and UiB. I thank Arne Skauge for his input and encouragement to me to finish this dissertation. Henning Nøttveit is thanked for sharing his knowledge and ideas on reservoir modelling and upscaling, and particularly for constructive discussions that led to robust solutions for the problems appeared in my research. The work by Niclas Fredman has been an important foundation to my research. I thank Niclas for our discussions during my time at Uni CIPR. Although the number of the discussions is few, the one that we had after his trial lecture had provided me with an important breakthrough. David Moreno had been very helpful to me. His lessons on parallel machines and football tricks are much appreciated. Alif Be is thanked for helping me in handling reservoir simulation problems. I thank Anita Torabi, Eivind Bastesen, Walter Wheeler, Alexandra Seiler, Dmitriy Kolyukhin, Dongfang Qu, Abul Fahimuddin, and Shaaban Bakr for fruitful and entertaining discussions. Edin Alagic and Bartek Vik are thanked for making Uni CIPR, at least to me, more than just a research centre. Moreover, it would be an overstatement to say that without the assistances related to human resource management, IT, and PhD adminstration this work would had been straightforward. I thank Mona Wolff, Irene Husa, Kristin Miskov Nodland, and Caroline Ertsås Christie for their support on these matters during my time at Uni CIPR and UiB, allowing me to be effective during the work.

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Preface

This is a paper-based dissertation. The bulk of this dissertation consists of four scientific papers published in and for submission to relevant peer-reviewed international journals. As they represent separate contributions on related topics, there are some overlaps among the works presented by the papers. As required by regulations for PhD theses at the University of Bergen, the papers are preceded by an introduction to provide the motivation of the research, an overview of the relevant literature, the background and scientific justifications of the research, and detailed research goals.

Following the papers, the final chapter, Synthesis, features the main results and conclusions of the research. Possible future research paths based on the presented study are discussed together with the conclusions.

PAPERS AND AUTHORSHIP STATEMENT

Information and status of the four scientific papers forming the bulk of this dissertation are described in this subsection. I am the principal author of all papers and responsible for the bulk of the research, writing, and preparation of figures and tables. As there are several authors contributing to each paper, their contributions are also described in this subsection.

Paper 1, entitled "**The impact of fault envelope structures on fluid flow: A screening study using fault facies**", by Muhammad Fachri, Jan Tveranger, Nestor Cardozo, and Øystein Pettersen, is published in 2011 in the American Association of Petroleum Geologists (AAPG) Bulletin volume 95. Results from this study were presented as an oral presentation at the AAPG Annual Convention & Exhibition in April 2008 and as a poster presentation at the Geological Society London Conference – Fault Zones: Structure, Geomechanics and Fluid Flow in September 2008. The initiative for this research was taken by J. Tveranger, based on which I and J. Tveranger designed the screening study (experimental design). All sections of this paper were written by me, including the generation of the figures and tables, and I was responsible for the interpretation of the flow simulation results. J. Tveranger and N. Cardozo provided comprehensive editorial reviews and discussions to the earlier versions of the manuscript. N. Cardozo also strengthened the manuscript regarding strain. Ø. Pettersen ensured accurate reservoir simulation setup and interpretation.

Paper 2, entitled "**Sensitivity of fluid flow to deformation-band damage zone heterogeneity: A study using fault facies and truncated Gaussian simulation**", by Muhammad Fachri, Jan Tveranger, Alvar Braathen, and Sylvie Schueller, is published in 2013 in the Journal of Structural Geology volume 52. The initiative for this research was taken by me. All sections of this paper were written by me, including the generation of the figures and tables. I was responsible for the design of the sensitivity analysis and the interpretation of the flow simulation results. J. Tveranger provided comprehensive editorial reviews and discussions to the earlier versions of the manuscript, especially the first version, which significantly improved the final manuscript. A. Braathen and S. Schueller strengthened the manuscript regarding fault zone description and damage zone statistics, respectively.

Paper 3, entitled "**Fluid flow in relay zones revisited: Towards an improved representation of small-scale structural heterogeneities in flow models**", by Muhammad Fachri, Atle Rotevatn, and Jan Tveranger, is published in 2013 in the Marine and Petroleum Geology volume 46. The results of this research were presented as a poster presentation at the 3rd International Conference on Fault and Top Seals, European Association of Geoscientists and Engineers (EAGE), in October 2012. The initiative for this study was taken by A. Rotevatn who also wrote the first two sections of the paper. The remaining sections of the paper were written by me. All authors were responsible for the design of the flow simulation setup, but I was responsible for the interpretation of the flow simulation results. J. Tveranger and A. Rotevatn provided comprehensive editorial reviews and discussions to the earlier versions of the manuscript.

Paper 4, entitled "**Volumetric faults in field-sized reservoir simulation models – A first case study**", by Muhammad Fachri, Jan Tveranger, Alvar Braathen, and Per Røe, is a manuscript to be submitted to a peer-reviewed international journal. The results of this research were presented as oral presentations at the Society of Petroleum Engineers (SPE) Workshop in Arctic Norway in March 2013 and at the 75th EAGE Conference & Exhibition in June 2013. The initiative for this research was taken by me. All sections of this paper were written by me, including the generation of the figures and tables. I was responsible for the design of the flow simulation setup and the interpretation of the flow simulation results. J. Tveranger provided comprehensive editorial reviews and discussions to the manuscript. A. Braathen and P. Røe strengthened the manuscript regarding fault zone description and 3D gridding, respectively.

Abstract

Fault zones in siliciclastic rocks form distinct volumetric entities and typically exhibit great structural complexity. While it has been considered that the main impact of fault zones to fluid flow is to baffle or block the flow, observations suggest that fault zones can (i) act as dual baffle-conduit conduit systems, (ii) host long-distance flow in both along-dip and along-strike directions, (iii) act as pure conduit systems exhibiting higher flow rates than the surrounding host rock. However, the complex flow behaviours inside fault zones cannot be readily captured or forecast in traditional reservoir models, as faults are conventionally implemented as 2D modelling objects. A comprehensive and integrated approach has been adapted for providing a new feasible method, i.e. "fault facies modelling", for volumetric fault representation in industrial reservoir models. To date, research on fault facies modelling is in many ways still in its early stages of development, with emphasis being placed on establishing frameworks for fault zone characterization suitable for modelling purposes and modelling algorithms for implementing them. The principal aims of the present study are to:

1. Improve the key aspects of fault facies modelling, i.e. the use of outcrop-based facies maps, 3D gridding, property modelling, upscaling, and application on field-scale models.
2. Advance current knowledge on the impact of fault zone structure on reservoir fluid flow.

To increase the capability of fault facies modelling with regard to reproducing outcrop observations, a new way of utilizing outcrop observations is introduced. Prior to modelling, outcrop-based fault facies maps are created by discretising outcrop observations using grid resolutions that are deemed to be high enough to resolve fault facies units depending on flow scale considered. The maps form conceptual templates for (i) selecting the most suitable stochastic modelling techniques and workflows, (ii) establishing representative geostatistical properties of fault facies and fault facies associations, (iii) assessing the quality of the resulting fault facies models.

With respect to fault zone property (facies and petrophysical) modelling, the present study focuses on the applications of fault zone displacement functions and stochastic modelling methods. Automated scripts are employed to define fault zone displacement functions to allow more flexibility in the application of the functions. This, in turn, makes it easier to handle outcrop-based statistics such as (i) damage zone width as a function of fault throw, (ii) fault core thickness as a function of fault throw (iii) the fractions of total fault throw accommodated by fault core and damage zones, and (iv) the types of displacement function (quadratic, cubic, and quartic) in fault core and damage zones.

Truncated Gaussian simulation (TGS) is used for modelling damage zone features. This has not been tried before. In different fault system configurations, i.e.: (i) single isolated faults, (ii) single-tip interacting faults (branching of two fault segments), and (iii) double-tip interacting faults forming a relay ramp, the applications of TGS are constrained by conceptual and outcrop-based conditioning parameters. Comparison between the resulting models and the discretized damage zone observations show that important observed characteristics such as variations of fault facies thickness, -length, -adjacency, and compartment geometries are reproduced by the models.

For fault core modelling, a hierarchical approach employing object-based simulation technique is demonstrated. To reproduce a complex fault core lens configuration where lenses are stacked one to another, lensoid objects are populated by setting very high volumetric proportion of the simulated objects (hence, very low background volumetric proportion). Subsequently, the lens models are refined non-proportionally (for creating thin and thick cells) and slip zones are implemented in thin cells separating two different lensoid objects. Comparison between the resulting models and the discretized fault core observation show that the models reproduce important fault core characteristics such as (i) lenses with varied thickness and aspect ratio and (ii) lens size distribution that shows a higher number of smaller lenses, and (iii) the distribution of slip zones, i.e. flow baffles/conduits, that

is closely related to the lenses distribution. Moreover, combined with flow-based upscaling, the hierarchical approach makes it possible for employing reliable and accurate fault facies modelling on a full-field scale within the framework of existing reservoir modelling tools.

Work performed on flow simulation and sensitivity testing and analysis have provided new insights into the impact of different fault zone parameters on reservoir fluid flow. When both fault core and surrounding damage zones are considered, fault facies modelling parameters can be ranked according to their impact on reservoir responses in the following descending order: (i) fault core thickness, (ii) the type of displacement function, (iii) sedimentary facies configuration, (iv) fault core throw percentage, (v) fault system configuration, (vi) maximum damage zone width. When considering the damage zone separately, the impact of fault facies modelling factors can be ranked in descending order as: (i) fault facies volumetric proportion, (ii) deformation band frequency, (iii) damage zone width, (iv) deformation band permeability, and (v) fault facies cluster extent.

Flow simulation study performed on outcrop-based relay zone models corroborates conclusions from earlier studies that the main factor controlling fluid flow in relay zones is deformation band permeability. Observations on variations in shape and migration velocities of fluid fronts in the relay zone show that, within k_{hr}/k_{db} range of 10^1 to 10^5 (where k_{hr} and k_{db} are host rock and deformation band permeability, respectively), increasing k_{hr}/k_{db} causes increased fluid flow complexity as indicated by amplified deviation from piston-like fluid displacement. High deformation band permeability allows injected water to saturate the entire oil column with ease and hence relay zones with high permeability bands provide good vertical sweep efficiency. For lateral sweep efficiency, however, relay zones with medium deformation band permeability show better performance due to enhanced flow tortuosity in the presence of pervasive but weak flow baffles.

Field-scale flow simulations indicate that fault cores with membrane slip zone clusters act as dual baffle-conduit systems. Sweep efficiency in reservoirs with baffle-conduit fault cores is closely related to injector-producer configuration. Baffle-conduit fault cores subparallel to injector-producer pairs focus injected fluids, hence decreasing sweep efficiency. Baffle-conduit fault cores perpendicular to injector-producer pairs partition and distribute the injected fluids and therefore increase overall sweep efficiency. Reservoirs with baffle-conduit fault cores exhibit two behaviours: (i) water breakthrough occurrence, time, and sequence are not sensitive to the choice of injection-production scheme and (ii) sweep efficiency decreases when field production rate is lowered. Fault cores with conduit slip zones, however, act as thief pathways. Sweep efficiency in reservoirs with conduit fault cores is less dependent on injector-producer configuration. Two distinct behaviours of reservoirs with conduit fault cores are: (i) water breakthrough occurrence, time, and sequence are highly sensitive to the choice of injection-production scheme and (ii) sweep efficiency increases when field production rate is lowered. These simulation results show that the improved realism added by incorporating volumetrically expressed fault cores substantially influences forecasts of field behaviour, and consequently should be considered during oil/gas production planning.

List of papers

Paper 1	Fachri, M., Tveranger, J., Cardozo, N., Pettersen, Ø., 2011. The impact of fault envelope structures on fluid flow: A screening study using fault facies. AAPG Bulletin 95(4), 619-648.
Paper 2	Fachri, M., Tveranger, J., Braathen, A., Schueller, S., 2013. Sensitivity of fluid flow to deformation-band damage zone heterogeneity: A study using fault facies and truncated Gaussian simulation. Journal of Structural Geology 52, 60-79.
Paper 3	Fachri, M., Rotevatn, A., Tveranger, J., 2013. Fluid flow in relay zones revisited: Towards an improved representation of small-scale structural heterogeneities in flow models. Marine and Petroleum Geology 46, 144-164.
Paper 4	Fachri, M., Tveranger, J., Braathen, A., Røe, P. Volumetric faults in field-sized reservoir simulation models – A first case study. To be submitted.

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Introduction

The general aim of the present study has been to address and improve the key aspects of a new modelling method, i.e. fault facies modelling, for integrating explicitly rendered faults zones in industrial reservoir simulators. In contrast to existing conventional fault modelling techniques (see review in Manzocchi et al., 2008), the fault facies modelling allows fault zones and their internal structure to be handled as explicit volumetric elements in geocellular reservoir models (Tveranger et al., 2005; Syversveen et al., 2006; Fredman, 2007; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007; Braathen et al., 2009). The potential benefits of using this approach are obvious: detailed structural information currently handled implicitly by using proxy parameters can be rendered explicitly, thus producing fault models which in appearance more closely resemble faults as seen in nature. This facilitates detailed studies of the complexities of flow behaviour in and around fault zones that commonly presents a significant source of uncertainty in reservoir simulation models.

However, the development of the method is still in its early stages. Practical application of the fault facies concept for industrial purposes requires first of all a sound understanding of how fault zone models can best be generated using realistic input data. A key question to ask is if it is possible to capture general and important characteristics of fault zone structures as seen in nature and how different modelling parameters can be used for this purpose.

Another important issue is how fluid flow in fault facies models responds to changes in input parameters. Only a very few systematic studies have so far addressed this topic (Fredman, 2007; Fredman et al., 2007). Improving our knowledge of the interaction between input and response serves several purposes. First of all it gives an insight into fluid flow in fault zones in general. Secondly it helps to rank input parameters according to the impact they have on fluid flow. This in turn will help user of the fault facies method to focus on getting the input parameters that matter right.

A major concern with respect to employing the method for industrial purposes is the apparent need to add high-resolution fault envelope grids to kilometre-scale full-field reservoir models (Rivenæs and Dart, 2002; Manzocchi et al., 2008). Adding a substantial number of cells to a model comes at a high cost in terms of CPU time, which can render models unmanageable. Commonly this issue is handled by upscaling high resolution models into coarser grids which reduces the number of cells and replaces detailed heterogeneities distributed over several cells in the original model with averaged values in larger cells occupying the same volume. Although being a well-established technique for handling high-resolution sedimentary facies models, the extent of fine-scale 3D heterogeneity in fault zones offer additional challenges to upscaling. Initial tests (Soleng et al., 2007) suggest that fluid flow patterns observed in high-resolution fault facies models are reproduced during upscaling. A further investigation is required to demonstrate the modelling and upscaling of fault facies using a field-wide reservoir model with emphasis on the reliability of the resulting fault zone model and flow simulation. Hence, another key question to ask is if it is possible to model and upscale fault facies using a field-wide reservoir model by maintaining the reliability of the resulting fault zone model and flow simulation.

The present thesis addresses the issues outlined above and investigates reservoir modelling aspects such as the utilization of outcrop-based facies map, 3D gridding, property modelling, upscaling, full field application, fluid flow simulation, and sensitivity analysis. This introduction section provides an overview of the relevant literature covering the modelling aspects, the limitations of the conventional fault modelling approaches, the state-of-the-art of reservoir modelling with volumetric faults, and the progress in fault facies modelling research. Closing this introduction section, the detailed objectives of the present study are outlined.

FAULT ZONES IN SILICICLASTIC ROCKS

In porous siliciclastic rocks, a fault zone evolves from the nucleation and growth of a deformation band, the development of a deformation band cluster which can be preceded or accompanied by the nucleation and growth of short discontinuous slip surfaces, and the formation of continuous slip surfaces through the deformation band cluster (Aydin and Johnson, 1978, see their Figure 7; Shipton and Cowie, 2001, see their Figure 16; Rotevatn et al., 2008). Slip surface formation is accompanied by the development of fault rocks along the surface's walls (Antonellini and Aydin, 1994; Foxford et al., 1998; Shipton and Cowie, 2001, Braathen et al., 2009, Tueckmantel et al., 2010). The combination of slip surface pair and associated fault rocks is termed slip zone (Foxford et al., 1998). When offsetting shale layers, slip surfaces are typically accompanied by the formation of shale smears (Gibson, 1994; Yielding et al., 1997; Aydin and Eyal, 2002; Davatzes and Aydin, 2005; Færseth, 2006).

Further evolution of a fault zone involves an increasing displacement accumulation within a region called fault core (Caine et al., 1996; Berg and Skar, 2005, see their Figures 2 and 3; Davatzes and Aydin, 2005; Flodin et al., 2005, see their Figure 2; Johansen and Fossen, 2008; Braathen et al., 2009, see their Figure 2) accommodated by the propagation of slip surfaces and the formation of slip zones (Shipton and Cowie, 2001; Shipton et al., 2005), the linkage of slip zones forming several orders of lenses (Cruikshank et al., 1991; Childs et al. 1996; Walsh et al., 1998; Berg and Skar, 2005, who use 'horses' terminology instead of lenses; Braathen et al., 2009; Childs et al., 2009), the formation of pockets of thick fault rocks (Shipton et al., 2005; Braathen et al., 2009), and the thinning and breaching of shale smears by growing slip zones (Gibson, 1994; Aydin and Eyal, 2002; Davatzes and Aydin, 2005). Slip zones accommodate most of fault zone displacement and there are typically one or two main slip zones accomodating significantly larger displacement than the surrounding slip zones that are oriented parallel to sub-parallel to the main slip zones and altogether commonly show an anastomosing pattern (Childs et al., 1996; Walsh et al., 1998; Shipton and Cowie, 2001; Berg and Skar, 2005; Braathen et al., 2009). Lenses are elongate rock bodies exhibiting various degrees of strain, ranging from undeformed to highly deformed, but commonly can still be recognized as host rock and, when present, they are the volumetric dominant component of a fault core. (Foxford et al., 1998; Braathen et al., 2009). Fault rock pockets can be sandstone cataclasites, breccia sheets, shale smears, and sand and shale gouge that form separate distinct rock bodies from fault rocks that comprise slip zones. They form continuous/discontinuous lensoid to tabular rock bodies oriented parallel and adjacent to slip zones and are commonly developed in fault core regions where kinematic incompatibilities take place (Foxford et al., 1998; Walsh et al., 1998; Shipton et al., 2005; Braathen et al., 2009).

The thickness of a fault core varies spatially. A fault core is very thin in regions where a single slip zone accommodates most of the fault zone displacement and, in contrast, very thick in regions where lenses are entrained in the fault core (Childs et al., 1996; Foxford et al., 1998; Shipton and Cowie, 2001; Braathen et al., 2009). Fault core thickness (T), as observed in outcrops, shows positive correlations with fault displacement (D) (Hull, 1988; Marrett and Allmendinger, 1990; Knott, 1994; Little, 1995; Caine et al., 1996; Childs et al., 1996; Knott et al., 1996; Foxford et al., 1998; Sperrevik et al., 2002; Childs et al., 2009). For faults with a displacement of 10-100 m, the outcrop data presented in these studies show persistent data points around D:T ratio = 0.5, suggesting that subsurface seismic-scale faults with thick fault cores comparable to fault displacement are not uncommon. Therefore, in faulted subsurface siliciclastic reservoirs, fault cores can have discernible volumes that might need to be represented accurately in reservoir models.

A fault core is surrounded at the footwall, hanging wall, and fault tip sides by less deformed damage zones which grow simultaneously with the fault core development by the nucleation, growth, and linkage of deformation bands and short discontinuous slip surfaces (Knott et al., 1996; Beach et al., 1999; Fossen and Hesthammer, 2000, see their Figure 7; Shipton and Cowie, 2001, see their Figure 16; Shipton and Cowie, 2003, see their Figure 4; Berg and Skar, 2005, see their Figures 2 and 3; Fossen et al., 2007, their Figure 7; Johansen and Fossen, 2008; Schueller et al., 2013). Deformation bands are the main structural component of damage zones in porous rocks. They can occur as a single millimetre-thick tabular deformation zone or as clusters, and accommodate millimetres to centimetres shear offset (Davatzes and Aydin, 2003; Fossen at al., 2007). Deformation bands are typically oriented parallel to sub-parallel to main slip zones and exhibit synthetic and antithetic orientations, but oblique orientations can occur locally (Shipton and Cowie, 2001; Berg and Skar, 2005). In sandstone-shale sequences, damage zone deformation bands and, especially, deformation band zones in sandstone layers could transform into slip surfaces (e.g. Johansen and Fossen, 2008) or mesoscopically dissipate by ductile deformation in shale sequence (Davatzes and Aydin, 2005; Johansen and Fossen, 2008). Deformation band (in sandstone) and slip surface (in shale) densities generally increases toward a fault core (Beach et al., 1999; Berg and Skar, 2005; Johansen and Fossen, 2008; Schueller et al., 2013). Slip zones in sandstone damage zones have relatively minor extension and offset compared to those in fault cores. They are typically associated with deformation band clusters (Aydin and Johnson, 1978; Antonellini and Aydin, 1994; 1995), but can also occur within isolated bands (Rotevatn et al., 2008).

Previous field studies conclude that damage zones grow with increasing fault displacement based on positive correlations between fault displacement (D) and damage zone width (W, footwall and hanging wall summed) (Knott et al., 1996; Beach et al., 1999; Fossen and Hesthammer, 2000; Shipton and Cowie, 2001; Schueller et al., 2013), though the data sets show very diverse correlation coefficients. In the outcrop data presented in Knott et al. (1996) and Shipton and Cowie (2001) and the subsurface data presented in Fossen and Hesthammer (2000), data points with D:W ratio in the range of 0.5-1 are common, with increasing ratio as fault displacement increases. This indicates that it is very common for subsurface seismic-scale faults with displacements of 10-100 m to have damage zones width of 20-100 m. These widths are comparable to the typical lateral dimensions of reservoir model grid cells.

Two isolated fault zones can grow, interact, link, and amalgamate to become one longer continuous fault zone (Peacock and Sanderson, 1991; 1994; Trudgill and Cartwright, 1994; Cartwright et al., 1995; Imber et al., 2004; Davatzes et al., 2005; Fossen et al., 2005; Johansen et al., 2005; Rotevatn et al., 2007). Compared to the damage zones of isolated fault zones, damage zones associated with interaction and linking of two fault zones indicate widening of the zones, hence increasing damage zone volume in reservoir models, and increased structural density and orientation variation (Davatzes et al., 2005, see their Figure 5; Fossen et al., 2005, see their Figure 11; Johansen et al., 2005, Rotevatn et al., 2007). Moreover, these damage zones and adjacent fault cores are more susceptible to younger tectonic deformation and hence more favourable places for structural reactivation (e.g. by changing the slip directions of pre-existing slip surfaces) and overprinting (e.g. by extensional joint formations along pre-existing deformation bands and slip surfaces) (Davatzes and Aydin, 2003; Davatzes et al., 2005).

FAULT ZONE IMPACTS ON SUBSURFACE SILICICLASTIC RESERVOIRS AND FLUID FLOW

In the simplest case, faulting affects subsurface siliciclastic rock by splitting it into two or more blocks and translating these blocks relative to each other. Over geological time, faulting can also be accompanied by rotation and local changes in the shape and volume of the fault blocks (e.g. Fossen and Hesthammer, 1998), intermittent or continuous hydrocarbon migrations through the fault zones (Hooper, 1991; Gibson, 1994; Karlsen et al, 2004), development of folds, reservoir/non reservoir juxtaposition, and the generation of low permeability fault rocks to form hydrocarbon structural traps (e.g. Holland et al., 1990), and dynamic distribution of hydrocarbons across faulted compartments (Watts, 1987; Fisher et al., 2001).

Over time periods relevant to hydrocarbon production activities, fault zones can compartmentalize siliciclastic reservoirs into regions with different fluid distribution (Taylor and Dietvorst, 2007;

Watters et al., 1999), act as baffles/barriers to intra-reservoir fluid flow to reduce lateral fluid flow communication (e.g. Lia et al., 1997; Jolley et al., 2007), form capillary traps to hydrocarbon as non-wetting phase in waterflooding recovery (Ringrose et al., 1993; Manzocchi et al., 1998; Manocchi et al., 2002), and act as hybrid baffle-conduit for fluid flow to increase both lateral and vertical fluid flow communications (e.g. Haney et al., 2005). However, because most deformation bands and slip zones have been observed as zones of reduced porosity and permeability (Antonellini and Aydin, 1994; Fisher and Knipe, 2001; Flodin et al., 2005; Fossen and Bale, 2007; Tueckmantel et al., 2010), the prevailing view of a fault in siliciclastic rocks in fluid flow simulation studies using conventional reservoir model is essentially of a 2D baffle/barrier (Walsh et al., 1998; Manzocchi et al., 1999; Manzocchi et al., 2008), whereas the roles of high-permeability fault zones as fluid flow conduits are merely mentioned and have never been implemented (e.g. Manzocchi et al., 2010). At larger flow scale (e.g. reservoir scale), in which single-phase flow properties (i.e. absolute permeability and thickness) of fault zone structural elements (e.g. deformation bands and slip zones) are more important, this is at odds with abundant currently-occurring, direct and indirect evidence of the role fault zones play as combined along-fault conduits and across-fault baffles for fluid flow in siliciclastic reservoirs described below.

Fault zones in very shallow siliciclastic reservoirs under burial process, such as the Champion East field, offshore Brunei Darussalam (van Kessel, 2002) where the reservoir is located as shallow as 200 meters, are affected by very small differential stress, whereas fault zones in ultra-shallow siliciclastic reservoirs experiencing uplift and overburden erosion, such as the Duri field in Indonesia (Waite et al., 1997) where the reservoir depths can be as shallow as 61 meters, are affected by tension stress state. These depths and types of state-of-stress promote the formation of conduit fault-related structural features (Engelder, 1993; Fossen et al., 2007) and therefore the corresponding fault zones most probably act as combined baffle-conduit systems to subsurface fluid flow as can be observed at Casper aquifer, Wyoming, USA (Huntoon and Lundy, 1979), the Cidurian fault, Banten, Indonesia (Fachri and Harsolumakso, 2003) the Roer Valley rift system, Central Europe (Bense et al., 2003a; Bense et al., 2003b; Bense and Van Balen, 2004; Bense and Kooi, 2004), the Sandia fault in the Albuquerque basin, USA (Grant, 1982; Haneberg, 1995), the Tensleep sandstone in the Big Horn Basin, USA (Bredehoeft et al., 1992) the Baton Rouge fault, Louisiana, USA (Stoessel and Prochaska, 2005; Bense and Person, 2006), and the Causeway and Goose Point faults, Louisiana, USA (Stoessel and Prochaska, 2005). Similarly, fault zones in deep siliciclastic reservoirs experiencing uplift (e.g. Snøhvit field in the Barents Sea, Wennberg et al., 2008), tectonic inversion (e.g. the West Sole field in the southern North Sea, Barr, 2007), and critical stress state in fault zone regions (e.g. the CS field in Timor gap, Paul et al., 2009) might also act as dual baffle-conduit systems to fluid flow since the geological processes promote the formation of fault-related open fractures. Moreover, consistent observations and measurements of present-day reservoir fluid flow in the South Eugene Island 330 field in the Gulf of Mexico (Anderson et al., 1994; Roberts et al., 1996; Losh, 1998; Losh et al., 1999; Revil and Cathles, 2002; Haney et al., 2005) provide an irrefutable proof of the role of fault zones as hybrid baffle-conduit system to fluid flow. These engineering and seismic imaging studies have been able to periodically map the ascent of large pulses of overpressured fluid that move at 100 meters per year along a growth fault zone (Haney et al., 2005).

In damage zones, the abovementioned conduit characteristics of fault zones can be provided by high-permeability through-going dilatant disaggregation bands (Fisher and Knipe, 2001; Bense et al., 2003b) and open or critically-stressed slip surfaces (Roberts et al., 1996; Losh et al., 1999; Shipton et al., 2002, Paul et al., 2009). Damage zone slip surfaces reduce the sealing capacities of fluid flow baffle/barriers (e.g. shale and diagenetic carbonate layers) (e.g. Johansen and Fossen, 2008) and therefore increase the connectivity among otherwise vertically and laterally isolated reservoir units. Previous field studies focusing on the relationships between structural complexity and paleo fluid flow suggest that these connectivity enhancements are more pronounced in damage zones associated with interaction and linking of two fault zones (e.g. Eichhubl et al., 2009). In fault cores, slip zones are longer and more continuous and hence, when they are able to host focused flow, are significantly more effective components contributing to the fault zone conduit characteristics (e.g. Shipton et al., 2002). Moreover, even if fault core slip zones do not effectively accommodate along-fault fluid flow, amalgamated host rock lenses in thick fault cores can host vast long-distance along-fault fluid flow (e.g. Berg and Øian, 2007).

At smaller flow scale (e.g. pore scale), due to clustered strain localizations, fault cores and damage zones are highly heterogeneous geological features characterized by contrasting porosity and permeability in close proximity (e.g. Antonellini and Aydin, 1994; Shipton et al., 2002; Flodin et al., 2005). The resulting short-distance differences in local capillary pressures, under several typical conditions in hydrocarbon production such as recoveries through aquifer support and gas expansion (Al-Busafi et al., 2005; Ziljstra et al., 2007) and recovery through low-rate artificial water injection (e.g. Ringrose et al., 1993), cause capillary forces to be more dominant than viscous forces in controlling fluid flow mechanism (Ringrose et al., 1993; Manzocchi et al., 1998; Manocchi et al., 2002). In reservoirs with fault zones exhibiting permeability-reducing structures and hydrocarbon as non-wetting phase this promotes the trapping and bypassing of hydrocarbon behind the structures and, in turn, decreases small-scale reservoir performance (Ringrose et al., 1993; Manzocchi et al., 1998). If small-scale structures are considered cumulatively, these effects remain at large-scale reservoir performance (Ringrose et al., 1993; Rivenæs and Dart, 2002). Therefore, multi-phase flow properties (i.e. relative permeability and capillary pressure functions) of fault zone structural elements should be represented accurately in reservoir simulation models. How these small-scale capillary effects affect reservoir performance at larger scale depends on the geometry, relative positions, and relative proportions of the small scale geological features (Ringrose et al., 1993; Manzocchi et al., 1998). For example, when capillary forces are dominant in a damage zone with deformation band permeability two-order of magnitude lower than host rock permeability, Manzocchi et al. (1998) shows that varied deformation band connectivity, which in turn is controlled by deformation band length, orientation, and clustering, yield differences in oil recovery of more than 10%. These differences can be expected to be significantly larger if deformation band permeability are lower and slip zones are present.

The above description shows that: (i) whilst the roles of fault zones as fluid flow baffles/barriers are important, fault zones roles as dual baffle-conduit systems to fluid flow should not be ruled out in reservoir simulation work, (ii) along-fault fluid flow might take place in large 3D volume covering not only fault core regions, but also the flanking complex damage zone regions, (iii) fault cores can accommodate vast long-distance fluid flow in both along-dip and along-strike directions, and (iv) geometry, relative positions and relative proportions of small scale fault zone structural elements influence large scale fluid flow especially when more than one fluid phase are involved, hence their accurate implementations in reservoir models are imperative.

FAULT ZONES IN CONVENTIONAL RESERVOIR MODELS

Fault objects as used in conventional reservoir models are typically derived from the interpretation of vertical sections of 2D and 3D seismic data in which fault positions are mapped as sticks or planes along which displacement of the stratigraphy is evident. These data are subsequently employed for modelling the shape of fault surfaces along which 3D modelling grid is offset, mimicking fault displacement. Within this framework, fault juxtaposition (Allan, 1989; Knipe, 1997) and fault rock properties (using proxy-properties such as shale gouge ratio; Yielding et al., 1997) are used to estimate fault sealing capacity. These proxy-properties and correlation between fault throw and fault core thickness are then used to estimate fault core permeability and thickness, respectively, which in turn are used to calculate single-phase flow properties of fault rocks expressed as fault transmissibility multipliers (FTM) between juxtaposed cells on either side of the fault planes in reservoir simulation models (Manzocchi et al., 1999, see their Figure 1).

This 2D FTM method was further developed to capture the effects of complex 3D fault zones on fluid flow by using geometrical upscaling which principally works by (i) creating user-defined higher-resolution 3D fault zone models (fault zones with e.g. normal drag zones, damage zones, paired slip surfaces, fault lens, and relay ramp) which subsequently are used for (ii) defining connections and across-fault transmissibilities between physically-connected faulted cells and between faulted cells that are not physically neighbours in the coarse reservoir simulation models with planar faults (Manzocchi et al., 2008, see their Figure 10; Manzocchi et al., 2010). This procedure typically increases the number of fault connections. For example, in a fault segment of a reservoir model with a thickness slightly smaller than the fault throw, there are no physical fault connections. However, if the fault zone is seen as consisting of a large lens body bordered by two slip zones each accommodating half of the total fault displacement, a cell in the upper part of the footwall block can have connections to the cells in the lens body which in turn also have connections to the cells in the lower part of the hanging wall block. Geometrical upscaling maps and collects these connections and calculates the corresponding across-fault transmissibilities in the reservoir simulation model with planar faults using the abovementioned fault core permeability and thickness predictors. In addition, the flow properties of the lens and surrounding damage zone cells can be modified to represent higher degrees of deformation, i.e. permeability decrease, and their effects are added by decreasing the transmissibility multiplier of the corresponding fault connections.

The above explanation shows that geometrical upscaling is capable of generating faults that can host short, limited, and temporary along-dip flow in reservoir simulation models. However, because (i) the faults and structural elements in the reservoir simulation models and 3D fault zone models are not volumetric objects and (ii) the transformation from 3D fine-scale fault zone models to 2D fault planes only take into account connections in fault-perpendicular direction, long and large along-fault flow cannot be modelled, and fault zones acting purely as conduits, i.e. those with higher permeability than the surrounding host rocks, cannot be represented in the reservoir simulation models. These make geometrical upscaling incapable of handling faults that act as large-scale dual baffle-conduit system to fluid flow, which are a quite common natural phenomena in faulted siliciclastic reservoirs. Similarly, since the effects of damage zones are captured by reducing transmissibility multipliers of the nearby fault connections, the resulting reservoir simulation models do not render accurate fluid flow calculations in the damage zones (e.g. due to the omission of flow tortuosity and increased gravitational fluid segregation due to small-scale structures) which can be spatially extensive, hence occupying several cells in both footwall and hanging wall sides, especially in fault intersection regions.

Within the 2D FTM constructions in reservoir simulation models, two-phase flow properties of fault rocks are included using directional, irreversible pseudo-relative permeability functions (Manzocchi et al., 2002). These functions are created by performing fluid flow simulation in fine-scale models using flow rates comparable to those expected to take place in the reservoir. In these fine-scale models, capillary pressure and relative permeability curves are assigned to both fault and undeformed rocks. The pseudo-relative permeability functions are obtained by scaling up the effects of the two-phase flow properties of fault rocks, as observed from the simulation results in the fine-scale models, into the upstream faulted cells in the reservoir simulation models (Manzocchi et al., 2002). This method is considered as the most pragmatic approach in representing two-phase flow properties of fault rocks as it circumvents the use of discrete grid cells for fault zone representation (Manzocchi et al., 2008; Manzocchi et al., 2010). However, with respect to simulation-model representation of two-phase flow properties of fault rocks, not employing volumetric fault zones comes at the price; it does not allow: (i) the incorporation of much wider range of single-phase flow properties of fault rocks during the two-phase upscaling (e.g. anisotropic conduit fault zones; Evans et al., 1997; Faulkner and Rutter, 1998), (ii) full accuracy in capturing the effect of fault rock two-phase flow properties (e.g. Manzocchi et al., 1998; Rivenæs and Dart, 2002) and heterogeneous fault zone structures (Ringrose et al., 1993; Berg and Øian, 2007), and (iii) direct adaptation of the multi-scale modelling methods developed for accurate scaling up of multi-phase flow properties of undeformed sedimentary rocks (e.g. Corbett et al., 1992, see their Figure 13, Ringrose and Corbett, 1994; Pickup et al., 2000).

VOLUMETRIC FAULT ZONE MODELLING

Previous subsection shows that the fundamental limitations of the FTM method with respect to capturing the impact of fault zones on fluid flow lie in the exclusion of volumetric fault representation in reservoir simulation models. A number of reservoir simulation studies have investigated fluid flow behaviours in fault zones using volumetric representation and the incorporation of structural and petrophysical details of structural elements occurring in the fault zones. Some of these studies are responses to the limitations imposed by the FTM method, focusing on particular aspects such as multi-phase flow properties (Rivenæs and Dart, 2002; Al-Busafi et al., 2005; Berg and Øian, 2007) and fault zone architecture (Flodin et al., 2001; Harris et al., 2003; Odling et al., 2004; Berg and Øian, 2007; Rotevatn et al., 2009). These studies demonstrate that the combination of volumetric representation of fault zones and the 3D description of fault zone elements yields a more flexible and accurate rendering of fault zone flow properties than those that can be provided by the FTM method, such as facilitating the incorporation of high permeability conduit slip surfaces and joints (Flodin et al., 2001; Paul et al., 2009), the inclusion of fault zone structural elements of different length scales in a hierarchical fashion (Berg and Øian, 2007), the representation of different orientations of deformation band populations to capture volumetric bulk permeability, flow tortuosity, and fluid gravitational segregation in damage zones and relay ramps (Harris et al., 2003; Odling et al., 2004; Rotevatn et al., 2009), and the accurate calculation of large-scale along-strike and along-dip fluid front movement within fault zones (Flodin et al., 2001; Berg and Øian, 2007).

However, these volumetric fault studies only emphasize particular aspects. The studies using synthetic models (Al-Busafi et al., 2005; Berg and Øian, 2007), outcrop-based models (Bredehoeft et al., 1992; Flodin et al., 2001; Rotevatn et al., 2009), and real-field models (Haneberg, 1995; Roberts et al., 1996; Rivenæs and Dart, 2002; Paul et al., 2009) focus on concept evaluation using deterministic approaches and hence do not exploit the possibilities offered by stochastic modelling techniques for evaluating systems with substantial attached uncertainties such as subsurface faulted petroleum reservoirs. Some works employ stochastic modelling techniques to represent complete architectural elements of fault zones (i.e. fault core and damage zones) but use highly simplified petrophysical properties since the method for capturing the internal fault zone architecture was not developed simultaneously (O'Brien et al., 1996) whereas the studies that capture detailed structures and petrophysical properties in fault core and damage zones do not use typical conditioning parameters such as fault throw (López and Smith, 1996; Caine and Forster, 1999; Harris et al., 2003; Odling et al., 2004) which are important for predicting spatial variations of subsurface fault zone characteristics. The studies that use structured grids provided by standard industrial modelling tools implement volumetric fault zones only for damage zones (Rivenæs and Dart, 2002; Harris et al., 2003; Odling et al., 2004; Paul et al., 2009; Rotevatn et al., 2009) whereas those that implement fault core cells (e.g. Berg and Øian, 2007) generate the fault envelope model using a manual procedure.

Furthermore, a common feature of these studies is the use of high-resolution small-size fault zone models which, with the limitations of today's computing power, need to be scaled up for large-scale fluid flow calculation. A number of studies have demonstrated the feasibility of upscaling procedures to estimate fault zone bulk permeabilities by investigating the use of flow-based averaging techniques (Jourde et al., 2002), the combination of flow-based averaging techniques and power averaging for more efficient computation (Flodin et al., 2001), the impact of several different local boundary conditions on flow-based averaging results (Flodin et al., 2004), and, in fault zones with long, through-going, high-permeability slip surfaces, the use of partial upscaling technique where the upscaling is performed without the slip surfaces but the high-permeability structures are reintroduced in the resulting coarsened models (Flodin et al., 2004). The fine-scale geological and permeability models used in these studies, however, are generated by directly implementing field observations into reservoir models. Thus, whilst these studies enhance our collective understanding on fault zone bulk permeability and fluid flow, the missing aspects related to 3D gridding, stochastic modelling, and conditioning parameters constrain the applications of their methods in industrial reservoir modelling and simulation workflows.

FAULT FACIES MODELLING

Considering that a number of modelling aspects should be taken into account simultaneously, as described in previous subsection, a solution for the problems of volumetric implementation of fault zones in industrial reservoir models needs to be comprehensive (Tveranger et al., 2005): (i) tools and functionalities for generating fault envelope grids should be added or adapted to industrial reservoir modelling software, (ii) outcrop studies of fault zone architectures and their petrophysical properties should be used as the basis for the solution, (iii) property modelling methods for incorporating these outcrop studies into 3D reservoir models should be provided, in which the most straightforward way is to use the geostatistical techniques typically available in industrial reservoir modelling software in combination with the use of conditioning parameters which are specific for fault envelop structures, and (iv) to ensure its practical usefulness, the improved method should be easily fitted into typical industrial reservoir modelling workflows.

A concerted effort under the Fault Facies project for providing a feasible method for volumetric fault representation in industrial reservoir models has been in progress for some time (Tveranger et al., 2005; Syversveen et al., 2006; Fredman, 2007; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007; Cardozo et al., 2008; Braathen et al., 2009). Unique to this method is the adaptation of the facies concept (Middleton, 1978; Reading, 1986) into the realm of faulted rock bodies (Braathen et al., 2009). This adaptation is chosen to exploit the advantages of facies approach for flexible subdivision of fault rock bodies into smaller distinct elements at any scale, hence enabling efficient systematic description and quantification, pattern recognition, and hierarchical modelling of subsurface fault zone properties (Fredman, 2007; Braathen et al., 2009). To date, the development of fault facies modelling uses the combination of RMS^{TM}, an industrial reservoir modelling software developed by Roxar Software Solutions (now Emerson), and Havana^{TM}, a software developed by Norwegian Computing Center for describing faults and their impact on fluid flow, including fault envelope generation, in standard reservoir models.

The workflow for generating a fault facies geomodel starts by constructing a fault envelope grid (Syversveen et al., 2006). A faulted corner-point grid (Wadsley, 1980; Goldthorpe and Chow, 1985) and a fault model (fault surfaces and fault lines) created in RMS^{TM} are exported to Havana^{TM} which is then used to (Syversveen et al., 2006, see their Figures 2 and 3): (i) delineate fault envelope cell stacks in the footwall and hanging wall sides of the fault grid split, (ii) stretch the footwall cell stacks in fault-dip downward direction until their bottom surface align with the bottom surface of the hanging wall cell stacks, (iii) stretch the hanging wall cell stacks in fault-dip upward direction until their top surface align with the top surface of the footwall cell stacks, (iv) refine the fault envelope grid proportionally, i.e. the resulting smaller cells have similar dimension, and (v) export the resulting fault envelope grid to RMS^{TM}. Steps (ii) to (iv) are performed sequentially throughout the fault envelope grid, starting with the cell stacks around fault intersections and then cell stacks related to single fault segments.

Having provided a fault envelope grid, the subsequent step is to populate the grid with realistic, volumetrically expressed geological objects, i.e. fault facies. Fault facies can be defined at millimetre scale to better resolve individual deformation band and slip surface (Braathen et al., 2009). However, common to the existing fault facies modelling studies (Syversveen et al., 2006; Fredman, 2007; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007), fault facies are classified at metre scale (hence containing both deformation band or slip surfaces and interspaced unstrained rocks) based on strain intensity and host rock lithology. Based on outcrop studies (e.g. Fredman, 2007; Braathen et al., 2009), each fault facies is then assigned geological characteristics such as structural elements contained, spatial probability of occurrence, spatial distribution trend, and correlation lengths. Furthermore, to reproduce realistic fault zone structure and complexity at the given scale, fault facies property modelling uses three conditioning factors (Soleng et al., 2007; Cardozo et al., 2008; Fredman et al., 2008, see their Figures 10 and 11): (i) the volumetric proportions and spatial distribution of undeformed host rock facies originally present in the position of the fault envelope prior to faulting, (ii) fault product distribution factor (FPDF) representing a 3D displacement field within the fault envelope, and (iii) strain parameter describing the spatial distribution of deformation intensity in the fault envelope. These factors are further combined to provide probability parameters of fault facies which subsequently used for populating fault facies using stochastic modelling techniques.

The feasibility of using sequential indicator simulation (SIS), object-based simulation, and the combination of both has been investigated in previous fault facies modelling studies (Syversveen et al., 2006; Fredman, 2007; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007). In Fredman et al. (2008), for example, SIS is used to capture large-scale fault envelope subdivision, i.e. fault core, damage zones, and undeformed host rock. With the SIS model as the background, object-based simulation is used to model lenses in the fault core after which optional deterministic procedures can be used to create slip zones around the lenses. Constrained by the fault facies model, petrophysical modelling is then carried out deterministically (Fredman et al., 2007) or using stochastic modelling techniques such as sequential Gaussian simulation (Syversveen et al., 2006; Fredman, 2007; Skorstad et al., 2007; Soleng et al., 2007). The resulting fault envelope model in most cases must be scaled up so that the number of cells is not prohibitive for the subsequent reservoir simulation (Soleng et al., 2007) after which it is exported again to Havana™ to be merged with the original standard reservoir model as a local grid model.

The abovementioned progress in fault facies modelling studies, however, should be advanced in some aspects described below:

1. Although several function types have been used in previous fault facies modelling studies to represent fault zone displacement distributions, i.e. (i) Gaussian functions (Fredman et al., 2008), (ii) symmetric functions derived from stain modelling which has taken into account damage zone width (Cardozo et al., 2008; Fredman et al., 2008), and (iii) piece-wise linear functions (Soleng et al., 2007), more flexibility in displacement function definition are needed to better represent typical relationships observed in outcrops, such as fault core thickness and damage zone width vs. fault throw. This flexibility is also required since the symmetric characteristics in the available displacement functions are at odds with asymmetric displacement distribution observed in fault cores (Braathen et al., 2009) and damage zones (Berg and Skar, 2005; Schueller et al., 2013).
2. Industrial reservoir modelling software offers more options for facies property modelling than those that have been used in previous fault facies modelling studies, i.e. sequential indicator simulation and object-based simulation techniques. These may offer new possibilities with respect to modelling fault facies. Since previous fault facies modelling studies use metre-scale grid-resolution, further feasibility studies on other stochastic modelling techniques are required, particularly when higher-resolution grids (i.e. centimetre- and millimetre-scale) are used in which the challenges related to capturing fault zone heterogeneities increase drastically. In addition, since combined object-based simulation and deterministic techniques are incapable of modelling fault core slip zones accurately (see discussion in Fredman et al., 2008), other approaches with respect to using object-based simulation techniques should be sought.
3. Fault zone model quality controls in the form of visual comparison between the resulting fault facies models and outcrop observations have been shown in previous fault facies modelling studies. Most of these studies focus on technical feasibilities of the new modelling method and therefore the comparisons are conceptual. Detailed comparison involving matching models and outcrops of similar dimensions were not sought. In Fredman et al. (2007) and Fredmand et al. (2008), for example, field observations showing fault core with maximum thickness of 30 cm have been compared with fault core models with fault-perpendicular cell length of 65 cm and 3.33 m, respectively. Thus, improvements of fault facies modelling with respect to benchmarking modelling results to reproducing outcrop observations are required. In addition, considering that most of previous fault facies modelling studies use simple fault systems, these improvements should be done in more complex fault systems.

4. Employing fault facies modelling on a field-sized reservoir model and upscaling of fault facies petrophysical models have been demonstrated by Skorstad et al. (2007) and Soleng et al. (2007), respectively, where considerations on most modelling factors, especially facies modelling techniques, are given. As these studies emphasize the technical feasibility aspects, these considerations do not go too much into detail and some modelling aspects such as justification for the choice of grid resolution and concerns about modelling accuracy, e.g. slip zone implementation as discussed in Fredman et al. (2008), are not addressed. Therefore, further study on the modelling and upscaling of fault facies using a field-wide reservoir model with emphasis on the reliability and accuracy of the resulting model, taken into account the conclusions brought forth by previous fault facies modelling studies, should be carried out. Furthermore, this effort should be complemented with an investigation into upscaling of two-phase flow properties of fault zone elements as this information becomes increasingly available (Tueckmantel et al., 2012).
5. Even though previous fault facies modelling studies have shown the method's capability to handle varied modelling factors, the investigation of their impacts on fluid flow and reservoir performance have not been comprehensive. The factors that have been investigated include fault core architecture (with constant thickness) and petrophysical properties (Fredman et al., 2007) and petrophysical modelling techniques (Fredman, 2007). Hence, systematic investigation on other modelling factors such as fault core thickness, damage zone width, and displacement function type should be performed to fully understand fault facies model behaviour. Furthermore, the modelling studies suggested in points 1-4 above should be complemented with investigations on fluid flow characteristics and reservoir performance, as well as with benchmarking against models developed using conventional methods.

OBJECTIVES OF THE STUDY

To fill the technical and knowledge gaps discussed in previous subsection, the detailed objectives of the present study have been to:

1. Increase the flexibility of fault facies property modelling method by enabling the definition of higher number and more complex input parameters:
    a. Damage zone width as a function of fault throw.
    b. Fault core thickness as a function of fault throw.
    c. The fractions of total fault throw accommodated by fault core and damage zones.
    d. The types of displacement function (quadratic, cubic, and quartic) in fault core and damage zones.

   in reservoir models with different sedimentary facies and fault system configurations (see **Paper 1**).
2. Enrich options for fault facies property modelling with new workflows that use stochastic modelling methods and approaches that have never been used in previous fault facies modelling studies. This is achieved by:
    a. Designing and implementing workflows with truncated Gaussian simulation that use conceptual and outcrop-based conditioning parameters (see **Papers 2 and 3**).
    b. Outlining a workflow for using multi-point statistics as part of a hierarchical modelling of fault facies (see **Paper 2**).
    c. Designing and implementing a workflow that involves multi-scale object-based modelling (see **Paper 4**).
3. Improve the capability of fault facies modelling with respect to reproducing discretised fault core and damage zone outcrop observations in more complex fault systems. The works to accomplish this objective are carried out using higher resolution grids (i.e. centimetre-scale resolutions, much finer than the metre-scale resolutions used in previous fault facies modelling studies) and different model types, i.e. (i) synthetic, (ii) outcrop-based, and (iii) real-field reservoir models, with increasing fault system complexity:

   a. Single isolated fault.
   b. Two parallel non-interacting faults.
   c. Single-tip interacting faults (branching of two fault segments).
   d. Double-tip interacting faults forming a relay ramp.

   (See the sections on the resulting geomodels in **all papers**).
4. Enable a reliable and accurate modelling of field-sized reservoir with volumetric faults within the framework of the standard reservoir modelling tools. This is achieved by:
   a. Designing and implementing a workflow that involves combined multi-purpose gridding and multi-scale property modelling, and successive flow-based upscaling of fault envelope segments.
   b. Outlining alternative more efficient workflows that utilize database of upscaled petrophysical properties.
   c. Outlining a procedure to scale up two-phase flow properties of fault zone elements.

   (See **Paper 4**).
5. Advance current knowledge of the impact of fault zone structure on reservoir fluid flow. This is accomplished by simulating fluid flow in the generated reservoir models with volumetric faults and investigating:
   a. The sensitivity of fault facies modelling parameters on reservoir performance using experimental design (factorial design at two levels). These parameters include (i) fault core thickness, (ii) displacement fractions of fault core and damage zones, (iii) displacement function types of fault core and damage zones, (iv) number of reservoir layers, (v) number of faults, (vi) damage zone width, (vii) volumetric proportions of damage zone fault facies, (viii) deformation band frequency, (ix) deformation band permeability, and (x) fault facies extent (see **Papers 1 and 2**).
   b. Displacement patterns (swept and bypassed regions) and reservoir performance in the parallel faults (see **Paper 1**) and relay ramp (see **Paper 2**) fault facies models. The latter is carried out with comparison to the responses of the deterministic models of a previous study of the same relay zone.
   c. Streamline patterns (swept and bypassed regions) and injected fluid breakthrough response in the full-field reservoir models with volumetric faults, and the sensitivity of field injection-production rates on these responses. This is carried out with comparison to the responses of the corresponding conventional reservoir models with fault transmissibility multipliers (see **Paper 4**).

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SYNTHESIS

Synthesis

The research presented in this dissertation constitutes a contribution to the field of 3D reservoir and volumetric fault modelling. The study has specifically been aimed towards enhancing the key aspects of fault facies modelling which include the utilization of outcrop-based fault facies map, 3D gridding, property modelling, upscaling, full field application, fluid flow simulation, and sensitivity analysis. The main conclusions and future research on these key aspects drawn from the present study are summarized below.

ON OUTCROP-BASED FAULT FACIES MAP

As opposed to previous fault facies modelling studies (Syversveen et al., 2006; Fredman, 2007; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007), the present study makes extensive direct use of fault zone outcrop observations. Prior to modelling, fault zone outcrop observations are discretised using grid resolutions that are deemed to be high enough to resolve fault facies units depending on flow scale considered (Papers 2, 3 and 4). The discretised observations, named as outcrop-based fault facies maps, form conceptual templates for subsequent property modelling. The advantages of this approach are obvious as the templates can be used as robust basis for (i) selecting the most suitable stochastic modelling techniques and workflows, (ii) determining representative geostatistical properties of fault facies and fault facies associations, and (iii) assessing the quality of fault facies models.

Discretization of well-described fault zone outcrops using millimetre-, centimetre-, and metre-scale resolution has been demonstrated in the present study. It has been shown that, using only few outcrops, different discretization resolutions leads to the selections of different stochastic methods for fault facies modelling and thus different geostatistical properties of fault facies and fault facies associations. This indicates that more variation in conceptual templates for property modelling will appear when the discretization are carried out using many other fault zone outcrop observations, which are available in the literature, or using the same outcrops but with different discretization resolutions. Therefore, future fault facies modelling studies should put efforts to enrich conceptual templates for property modelling by generating more outcrop-based fault facies maps.

ON FAULT ENVELOPE GRIDDING

Complementing previous fault facies modelling studies (Syversveen et al., 2006; Fredman et al., 2008, Skorstad et al., 2007; Soleng et al., 2007), the present study demonstrates that fault envelope gridding using automated local grid refinement (using Havana^{TM}) in simple synthetic models is technically feasible (Paper 1). In addition, the present study shows that the associated flow simulations in the local grids give expected and accurate results.

For the application of fault facies modelling on a full-field scale in combination with including an efficient method for capturing millimetre-scale flow domains, the present study demonstrates an approach that employs global and non-proportional grid refinements for creating fault envelope grids in flow simulation models (Paper 4). The use of global grid refinement partly follows Fredman (2007) who highlighted the need to have gridding algorithms that offer flexible implementation of varied fault envelope width (as opposed to constant width based on cell number in Havana^{TM}), whereas non-proportional refinement is used to separate regions dominated by damage zones and fault cores in fault envelope grids. Currently, there is no standardized tool for automatically implementing this global refinement approach. However, though implemented manually, in the present study the global grid refinement approach was employed in a systematic fashion. Hence, for future fault facies modelling studies, it would be straightforward to complement Havana^{TM} with a module that can implement fault envelope grids as global grid and non-proportional refinements.

ON FAULT ENVELOPE PROPERTY MODELLING

Fault zone displacement functions

Different from previous fault facies modelling studies where fault zone displacement functions are applied using Havana^{TM} (Syversveen et al., 2006; Fredman et al., 2008, Skorstad et al., 2007; Soleng et al., 2007), in the present study fault zone displacement functions are defined and applied using automated scripts in RMS^{TM} (Papers 1 and 4). Using this approach, it has been shown that fault zone displacement functions can be defined and applied in a much more flexible way and that the functions are more related to outcrop-based statistics such as fault throw-damage zone and fault throw-fault core thickness relationships. In addition, the fractions of accommodated displacement and the types of displacement function (quadratic, cubic, and quartic) in fault core and damage zones can also be included as variables in fault zone displacement functions.

Since the present study focuses on sensitivity analysis of fault zone displacement function on fluid flow, actual representations of across-fault displacement distributions are not sought. In each case, a fault zone is assumed to have a constant displacement function in along-strike and along-dip directions. Natural fault zones, however, show spatial variations in displacement distribution. Fault zone field observations that can reliably constrain these variations might be few as they need continuous, well-exposed fault zone outcrops. Lunn et al. (2008) is an example of a study that might be directly incorporated for displacement function definition. Their outcrop observations demonstrate that a spatially correlated random field with a spherical covariance structure can be used to describe along-strike fault core thickness variation which is an important variable for defining fault zone displacement functions. Future fault facies modelling studies should venture to extract spatial variations of fault zone displacement functions based on actual displacement distribution observed in the field.

Conditioning parameters and stochastic modelling methods

The present study demonstrates successful implementation of user-defined (Papers 1, 2 and 4) and outcrop-based (Paper 3) conditioning parameters for fault facies and fault facies associations. The user-defined conditioning parameters are created based on qualitative trends observed in the field and their implementation in the models is controlled by fault zone architectural elements, lithology, and local displacement gradients (strain). Outcrop-based conditioning parameters are derived based on structural population/orientation and density maps from field observations which are discretised and implemented in the models without modifications.

Complementing previous fault facies modelling studies (Syversveen et al., 2006; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007), the present study further demonstrates the feasibility of sequential indicator (Paper 1) and object-based (Paper 4) simulation techniques for populating fault facies that use user-defined conditioning parameters. The present study, however, uses finer grid resolutions to capture more complex fault zone features.

The present study presents a wider spectrum of options for fault facies property modelling by demonstrating successful application of truncated Gaussian simulation to model damage zones (Papers 2 and 3). This modelling method is investigated because centimetre-scale discretized fault zone outcrops show, for each fault facies group, a general ordering of fault facies occurrence according to the level of deformation density. The application of this modelling method is constrained by conceptual and outcrop-based conditioning parameters in different fault system configurations: (i) single isolated fault, (ii) single-tip interacting faults (branching of two fault segments), and (iii) double-tip interacting faults forming a relay ramp. In all cases, the resulting damage zone models captures important field observations, as shown by the corresponding discretized damage zone conceptual models, such as variations of fault facies thickness, -length, -adjacency, and compartment geometries.

Furthermore, the present study demonstrates a hierarchical approach to model fault cores using object-based simulation techniques (Paper 4). Lensoid objects are populated by setting very high volumetric proportion of the objects as compared to background volumetric proportion. This option is taken to reproduce complex fault core lenses configuration where lenses are stacked one to another. Subsequently, the lens models are refined non-proportionally (for creating thin and thick cells) and slip zones are implemented within thin cells separating two different lensoid objects. In this way, important lenses characteristics, e.g. (i) lenses with varied thickness and aspect ratio and (ii) lens size distribution that shows a higher number of smaller lenses, are reproduced by the lens models. Moreover, since slip zone distribution are closely related with the distribution of lenses, the fault core models also capture accurately the distribution of flow baffles/conduits.

Similarly, for fault facies modelling in damage zones, the present study outlines the use of hierarchical approach using combined truncated Gaussian simulation and multi-point geostatistics (Paper 2). It is envisaged that multi-point geostatistics can be used to model millimetre-scale fault facies based on training images of fault zone outcrop line drawings. The utilized millimetre-scale grids are global refinements of centimetre-scale fault envelope models (e.g. those that use truncated Gaussian simulation). During the millimetre-scale multi-point geostatistics modelling, the centimetre-scale truncated Gaussian simulation models are used as spatial constrains.

From the above description, as most standard stochastic modelling methods have been investigated, future fault facies modelling studies should involve advanced use of these methods. This could include the implementation of combined truncate Gaussian simulation and multi-point statistics in a hierarchical fashion, the utilization of seismic attributes, the incorporation of strain- and geomechanical-constrained conditioning parameters, and the updating of fault envelope models using production history data.

Quality control of fault envelope models

For model quality control, the resulting fault envelope models have been visually compared to the related discretized fault zone outcrop observations. The comparisons use the same scales and observation windows of outcrop views (all papers) and eagle views (Papers 3 and 4) for smaller and larger scale comparisons, respectively. Future fault facies modelling studies should use the same approach for fault envelope model quality control. In addition, apart from using visual inspections, it is also recommended that the statistics of fault envelope models are compared to related outcrop-based statistics.

Petrophysical modelling

Since the present study focuses on sensitivity analysis of fault facies proportion and configuration on fluid flow, the corresponding effect of petrophysical property variation within fault facies, which can be investigated using stochastic modelling techniques, is not sought. Hence, in all cases the petrophysical properties of each fault facies are modelled deterministically by assigning constant values. The effect of modifying petrophysical modelling techniques from deterministic to stochastic on reservoir performance is not significant as compared to the effects of applying other parameters such as displacement function (Fredman, 2007). In addition, compared to previous fault facies modelling studies (Syversveen et al., 2006; Fredman et al., 2007; 2008, Skorstad et al., 2007; Soleng et al., 2007), the present study put significant efforts into capturing more complex fault zone features using higher grid resolutions and more varied fault facies classifications with expected narrower petrophysical properties ranges. This minimizes the need to use stochastic techniques for fault facies petrophysical modelling.

However, if after classifying fault zone rocks into fault facies individual facies exhibit large petrophysical property standard deviations, it is important to use stochastic techniques when populating the fault facies with petrophysical properties. In this case, future fault facies modelling studies should investigate more on the use of sequential Gaussian simulation for petrophysical modelling of fault facies (cf. Fredman, 2007).

ON FULL-FIELD APPLICATION

Workflow

The present study has demonstrated a reliable and accurate fault facies modelling of a field-sized reservoir with volumetric fault cores within the framework of standard reservoir modelling tools (Paper 4). This is achieved by using a workflow that involves multi-purpose gridding, multi-scale modelling, and flow-based upscaling, i.e. (i) metre-scale (low-resolution) grids for upscaled fault envelope models and flow simulations, (ii) centimetre-scale (medium resolution) uniform grids for displaced property and stochastic lens models, (iii) millimetre-scale (high-resolution) non-uniform grids for merged slip zone and displaced property models, and (iv) flow-based upscaling of petrophysical properties in the merged models to the metre-scale grids.

Because the high resolution (millimetre-scale) full-field modelling in the present study involves a very large number of cells, property modelling and upscaling steps are executed sequentially fault-segment by fault-segment. Manual, but systematic, approach has been used for these steps. An automatic execution of this workflow requires a seamless connection between RMS^{TM} and an operating system such as Unix^{TM} so that the grid and 3D parameter files of a fault segment can be successively transferred between the two systems and stored and erased (if necessary) in the operating system. This seamless connection is a requirement and has been used for state-of-the-art reservoir model updating (e.g. Skjervheim et al., 2012) and hence can be adapted for fault facies modelling studies. For full-field applications, future fault facies modelling studies should put efforts on automating and streamlining the workflow detailed in the present study.

Database approach for efficient workflow

A database approach can make the complete modelling workflow for full-field application more efficient (Papers 2 and 4). Instead of going through a complete set of steps for all fault envelope/damage zone cells, the most time-consuming workflow steps such as millimetre-scale slip zone and deformation band modelling are carried out only in selected number of fault envelope/damage zone cells representative of a wide range of fault throws, host rock permeability, and fault configurations. The result of this procedure is a database with statistical relationships that can be used to populate the remaining fault envelope/damage zone cells with estimated upscaled permeabilites. In addition, standard deviations given by the database can be used for stochastic modelling of upscaled permeabilities using e.g. sequential Gaussian simulation. Future fault facies modelling studies should investigate the implementation of this database approach, with focuses on optimising and possibly automating the sampling procedure.

Two-phase flow properties of fault zone elements

Accurate 3D representation of small-scale geological features and capability to execute straightforward flow simulation in the fine-scale model are mandatory requirements when two-phase flow properties are being considered. Hence, although the present study only considers single-phase and uniform two-phase flow properties, combined multi-purpose gridding, multi-scale modelling, and successive upscaling presented here provide a complete technical framework for scaling up of varied two-phase flow properties of fault zone elements (Paper 4). As outlined in this thesis, the use of volumetric fault zones in reservoir models make it possible for fault facies modelling to adapt multi-scale modelling methods developed for accurate scaling up of two-phase flow properties of undeformed sedimentary rocks (e.g. Corbettt et al., 1992, Ringrose and Corbett, 1994; Pickup et al., 2000). Future fault facies modelling studies should investigate upscaling of two-phase flow properties of fault zone elements for full-field application.

ON FLUID FLOW SIMULATION AND SENSITIVITY ANALYSIS

Important findings related to flow simulation and sensitivity analysis in the present study advance current knowledge of the impact of fault zone structure on reservoir fluid flow. They are summarised as follows.

1. When all fault zone architectural elements, i.e. fault core and damage zone, are considered, fault facies modelling factors can be ranked according to their impact on reservoir responses in the following descending order: (i) fault core thickness, (ii) the type of displacement function, (iii) sedimentary facies configuration, (iv) fault core throw percentage, (v) fault system configuration, and (vi) maximum damage zone width (Paper 1). Fault core thickness significantly affects reservoir response because it governs available spaces for along-dip flow. Other parameters affect reservoir response mainly because they control the geometry and continuity of across-fault and along-fault flow paths.
2. Damage zone fault facies modelling factors can be ranked according to their impact on reservoir responses in the following descending order: (i) fault facies volumetric proportion, (ii) deformation band frequency, (iii) damage zone width, (iv) deformation band permeability, and (v) fault facies cluster extent (Paper 2). Modifying fault facies proportion and damage zone width mainly change flow retardation/enhancement in damage zone, whereas modifying deformation band permeability and frequency mainly change flow tortuosity in damage zone.
3. The main factor in controlling fluid flow in relay zones is deformation band permeability (Paper 3). This corroborates previous flow simulation results presented by Rotevatn et al. (2009). Variations in shape and speed of fluid fronts show that, within k_{hr}/k_{db} range of 10^1 to 10^5, increasing k_{hr}/k_{db} causes increased fluid flow complexity in the relay zones. Vertical sweep efficiency in relay zones appears to be stimulated by high deformation band permeability since this allows injected water to saturate the entire oil column with ease. Relay zones with medium deformation band permeability show better lateral sweep efficiencies due to enhanced flow tortuosity in the presence of pervasive but weak flow baffles.
4. Fault cores with membrane slip-zone clusters act as dual baffle-conduit systems (Paper 4). Sweep efficiency in reservoirs with these fault cores is closely related to injector-producer configuration. Along-strike positioned injector-producer pairs focus flow into the fault cores, decreasing sweep efficiency. Injected fluids of injector-producer pairs positioned to drain perpendicular to the fault cores are partitioned and distributed by the fault cores and therefore increase overall sweep efficiency. Reservoirs with these fault cores exhibit two behaviours: (i) water breakthrough occurrence, time, and sequence are not sensitive to the choice of injection-production scheme and (ii) sweep efficiency decreases when field production rate is lowered.
5. Fault cores with conduit slip-zone clusters act as thief pathways (Paper 4). Sweep efficiency in reservoirs with these fault cores has less dependency to injector-producer configuration. Reservoirs with these fault cores exhibit two behaviours: (i) water breakthrough occurrence,

time, and sequence are highly sensitive to the choice of injection-production scheme and (ii) sweep efficiency increases when field production rate is lowered.

The present study has demonstrated that factorial design at two levels is an efficient and accurate method for sensitivity analysis related to reservoir simulation (Papers 1 and 2). In addition, when combined with property upscaling, the raw data of factorial design at two levels can be incorporated into a database of upscaled properties for efficient full-field modelling workflow (see 'On Full-field Application' subsection above). Moreover, to increase the understanding of fault zone fluid flow, the present study uses several visualisation techniques for extracting flow simulation results: (i) oil saturation through time in several vertical and horizontal sections (Papers 1 and 3), (ii) streamlines (Paper 4), and (iii) water breakthrough occurrence, sequence, and time (Paper 4). Future fault facies modelling studies, as suggested in previous subsections, should be complemented with (i) fluid flow investigations and (ii) optimal selection of sensitivity analysis and visualization techniques of reservoir simulation results.

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ERRATA

Errata for
3D stochastic modelling of fault zones in siliciclastic reservoirs

Implications for reservoir description and fluid flow modelling

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3 December 2014

Errata

Page 8 “(i) act as dual baffle-conduit conduit systems,” – Should be “(i) act as dual baffle-conduit systems,”

Page 17 “For example, in a fault segment of a reservoir model with a thickness slightly smaller than the fault throw,” – Should be “For example, in a normal fault segment of a reservoir model with a thickness slightly smaller than the fault throw,”

Page 17 “a cell in the upper part of the footwall block can have connections to the cells in the lens body which in turn also have connections to the cells in the lower part of the hanging wall block.” – Should be “a cell in the lower part of the footwall block can have connections to the cells in the lens body which in turn also have connections to the cells in the upper part of the hanging wall block.”

Page 111 “the number of cells with increased fault-parallel permeability (PERMY, Figures 8B and 8D) is higher than the number of cells with increased fault-perpendicular permeability (PERMX, Figures 8B and 8D).” – Should be “the number of cells with increased fault-parallel permeability (PERMY, Figures 8F and 8H) is higher than the number of cells with increased fault-perpendicular permeability (PERMX, Figures 8E and 8G).”

Page 118 “Figure 8 is an example of a small subset of .” – Should be “Figure 8 is an example of a small subset of this database.”