Facies composition and scaling of extensional faults in sedimentary rocks

and its applications to modelling of fault zones

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Contents

Preface

This dissertation is the outcome of a PhD scholarship provided trough the Fault Facies and the Euro Margins projects at the Centre for Integrated Petroleum Research (CIPR), University of Bergen. The overall aim of this project is to improve the understanding of faulted reservoirs and to improve the implementation of faults in conventional reservoir models. The course of this activity is firstly the use of geological outcrop analyses and existing literature to construct quantitative and qualitative validated geological models, which secondly can be the foundation elements implemented in reservoir models.

For the readers accustomed to monographic doctoral dissertation, this is a short explanation of the layout of the current thesis. This thesis comprises an introduction, followed by several individual manuscripts where the essence of the research is presented (papers 1- 5). The main results are then summarized and discussed, followed by an overall conclusion. Some papers are published (papers 1 and 2), two papers are submitted (paper 3 and 4), and one paper (Paper 5) is nearly ready for peer review journal submission. Further, the papers are meant as stand alone contributions; therefore, there is some overlap between the different papers.

Paper 1, "*Fault Facies and its applications to sandstone reservoirs",* is based on works done by my supervisor Alvar Braathen. My contributions include field work and discussions. This paper considers the new concept of fault facies and presents descriptions and statistic analysis of faults in sandstone reservoir units studied in western Sinai, Egypt. The paper represents an important foundation for some of the ideas of the Fault Facies concept, and therefore some of the other papers in this thesis.

Papers 2 and 3: "*Extensional fault cores in micritic carbonates- case studies from the gulf of Corinth, Greece"* and "*Modelling complex fault architectures; case studies from the Gulf of Corinth, Greece"* are the outcome of an inter-disciplinary study comprising geology and mathematics. The first paper considers a detailed geological description of - and a comparison between the fault cores of two major extensional faults, the Doumena and Pisia faults from the Gulf of Corinth rift. In summary, the Pisia fault consists of planar corrugated slip surfaces bounding layers of calcite precipitation and layers of ultra breccia, whereas the Domena fault has a much more complex geometry of undulating slip surface bounding lenses consisting of micritic host rocks and fault breccia. The second paper describes a modelling approach to the fault geometry and fault elements of the Doumena fault. Here, the geological model is constructed based on the description of the Doumena fault, which is used mainly due to the complexities, including descriptions of lenses, and complex fracture network geometries. The more complex fault architecture of the Doumena fault may indicate a more intricate fluid flow pattern, in comparison to the simpler fault architecture of the Pisia Fault. In addition the outcrop style facilitate a three dimensional study, which represents a good foundation for modelling of major faults. These two papers are based mainly on fieldwork by myself and Henning Nøttveit. Alvar Braathen, Tore Skar and Roy H. Gabrielsen have contributed with field work and editorial works. The second paper is mainly written by Henning Nøttveit, who also carried out the modelling with additional guidance from Jan Tveranger and Magne Espedal. My contributions in this paper relates to discussions around the geological model, and editorial works.

Paper 4, "*Extensional faults in fine grained carbonates – analysis of fault core lithology and thickness displacement relationship*", is based on field studies of faults from three carbonate regions, the western Sinai, central Oman and Central Spitsbergen. The paper focuses on the geometry and facies composition of fault cores according to the relationship between thickness and displacement. The statistics cover over 100 faults spanning in displacement from cm to 350 m. The data collection and manuscript preparation is mainly done by myself, with my supervisor Alvar Braathen contributing with field work and manuscript editing.

Paper 5, "Comparison of scaling relationships of extensional fault cores in carbonate and porous sandstone reservoirs*",* is a statistical analysis and description of the thickness and displacement relationship of fault cores in reservoir sandstone and carbonate rocks. The data in this paper is strictly collected in Sinai, Egypt. The carbonate data is based on the same data of the work described in paper 4, whereas the sandstone data is gathered by Alvar Braathen and Tore Skar during database compilation in the Fault Facies project.

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Introduction

The main aim of the current study is to increase the understanding of tectonic deformation in carbonates, with special emphasis on application of fault outcrop data in numerical reservoir models. The required quantification of outcrop data goes through analysis of empirical trends (scaling laws) and statistical considerations of elements (facies in faults). It is well known that faults influence fluid flow in hydrocarbon reservoirs (e.g., Foxford et al. 1998; Aydin 2000; Shipton et al. 2005). In porous siliciclastic reservoirs, faults are considered as barriers to fluid flow, as they contain fault rocks of lower permeability and porosity than the host rocks (e.g., Fossen et al. 2007). On the other hand, faults in carbonate reservoirs act as both barriers and conductors, as fractures in these rocks increases the conductivity and may connect high permeable units of the reservoirs (e.g., Cello et al. 2003; Micarelli et al. 2006; Billi et al. 2008). However, fault sealing membranes in terms of shale smear, cementation and gouge formation are common, and can act as barriers to fluid flow both in carbonate and sandstone reservoirs (Færseth 2006). The background for this study is divided into two subjects:

1) Characterization of fault cores in carbonates.
2) Qualitative and quantitative description and characterization of fault cores in sedimentary reservoir rocks, and how these data can be implemented into three dimensional reservoir models.

Fault architecture

A fault formed under shallow burial depth is commonly described as a zone of focused deformation that can be sub-divided into domains/sub-zones of core and damage zone(s) (Chester and Logan 1986; Caine et al. 1996; Braathen et al. 2009). Observations of fault cores (e.g., Caine et al. 1996; Childs et al. 1997; Lindanger et al. 2007; Wibberley et al. 2008) show that they consist of elements such as slip surfaces, fracture/deformation band sets, fault rocks (gouge, breccias and cataclasites), shale smear, lenses of protolith or fault rock and cement. Bulk strain of the core can be regarded as semi-penetrative to penetrative, and core elements in most cases have significantly altered fluid transmissibility compared to their protolith. In contrast, the damage zone is a non-penetrative strain domain that hosts discrete structures including fractures and/or deformation band sets (Fig. 1). In tight rock such as carbonates, faults initiate as fractures, in contrast to faults in porous sandstones which initiate as porosity collapse structures, so-called deformation bands (Aydin et al. 1978; Fossen et al. 2007). Faults grow by linking of individual fault segments developing a complex and often irregular fault trace of soft linked and hard linked faults and fault lenses (e.g., Childs et al. 1997). Further movement shears of asperities and break down lenses to develop a smoother fault core geometry often outlined by a through going slip surface(s) (Gabrielsen & Clausen 2001; Childs et al. 2009). Further, the irregularity and the geometry of fault segments can be controlled by the host rock mechanical strength, i.e. faults in an extensional regime forms steep fault in stiff rocks and lower angle faults in softer rocks. Another aspect is the weakening of faults by for example smearing of shale layers (Lindsay et al. 1993; Færseth 2006). Smearing of multiple shale layers is reported by Færseth et al. (2007) to cause an increased complexity of the fault zones, in such cases consisting of lenses and multiple slip surfaces.

Faults in carbonates

Faults in carbonates has been a subject of increased interest the last decade (e.g. Hadizadeh 1994; Cello et al. 2003; Agosta & Kirchsner 2003; Billi et al. 2003; Micarelli et al. 2003; Agosta & Aydin 2006; Graham Wall et al. 2006; Micarelli et al. 2006a; 2006b; Tondi et al. 2006; Bonson et al. 2007; Benedicto et al. 2008; Bastesen et al. 2009; Gaviglio et al. 2009). Fault cores in carbonates host similar elements as faults in other rock types, such as fault rocks (gouge, breccia and cataclasites) (Micarelli et al. 2003; Billi et al. 2003), slip surfaces and shale smears (Braathen et al. 2009). On the other hand carbonates are more sensitive to rock fluid interactions, since calcite easy dissolves and precipitates. This results in major karstification and cementation in the fault zones (Roberts & Stewart 1994). These processes are further enhanced by that faults in carbonates act as major pathways for fluids (Micarelli et al. 2006a; Agosta & Aydin 2006), which most likely relates to deposition of large quantities of secondary cement (Benedicto et al. 2008). Dissolution by pressure solution is also common, but then at significant burial depths (Carrio Schaffhauser & Gavligo 1990; Cello et al. 2003; Agosta & Kirschner 2003; Labaume et al. 2004; Micarelli et al. 2005; Graham Wall et al. 2006). In this thesis fault cores in carbonates are studied in detail in paper 2 and 4. In paper two the internal geometry of two major and shallowly buried faults are presented, the Pisia and Doumena faults. There are large differences between the two faults, as the Pisia Fault has a simple planar fault core, whereas the Doumena Fault displays complex fault architecture. In addition these faults serve as excellent outcrops for quantifying and characterize different elements within the core, such as lenses, corrugations and fault rock layers, which have not previously been quantified in such detail. Paper four investigates the thickness and compositional facies of extensional faults in shallowly buried platform carbonates from Sinai, Oman and Central Spitsbergen. The study aims on describing faults in carbonates with different displacement scales. In the literature there are few published studies concerning thickness and displacement of faults in carbonates (Micarelli et al. 2006). However, both Robertson (1983) and Childs et al. (2009) suggests that fault cores in carbonates have different thickness-displacement relationship than other rock types. As the observation of general widening of fault cores with increasing throw points towards growth of faults, this paper also addresses how faults in carbonates initiate and develop (Petit et al. 1999; Billi et al., 2003; Micarelli et al. 2005; 2006b).

Faults in reservoir models

The second aim of this dissertation is to increase the understanding of how fault may be quantified and implemented into three dimensional numerical models, models which are used in the oil and gas industry for reservoir description, in prediction and in management. Data that are implemented in these models are collected from seismic sections (2D and 3D) and boreholes (1D), which gives valuable, but restricted information of the reservoir. The composition and architecture of sedimentary structures and in this case faults, cannot be described or observed in detail; therefore information from outcrop analogues are also used as guidelines in modelling building.

Conventional reservoir modelling tools include faults in a simplified way using combinations of offsets along grid splits and calculated transmissibility multipliers to capture fault impact on fluid flow across faults (Walsh et al., 1998; Manzocchi et al., 1999, Manzocchi et al., 2008). Fluid flow inside the fault can thus not be included explicitly, and flow between non-juxtaposed cells can only be included using history matching. Furthermore, a transmissibility multiplier does not consider the apparent complexity in terms of the great variability of fault core and damage zone width, and the variability of fault core components such as fault rocks layers, lenses and localized slip surfaces (Tveranger et al. 2005; Fredmann et al. 2007; Wibberley et al. 2008). The Fault Facies project aims on describing faults as volumes and by this implement the fault envelope as common grid cells in the reservoir models. Similar to sedimentary facies, fault facies refers to a distinctive body of rock, influenced by faulting in a particular environment (depth, temperature), with a characteristic set of properties. In this context, faults can be the subdivided into the fault core and the damage zone (Caine et al. 1996). The fault core is characterized by rock bodies that have experienced significant strain, whereas the damage zone is medium to low strain zone of discrete, small displacement structures. The fault core may be divided into lenses or pods of host rocks, layers of fault rocks, and cement veins (Fig. 1). These bodies may further be analysed through different influence of deformation (Braathen et al. 2009, this thesis). The Fault Facies method facilitates faults to be implemented as grid cells with distinct properties (including permeability) into reservoir models (Tveranger et al. 2005; Fredman et al. 2007; 2008). Although this method involves more CPU time considering fault evaluation than traditional transmissibility multiplier analysis, it renders fluid flow along the fault zone and between initially non juxtaposed grid cells on different sides of the fault. In addition, it leads to more elaborate fault zone evaluation and thereby to more realistic reservoir understanding. One important task during the fault facies project has been to establish geological fault models suitable to the fault facies grid. This includes to investigate existing geological models in literature and to collect additional quantifiable data from field analogues, thereby establishing sound databases. Such data collection and fault architecture classification is considered in all paper in this dissertation. Paper 1 investigates possible ways of describing faults as facies, and classifies several fault facies commonly encountered in sandstone reservoir. Paper 2 considers the intrinsic geometry and composition of two major faults in carbonates, the Pisia and Doumena faults, Gulf of Corinth, Greece. Paper 3 describes a method of implementing fault characteristics in a numerical reservoir model, using example from the Doumena Fault. In papers 4 and 5 the aim is to investigate the relationship between thickness and displacement of fault cores in carbonate and sandstone reservoirs. Many works concerning thickness and displacement relationships shows a positive linear increase in thickness according to displacement (e.g. Otsuki 1978; Scholz 1987; Hull 1988; Knott 1994, Sperrevik et al. 2002; Childs et al. 2009). Such data has been used in explaining growth of faults (Scholz 1987; Hull 1988) and to calculate trends which are used to predict fault thickness (Otsuki 1978) which, further, is used as input to calculate transmissibility multipliers (Walsh et al. 1998; Manzocchi et al 1999). However, most of these data reveals high uncertainties, by large variations in thickness values according to displacement. This variation is caused by datasets from different protoliths, effects of mechanical layering, depth of deformation and fault zone heterogeneity with cores consisting of lenses and anastomosing fracture network and thin gouge membranes. There also seems to be different characterization views applied in various studies (Blenkinsop 1989; Evans 1990; Wibberley et al. 2008). Childs et al. (2009) demonstrate that much of the scatter can be a result of the segmental nature of faults of hard linked and soft linked segments, while Shipton et al. (2006) point to the difficult separation of damage zones and fault cores, especially for large faults. Nevertheless, this problem might be easier to overcome by using the Fault Facies concept, since the fault core is expressed as a volume in which the apparent variation in thickness and displacement can be captured. I will return to this discussion in the end of the thesis, where the findings of the 5 papers are summarized in light of the current understanding of faults.

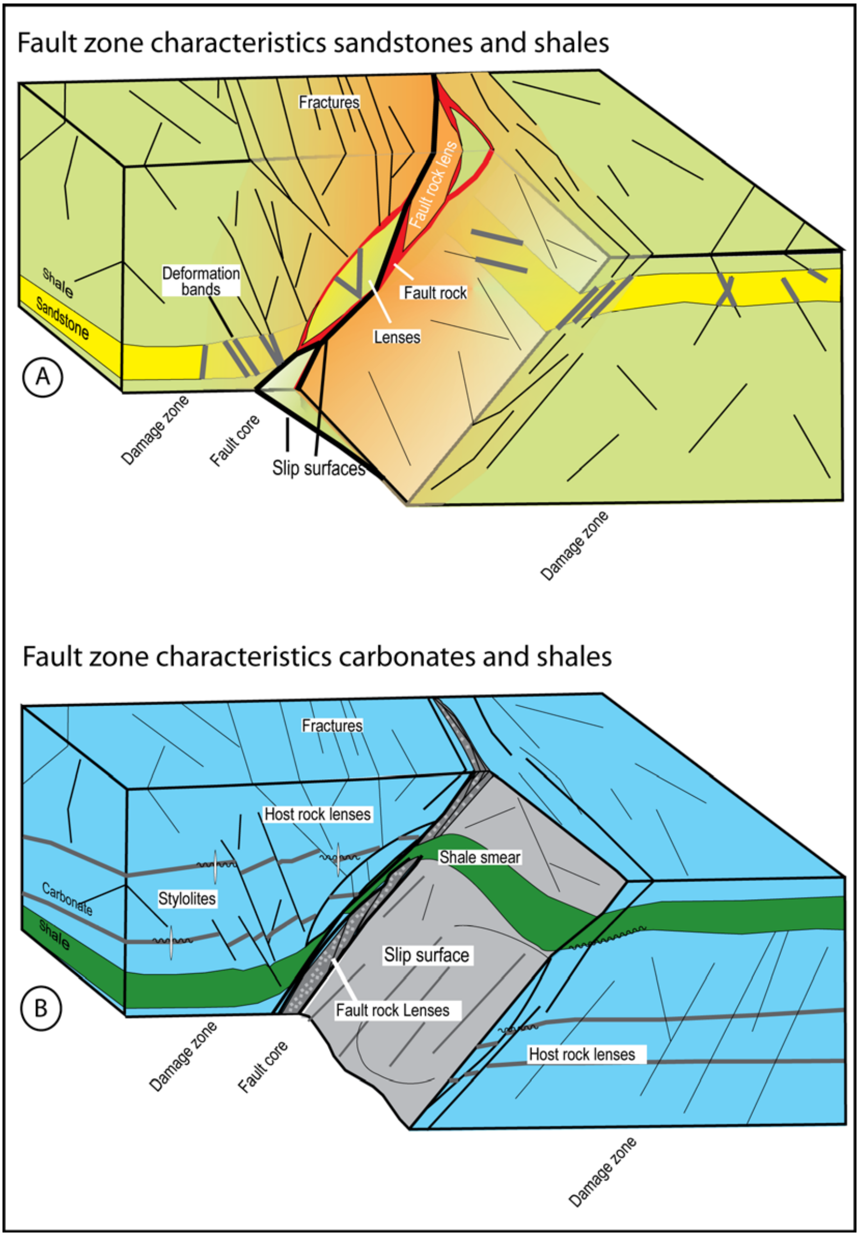

Fig.1 Fault models showing common structures encountered in extensional fault zones in reservoir (A) sandstones and (B) carbonates. The model is modified from Braathen et al. (2009).

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Discussion and Conclusion.

Due to extensive hydrocarbon production and possible CO_2 sequestration in carbonate and sandstone reservoir rocks, the understanding of faults in such reservoirs has attained generous attention (Yielding et al. 1997; Knipe 1998; Walsh et al. 1998; Sperrevik et al. 2002; Fredman 2007; 2008; Braathen et al. 2009). Faults have a major impact on fluid flow in reservoirs and can act as both fluid conductor and fluid flow barrier. The research presented in the current dissertation focuses on the general characterization of the geometry and composition of fault cores. In particular, the study is a contribution towards increased understanding of the architecture of major extensional faults in carbonates. Further, the study investigates important parameter such as the thickness and displacement relationships and facies composition. A second intention of this work is to improve the fault zone models concerning fluid flow in faulted reservoirs, by quantifying and describing faults in outcrops.

Fault cores in reservoir rocks

This dissertation is based on outcrop studies from several faulted areas, including Greece, Sinai, Oman and Spitsbergen. The faults studied span from cm displacement faults to km displacement faults. The primary aim of this thesis was to characterize faults both in a qualitative and in a quantitative way. The challenge has been to characterize the complex nature of faults, as fault cores display large lateral variations in geometry and composition. One method was to describe in detail large and well exposed fault surfaces such as the Doumena and Pisia faults. This is time consuming, but yields important information of the fracture network, lens geometry and fault surface morphology, which are features that are important for the flow potential of the fault. In this study it was shown that more complex fault core architectures is formed in fault bends in contrasts to simple architecture in planar parts of the faults. Knowledge of the difference in fault core composition and geometry along faults is important factors to implement into numerical models which describe faults as volumes (paper 3). Another method is to characterize larger quantities of faults, by investigating the thickness of the fault core, composition and geometry (paper 1, 4 and 5). A general result is that an extensional fault consists of fault rock layers, host rock and fault rock lenses, cemented zones and veins, deformation bands (porous rocks), fractures and slip surfaces. Further, the fault core architectures ranges from planar, localized fault cores to wide, distributed cores. Although these features are well documented in the literature, few works has for instance, quantified lens geometries and sizes, or comparing displacement-thickness data with the general fault core composition. The analysis shows that fault cores with high thickness (T) and displacement (D) relationship have fault cores of lenses, complex fracture networks, and a composite composition of for example cement veins, shale smears and fault breccia. On the other hand, planar faults have more commonly thin fault cores with low T/D relationships. These cores have a fairly homogenous composition of fault rock and slip surfaces and the thickness values are more laterally even. Most faults with considerable displacement (more than 1 m), display both a complex thick fault core geometry and a thin planar fault core geometry. This is demonstrated in the thickness and displacement plots where one fault may have a thickness range of up to three orders of magnitude. An example of the variability of geometry is demonstrated by the two major faults in Greece, where the Doumena Fault comprise a complex thick fault core with a network of protoliths and fault rock lenses of meter to decametre size, responsible for large fault surface undulations. In contrasts, the Pisia Fault has a planar fault slip surface bounding a localized zone of ultra-breccia. Therefore, a generalized fault core model, i.e. with similar thickness-displacement relationship and composition of flow retarding gouge, will be obscuring the observed complex geometry of faults.

Fault growth and the geometry of extensional faults

In this dissertation the focus on fault growth has been analyzed with respect to thickness increase due to increasing displacements. This topic has been investigated by a systematic collection of thickness data from faults in carbonates and sandstones. The results imply that for a given displacement most faults reveal large thickness variation, and fault thickness generally increases with increasing displacement. By comparing the presented data in this dissertation with previous published data two questions arise: (1) Is the fault thickness growing due to abrasive wearing and accumulation of host rocks material (Scholz, 1987; Hull 1988), or (2) is fault core thickness increasing by the scale independent successive linkage and break down of fault segments (Childs et al 2009)? In general, previous studies suggest that the fault thickness increase is scale independent regarding the displacement. In other words, the ratio between thickness and displacement is similar for small faults as well as for large faults. Childs et al. (2009) suggest that fault segments do not increase in thickness, but instead the break down of asperities and the “stretching” within the fault core due to increasing displacement accompanies the thinning of the fault core with increasing displacement. Widening of the fault core occurs when fault segments link together forming lenses and fault bends. In paper in this dissertation it is suggested that lenses disintegrate by the development of R, P and R` shears, which gradually break down host rocks lenses to fault rocks lenses and finally into fault rocks layers. Furthermore, there is observed a difference in growth of small faults (0-1 displacement) to mesoscopic 1-10 m and large faults (>10m). For small faults segment linkage processes and also the accumulation of host rock material is the most important deformation mechanism and controls the thickness, following the model of Childs et al. (2009). A change in thickness and displacement relationship between the small faults and large faults may be related to the development of a thoroughgoing slip surface and a subsequent general localization of the fault core. In paper 5 this localization is suggested to take place around 10 meters of displacement. However, awareness should be taken that large thickness changes is observed for the large faults as well and this can be related to for example; (i) the closeness to a major shale layer, (ii) the linkage of large fault segments, or (iii) by the influence of other faults.

In this dissertation also the differences between thickness and displacement relationships of carbonates and sandstones was investigated. The basic result is that fault cores in carbonates are generally thicker than faults in sandstones. The deformation of these two lithologies is different, especially for small scale faults, dominated by porosity collapse in sandstones in contrast to brittle fracturing and cementation in carbonates.

Modelling of fault cores

In the Fault Facies project, the aim has been to model faults as different facies, in which observed fault core elements of distinct properties are modelled as volumes, represented as grid cells (Braathen et al. 2009, this thesis). The fundamental outcrop database has been time consuming to generate, in that fault zone elements as found in existing literature in many cases can not be adapted, primarily because faults have not previously been described as facies. Quantitative methods in outcrop analysis similar to data collection in sedimentary facies analysis, involving detailed facies description, are therefore necessary, and will be so in the years to come. In numerical models, concerns are related to grid design and up scaling (see Nøttveit et al., paper 3). However, the Fault Facies workflow is by now fully automated, facilitating comprehensive sensitivity studies investigating the effects of various fault architectures on fluid flow. Since such model testing has its fundament in the outcrop analogue database more quantitative geological data is needed to fully utilize this method. Of great importance is the fluid conductivity or impediment quality of faults. Results from this thesis shows that these qualities are very different from faults in carbonates to faults in sandstones. This difference is depending on several factors, including host rock characteristics, fault geometry, and fault core composition. Shale are undoubtedly reducing the permeability of the fault core (Færseth 2006) and also influencing the composition in fault cores. Internal fractures may on the other hand increase the fluid conductivity. The study from Greece shows that in fault jogs/bends the fracture frequency and complexity is higher and these zones are more likely to conduct fluids, along but also across the fault. The fluid chemistry seems also important for the fault fluid flow property, whether the fluids are dissolving or precipitating calcite along faults. In the situation in which water dissolves calcite, the fault may act as major conductor. On the contrary with high cementation precipitation rate the fluids will flow more periodically depending on the opening of fractures and the consequent sealing of these. Another aspect is here the influence of pressure solution around faults with larger burial depths than the ones studied in the present study. Pressure solution will gradually lower the permeability due to cement sealing of voids and fractures (Labaume et al. 2003; Benedicto et al. 2008).

Limitations related to the current study

As discussed in paper 1, outcrop based studies of faults are challenging due to the fact that only a part of the structure of interest is observed (Braathen et al. 2009, paper 1 this thesis). For extensional faults, the observation from a given fault represents a progressively smaller window of the fault as fault throw increases. This issue is also important since the outcrop data gathering to some degree are depending on subjective considerations. The papers 2 and 3 illustrate different view on fault geometry, exemplified by the Doumena Fault. In paper 2 the fault surface is interpret as a continuous slip surface defining a mild ramp-flat-ramp geometry, whereas in paper 3 this fault is interpreted as an oblique exposure in which the fault core is exposed as the lower ramp and the damage zone core transition comprises the lens zone in the upper ramp-flat part. Both these interpretations might be right, since there are no exposures of the hanging wall section of the fault core that can further highlight the fault architecture of the fault. Therefore, it is questionable whether there is a more ductile shale dominated core above the exposed slip surface, such as the shale dominated core discovered in the Aigion Fault formed in similar host rocks (e.g. Micarelli et al. 2003), or that the loose un-consolidated core in the lower ramp can be extrapolated above the upper ramp flat as suggested by Nøttveit et al. (paper 3 this thesis).

Since the architecture, geometry and composition of faults in subsurface reservoirs have limited accessibility, fault outcrops are used as analogues in many studies. However, many uncertainties relate to such comparisons. Deformation in rocks in outcrop analogues may have occurred after the rocks were consolidated and the rocks where uplifted and subjected to erosion and consequently increased fracturing (Hesthammer & Fossen, 2000). Subsurface reservoirs have due to its present position a different uplift and consolidation history, where the deformation may have initiated recently after deposition and prior to consolidation. Thereafter, instead of uplift the rock has been subsequently buried (Hesthammer & Fossen, 2000).

Uncertainties are also related to the displacement and thickness definition of fault cores, especially when the displacement exceeds the outcrop size. In such cases a full stratigraphical control is necessary to establish throw, which in many cases give approximate displacements. It is likely that the thickness measurements of faults are influenced by the definition the structural geologist have in mind when he/she do the measurement. A strength of the enclosed data set in contrast to other published data is that the thickness measurements are always connected to a fault composition and a geometry description, which will make the data more reliable. In other words, these data connects to more than just thickness and displacement relationships.

Summary and conclusion

The overall aim of the present work is to increase the knowledge of fault composition and geometry in carbonate rocks in combination opening for an architectural description. Further, this dissertation focuses on how outcrop data can be used as inputs to numerical models, by classifying and quantifying fault core elements and evaluating thickness and displacement relationships (Fault Facies). The following conclusions can be drawn from this PhD thesis:

- Main elements in fault cores of carbonates are slip surfaces, layers and membranes of fault rocks, protolith and fault rocks lenses, shale smears, cemented veins and fault rocks. Overall fault cores have a great variability in architecture, ranging from planar simple and narrow faults to wide complex zones of heterogeneous composition and complex fracture and lens geometry.

- The Doumena and Pisia faults offer excellent outcrops, with sizes allowing architectural data to be gathered within a wide window of observation of two strikingly different fault cores. The Pisia Fault is a major planar fault, which shows distinctive development of corrugations and a simple fracture network consisting of R shears. Contrary, the Doumena fault is a major fault with irregular geometry, including bends and jogs. Within this fault more complex fault core characteristics are found, including lenses and complex networks of R, P, R` and Y fractures. Corrugations and slip surface undulations show aspect ratios of 1:19 and 1:14, whereas lenses in the Doumena Fault have an average length-width relationship of 3/2. Fluid flow in major extensional faults is parallel to fault core in planar faults, while in fault bends, fractures and lenses increase the potential for across fault fluid flow.

- The 3D model of the Doumena Fault is complex and challenging. The model is based on an architectural synthesis including a fault core consisting of fractures, lenses and fault parallel zones of fault rocks bound by a damage zone of an inner intense deformed part and an outer weakly deformed part. In the model the core is subdivided into an inner core comprising fault parallel layers of fault rocks and an outer part consisting of fracture dominated lenses. Structuring fault outcrop data involves compartmentalizing the different fault zone components considered most influential to fluid flow, eventually to form a hierarchy of different models. These hierarchies of models are after refinements finally incorporated to the full scale fault zone model.

- An important volumetric parameter is the thickness and composition of faults cores according to the displacement. Thickness and displacement relationships of faults in both sandstones and carbonates presented in this study feature a gradually decreasing thickness/displacement ratio, corresponding to a localization of faults with increasing displacement. In carbonate faults there is a relationship in which the geometrically complex faults have wide cores in contrast to geometrical simple cores, which is characterized by thin and even thick cores. There is also a change in fault core composition, where small displacement faults (D<3m) consists mainly of clay gouge and cement veins and larger faults (D>3m) is more likely to consist of fault rocks and major shale smears. However, fault rocks are most common in complex parts of faults such as bends, overlap and fault jogs. In order to capture carbonate faults as volumes in a realistic way, two predictive thickness-displacement trend lines can be used. One trend line describes thin fault segments consisting of gouge, shale and calcite cement, which in reservoir models could be approximated by a simple single cell fault layer with homogenous qualities. Further a second trend line describes the thickness of complex and composite fault cores which are expected to be of a complex architecture and is therefore best characterized by a fault facies volumetric description.

- The main aim of the Fault Facies project has been to describe and model fault zones as volumes and hence more similar to faults in nature. To do this descriptions and quantifications from outcrop examples are used. In this dissertation it is shown that faults can be divided into components such as slip surfaces, fault rock layers and membranes, host rock and fault rock lenses, clay gouge, shale smears, cemented veins and deformation bands. In a modelling perspective these components have large differences in properties such as permeability and porosity. Statistics of lenses shows that there is an apparent relationship between the thickness and along dip length, and along strike width and along dip length. However, the dimensions expressed by trend lines are different for different host rocks, and for different fault displacement. Larger faults have lenses with longer dip axis than smaller faults. Scaling laws achieved for the thickness and displacement measurements of faults show a considerable scatter, but trend lines indicate a power law function with an exponent of 0,5 for both sandstones and carbonates, indicating that the thickness-displacement relationship for small scale faults cannot be linearly extrapolated to large scale faults.

Future perspective

Numerical modelling

Results form papers 4 and 5 suggest that the ratio between the fault core thickness increase with increasing displacement based on a power law function, therefore a constant thickness displacement relationship cannot be utilized based on this study. This may be the results of consistent measurements of the fault core, which may cause that larger faults appear thinner than for previous studies. These data together with the knowledge of composition should therefore serve as input to reservoir models of the fault core. The thickness of the faults can be represented by the number of cells in the fault width dimension. In its most simple form, faults from this study (paper 4 and 5) which have complex and thick fault core geometries may be modelled with multiple grid cell layers of variable properties. Thin fault cores with a simple geometry may be modelled with a single layer grid cell. Also, it is possible to model the difference in fault core composition, as for instance breccias, have different properties than shale gouge.

Strain modelling

Although computer technology cannot fully compensate the natural variability of outcropping faults, it would be interesting to compare simulated faults formed in computer based strain models (discrete and finite elements) with natural faults from this study. Will these computer based programs simulate similar thickness of faults as in nature? If not, what is the discrepancy? Will a two-fold zonation occur, with simple straight segments in between complex jogs?

Cementation in fault zones

From this and many other studies of faults, cement seems to be a common and important fault core element (e.g. Boles et al., 2003; Agosta and Kirchner 2003; Eichhubl et al. 2009). Especially within carbonate faults, cementation is enriched near fault zones and along slip surfaces. However, the influence cementation may have on fluid flow in faults, and the cements potential to act as a sealing agent needs much more investigation. One of the observations is that cementation indicates that fluids have been flowing at least periodically, likely controlled by fault activity (Sibson 1975, Boles et al. 2004). The pattern of such periodical events of fluid flow is a great challenge in modelling fluid flow in reservoir settings (Jin et al. 2008). In tight carbonates, the crack seal mechanism is an important initiating mechanism for faults. On the contrary, in porous rocks cementation seems more common in faults with some displacement (Micarelli et al. 2006). This is most likely so because faults in porous rocks tend to lower the permeability. Therefore cement is precipitated along faults due to the permeability contrast. Secondly, a through going slip surface may generate a pathway for fluids, where cement is precipitated in the fault surface. Based on these observations several question arises: Where in the fault zone is cement most frequently accumulating, slip surfaces, damage zones, or in fault rocks? What is the cause, pressure solution or percolating fluids? Another interesting aspect is what consequence CO_2 sequestration may have on calcite cementation in fractured and faulted carbonate reservoirs? CO_2 sequestration and especially CO_2 mixing with water lowers the Ph in a carbonate reservoir. Predicted fluid Ph as low as 3,5 will cause more dissolution and thereby modify and influence the porosity and permeability of these reservoirs (Benson and Cole, 2008).

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