Fault zone modelling: A hierarchical approach for numerical modelling of fault structures, upscaling and flow simulation

Master thesis

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Acknowledgments

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## Contents

**Acknowledgments**

### 1 Introduction

1.1 Fault zones

1.1.1 Fault architecture

1.1.2 Permeability structure

1.2 Fault modelling

1.2.1 Numerical representation faults

1.3 Aim of study

1.4 Outline of the thesis

### 2 The Geological Setting of the Gulf of Corinth

2.1 Regional tectonics

2.2 The structure of the Gulf of Corinth rift system

2.3 Stratigraphy

2.4 The Doumena Fault Zone

### 3 Characterization of the Doumena Fault Zone

3.1 Introduction to the study area

3.2 Method

3.3 Characterization of the Doumena Fault Zone

3.3.1 Fault scarp inclination and morphology

3.3.2 Internal architecture of the fault core

3.3.2.1 Fault rocks

3.3.2.2 Fracture sets

3.3.2.3 Lenses

3.3.2.4 Spatial distribution of fault rocks and lenses

3.3.3 Fourier analysis

3.3.4 Quantification of fault zone components

3.3.4.1 Fault zone thickness

3.3.4.2 Lens dimensions
3.4 Fault zone model

4 Fault zone modelling
4.1 Model assumptions
4.2 The fine scale geologic model
  4.2.1 Preparing the input data
  4.2.2 Modelling the fault surface
  4.2.3 Generating the fault core and damage zone boundaries
  4.2.4 Designing the modelling grid
  4.2.5 Populating the grid by the use of facies modelling
4.3 Petrophysical properties
  4.3.1 Effect of the fracture sets on permeability
    4.3.1.1 Representing fractures as a permeable media
    4.3.1.2 Hydraulic aperture of the fracture sets
    4.3.1.3 Permeability estimate for the fracture sets
    4.3.1.4 Effect of fracture orientations on the permeability
  4.3.2 Permeability distribution in the lenses
    4.3.2.1 Model setup
    4.3.2.2 Upscaling algorithm and choice on boundary conditions
    4.3.2.3 Results
    4.3.2.4 Sources of uncertainty
  4.3.3 Permeability distribution in the fine scale geologic model
4.4 Simulation scale model
  4.4.1 Permeability representation and upscaling
  4.4.2 Coarse modelling grid
  4.4.3 Simulation style grid – Direct sampling from modelling grid
  4.4.4 Simulation style grid – Utilizing a transfer grid
4.5 Exporting the model to Eclipse

5 Flow simulation
5.1 Case setup
5.2 Results for the fine scale model
  5.2.1 Experiment 1: Damage zones included
  5.2.2 Experiment 2: Fault core only
5.3 Results for the coarsened models and comparison with the fine scale model

6 Conclusions

References

Appendices
Faulting is, next to sedimentary facies variations, the main factor introducing heterogeneities in hydrocarbon reservoirs. Faults occur on all scales, from major trap confining faults to smaller intra reservoir faults and fractures and show a wide range of properties; they may act as barriers, conduits or barrier/conduit systems and significantly influence reservoir performance. Given their complexity, in terms of architecture and property distributions, providing a proper description of faults is not an easy task, even in outcrops. Predicting these features in subsurface reservoirs presents even more of a challenge. In order to understand fluid flow behaviour in faulted reservoirs, a sound understanding of fault architectures and properties is primarily needed. Putting this knowledge into practical use in order to forecast production performance of petroleum reservoirs, it must, furthermore, be robustly implemented into reservoir models which allow fluid flow responses to be predicted.

In the present study a new conceptual method for fault modelling is investigated using an experimental reservoir model of a fault zone, based on field data from a well exposed fault. As an introduction to this, some present practices of fault and fault zone descriptions and fault representation in models are reviewed below.
1.1 Fault zones

1.1.1 Fault architecture

Faults consist of a footwall damage zone, fault core and hanging wall damage zone (Figure 1.1) (e.g. Caine 1996). The majority of the displacement is accommodated within the fault core, resulting in a complex architecture where slip planes, fault rocks and horses (lenses) are common features (Figs. 1.1, 1.2) (Childs 1996; Childs et al. 1997; Gabrielsen and Clausen 2001; Lindanger 2003). The lenses commonly consist of undeformed host rock, heavily fractured host rock or entirely of fault rocks (Gabrielsen and Clausen 2001; Berg and Skar In prep).

Figure 1.1: Simplified conceptual fault zone with the main components included, i.e. hanging wall damage zone, footwall damage zone and fault core with lenses and fault rocks. Figure from Braathen (unpublished).
The damage zones contain an abundance of minor faults and fractures (Fig. 1.2) (e.g. Bruhn et al. 1994; Caine et al. 1996; Lindanger 2003). Deformation is less intense compared to the fault core, and typically there is a gradual decrease in deformation intensity away from the fault core. For inclined normal faults the damage zone is often recognized to be asymmetric, with the hanging wall damage zone being wider than the footwall damage zone (Clausen et al. 2003; Doughty 2003; Berg and Skar In press).

Fault zones may possess simple or complex geometries depending on a number of factors, such as host rock lithology, the principal type of stress field, the depth of burial and the dynamic evolution of the fault (Gabrielsen et al. In prep). Complex fault zones can change significantly in strike and dip direction with respect to thickness distribution and composition (Fig. 1.2).

Figure 1.2: Schematic illustration showing the complexity within a fault zone. The figure demonstrates how the fault zone architecture may vary in strike and dip directions. Significant variations can occur even over short distances. Figure from Gabrielsen et al. (In prep).
1.1.2 Permeability structure

The permeability structure of fault zones is difficult to assess. The heterogeneous nature and spatial distribution of the fault zone components result in a highly variable permeability structure. Prediction of hydraulic properties of fault zones is therefore largely based on empirical relations (e.g. Sperrevik et al. 2002). The Shale Gouge Ratio (SGR) is one of the most widely applied parameters for quantifying the seal potential of faults. The SGR method uses the clay or shale content of the faulted lithology and fault throw to infer the seal capacity of the fault (Yielding et al. 1997). More specifically, the SGR is equal to the volume fraction of shale/clay content in the rocks that have slipped past the area of interest. Generally, a fault with SGR higher than 15-20% is considered to be sealing (Yielding 2002). Based on outcrop studies, Doughty (2003) argued that the SGR method is better in predicting fault zone hydraulic properties compared to other available algorithms such as Shale Smear Factor (Lindsay et al. 1993) or Clay Smear Potential (Bouvier et al. 1989).

Although the SGR method has proven its robustness, this method only applies to siliciclastic lithologies. Using SGR to describe the hydraulic properties of faults in carbonate rocks is inappropriate. In addition, fault zones have showed to be very heterogeneous and may vary in thickness and composition both laterally and vertically (Fig. 1.2) (Bruhn et al. 1994). The permeability structure thus varies accordingly.

1.2 Fault modelling

Understanding and predicting fluid flow across faults is an important parameter in reservoir modelling and reservoir simulation. Nevertheless, state of the art reservoir modelling software has limited functionality for modelling of faults, largely forcing users to employ various proxies to describe fault transmissibility’s instead of building accurate models of fault zones. Consequently, simulation of fluid flow is inherently hampered by the limited ability of the reservoir modelling tools to describe adequately the nature of flow across and along faults.
1.2.1 Numerical representation of faults

In conventional reservoir modelling software, faults are implemented as surfaces. Splits are introduced into the grid to account for juxtaposition. Resistance to flow across faults is conserved in the model by a transmissibility modifier, assigned to the cell faces adjacent to the fault surface (Fig. 1.3) (Manzocchi et al. 1999). A considerable effort has been made in recent years to develop methods for determining transmissibility based on outcrop analyses (e.g. shale gouge ratio). The transmissibility is derived from empirical methods (e.g. Sperrevik et al. 2002; Yielding et al. 1997), or calculated from production data whenever available. One of the shortcomings of the transmissibility concept is that it fails to account for fluid flow along fault zones.

The implicit representation of faults as zero-volume planes is a major simplification. In the past few years, modelling of faults as volumes has been attempted (e.g. Berg and Øian 2004). Clearly, this way of representing faults numerically is favourable, considering the large spatial variability in petrophysical properties throughout a fault zone. However, the implementation of faults in numerical models is complex, as faults typically consist of features on several length scales, i.e. fractures, slip-planes and lenses. Each scale must be represented with suitable techniques within the same model.

The limited computing power available implies that only the large scale features can be represented explicitly in the numerical models. The effect of minor structures has to be accounted for by different upscaling techniques (Flodin et al. 2001, 2004). Upscaling of numerical models is difficult and affiliated with uncertainty. This process also becomes increasingly difficult when more than one fluid phase is present.
Figure 1.3: Left: Highly simplified reservoir model with an incorporated fault. Right: An alternative way of representing faults in reservoir models. In this case flow along the fault zone is possible. Figure is from Tveranger et al. (2005).
1.3 Aim of study

The overall aim of this study has been to investigate and model fluid flow within fault zones, by using an experimental model, partly based on a non-conventional use of standard reservoir modelling software. The basic assumption is that faulting affects a volume of rock and that the spatial distribution of fault zone components with different permeability exerts important controls on flow through fault zones.

An accurate representation of faults in flow simulations is essential if realistic predictions about flow within reservoirs are to be attempted. In particular, models capturing as much of the structural heterogeneities as possible need be constructed.

The work is based on outcrop data from a major fault, the Doumena Fault Zone, in Corinth, Greece. The work is done in collaboration with Eivind Bastesen, who presents a dynamic geologic model for the studied fault. A systematic and detailed description of the fault zone has been carried out, as input to the numerical model.

The thesis attempts at establishing a general workflow for implementing structural data into a numerical model, thereby allowing the effect of faults on fluid flow to be investigated. A flexible and robust framework for modeling fault zones is presented, utilizing an existing reservoir modeling package, Irap RMS. Novel use of the concepts of object-based sedimentary modelling has enabled 3D modelling of faults and petrophysical properties of faults on various scales. By modelling fault zones as 3D volumes, flow within the fault zones is allowed.

Current limitations in computing power limits the representation of faults in simulation scale models to a small number of grid cells. The modeling framework, therefore, includes a section on upscaling, using flow simulation to quality check the performance of resulting coarse models.
1.4 Outline of the thesis

The thesis is inter-disciplinary, involving integration of detailed structural analysis and numerical modelling, as a step towards more accurate representation of faults in fluid flow modelling.

The workflow is reflected in the thesis outline and consists of:

1) Collecting data in the field.
2) Processing the data and develop methods for including the data into numerical models.
3) Build the actual models
4) Investigating flow properties of the models in a flow simulator.
5) Presenting the results
6) Extract the important steps during the whole process and construct a framework for dealing with similar problems.

These steps are presented within the different chapters. Chapter 2 gives a brief introduction to the regional geology of the study area, in order to place the studied fault into a regional context. Chapter 3 provides the results from the structural analysis of the Doumena fault. The results of the analysis form the basis for the development of a numerical fault zone model, which is presented in Chapter 4. This chapter also investigates different upscaling techniques available for coarsening the fault zone model. The performance of these upscaling techniques is investigated and discussed in chapter 5, where the fine scale model and the coarsened models are flow simulated in Eclipse. The main conclusions of the work are presented in chapter 6.
The Gulf of Corinth is situated in a region that is presently one of the most seismically active areas in the world. The geological history of the region includes both compressional and extensional tectonics related to the collision of the African-Arabian plate and the Eurasian plate, a process still ongoing. The aim of this chapter is to provide a short summary of the structural evolution of the Corinth rift system in order to place the study area into a regional context.

2.1 Regional tectonics

The relative plate tectonic movement and deformation in the eastern Mediterranean has during the last 70 m.y. been dominated by the collision between the African-Arabian and Eurasian continental plates (Fig. 2.1) (Le Pichon and Angelier 1979). Approximately 1000 km of N-S shortening has taken place over this time interval (Biju-Duval et al. 1977). The N-S shortening caused the development of the Hellenides fold and thrust belt (Dewey et al. 1973) and the Hellenic Trench, the latter along which the African-Arabian plate is subducted below the Eurasian plate (Ryan et al. 1970).

The dextral North Anatolian Fault Zone (NAFZ) in Turkey also plays an important role for both the development in the eastern Mediterranean and the deformation of the Aegean microplate, in which the Gulf of Corinth is situated (Fig. 2.1) (Le Pichon and Angelier 1979; Le Pichon et al. 1995).
Although the overall tectonic regime in the region is contractional, the Miocene-recent evolution of the Aegean microplate is mainly dominated by extensional tectonics. In Late Miocene an extensional regime prevailed, interrupted by two compressional events affecting the central parts of the Aegean region (Angelier 1978). Extension continued through the Plio-Quaternary in the interior of the Aegean micro-plate, while a compressional regime persisted along its Mediterranean margin.

Several mechanisms have been proposed for the extension observed in the Aegean region. McKenzie (1978) proposes that the surface motion reflect convective motions occurring in the astenosphere. Le Pichon and Angelier (1979) infer that gravitational spreading of the Aegean micro-plate along with subduction roll-back may explain the observed extension. Le Pichon (1995) relates the extension to the collapse of the Hellenides and the westward push of the Anatolian plate. More recent work proposes the westward motion of the Anatolian plate and subduction roll-back to be the controlling factors of the extension (Doutsos and Kokkalas 2001).

Extensive regional Quaternary uplift is observed in the western parts of the Aegean region, reaching a total of 2 km on the northern Peloponnese, just south of the Gulf of Corinth (Ori 1989; Sorel 2000). Time-averaged uplift rates in the order of 1.5 mm yr$^{-1}$ are identified for the northern Peloponnese decreasing in magnitude towards the east, where an uplift rate of 0.3 mm yr$^{-1}$ is inferred for the Corinth isthmus (Collier and Leeder 1992). Different mechanisms have been proposed to...
explain the observed regional uplift; underplating by subducted sediment (Le Pichon and Angelier 1981), post-orogenic isostatic uplift (Doutsos and Piper 1990), lower crustal flow (Armijo et al. 1996; Westaway 2002) and trench roll-back leading to differential uplift of the overriding plate (Leeder et al. 2003; Moretti et al. 2003).

2.2 The structure of the Gulf of Corinth rift system

The 140 km long and 40 km wide Corinth-Patras rift separates the pre-Neogene folded basement of continental Greece and Peloponnese (Doutsos and Poulimenos 1992). The rift consists of the WNW-trending Patras and Corinth grabens, which are connected by the NE-trending Rio graben. Generally, the Corinth-Patras rift is assumed to be an accommodation structure between the stable Eurasian plate and the southwestward moving South Aegean area (Angelier 1978; Le Pichon and Angelier 1979; Doutsos and Kokkalas 2001).

Figure 2.2: Structural map of the Gulf of Corinth region. The study area is located north of Kalavrita (The Doumena Fault Zone) and is indicated by the red arrow. The red line marks the position of the cross-section in figure 2.3. Rectangle marks the area of figure 2.4. Figure from Moretti et al. (2003).
The modern Gulf of Corinth (Fig. 2.2) has developed in the hanging wall of major north-dipping normal faults that are arranged en echelon along its south coast (Roberts and Jackson 1991). The surface traces of these faults typically extend 12-15 km parallel with the Gulf trend. These major faults define a series of fault blocks that are approximately equally sized (Fig. 2.3).

There are two competitive views on how these major faults relate at depth (Ori 1989; Doutsos and Piper 1990). The first group of models interpret the faults as listric that merge into a low-angle detachment at depth. The southernmost faults are believed to have formed first with new faults forming progressively to the north, rendering the faults to the south inactive. The major Gulf of Corinth Fault constitutes the southern active bounding fault of the Corinth graben at present, with an over 1000 m thick (Goldsworthy and Jackson 2001) syn-sedimentary succession deposited on top of the downthrown block (Higgs 1988; Doutsos and Poulimenos 1992; Sorel 2000). The second group of models contest the existence of such a detachment. These models suggest that two generations of faults were active at different times. The most recent generation of faults, including the Gulf of Corinth fault, was steeper, and affected the area at least as far south as the Doumena Fault Zone (Westaway 2002; Moretti et al. 2003). A portion of the uplift observed in the northern Peloponnese is related to foot-wall uplift associated with the major faults (Doutsos and Piper 1990; Collier and Leeder 1992). Stewart and Vita-Finzi (1996) estimates that at most 20% of the uplift can be considered to be footwall uplift.

Figure 2.3: Cross-section sketch from the Gulf of Corinth to Mt. Helmos. Black arrow points out the studied fault. The position of the cross-section is shown in figure 2.2. Figure from Solheim (2002), modified from Sverdrup and Aarseth (1998).
2.3 Stratigraphy

The west-verging stack of flat-lying nappes of the southwest Hellenides is what generally is referred to as basement in the area (Doutsos and Poulimenos 1992). Each of these nappes; the Plattenkalk nappe at the base, the Gavrovo-Tripolitsa nappe in the middle and the Pindos nappe at the top, consists of a 2-3 km thick competent sequence of Mesozoic carbonates and a thin incompetent cover of flysch (Doutsos and Poulimenos 1992).

The sedimentary succession that overlies basement represents rocks that were deposited during the tectonic evolution of the rift system (Fig. 2.4). The uplifted syn-rift sediments exposed in the northern Peloponnese, record that rifting in the Gulf of Corinth occurred in two phases. According to Ori (1989), the initial Miocene rifting phase developed a basin that was wider than the present Gulf of Corinth. The deposits are mainly of continental and shallow-water lacustrine origin that propagated towards the east, which indicates that there was no major fault-scarp relief during the initial subsidence. These deposits are overlain by a more than 1000 m thick Pliocene unit consisting of alluvial and marine deposits.

The second phase of rifting is marked by a change in sedimentation and subsidence rates in Early Pleistocene. This resulted in deposition of thick lacustrine deposits and deltaic sequences prograding towards the north. In general, the
Quaternary facies distribution varies significantly from south to north related to differential subsidence rates (i.e. more regional uplift in the south) (Sverdrup and Aarseth 1998). Alluvial fans and conglomerates are the dominant deposits in the south, whereas deep-water Gilbert-type deltas dominate in the central parts. In the north are mainly lacustrine carbonates and marine shales deposited. Three generations of fan deltas are recognized, including the fan deltas that are active today. The two former generations are uplifted some 300-400 m and 600-1200 m above sea-level, respectively.

2.4 The Doumena Fault Zone

The Doumena Fault Zone is located on the northern Peloponnese, approximately 15 km south of Aigion. The WNW-trending surface trace is around 9-12 km and terminates to the east towards the Vourikis transfer fault (Doutsos and Poulimenos 1992; Sverdrup and Aarseth 1998; Moretti et al. 2003). The total throw is estimated to about 240-1000 m, i.e. on the same scale as the other major block bounding faults in the area (Doutsos and Poulimenos 1992; Flotté and Sorel 2001). The Doumena Fault Zone is believed to form the boundary between two large fault blocks, named the alpha-block and the beta-block (Figs. 2.3) (Sverdrup and Aarseth 1998).

The NNE-dipping Doumena Fault Zone cuts through the Kerpini series and the underlying basement (Cretaceous limestones of the Pindos nappe) (Flotté and Sorel 2001). The Kerpini series probably relate to the transition between the first and the second phase of rifting, and consist of alluvial fan deposits, mainly conglomerates (Ori 1989). The pre-Neogene basement rock in the area consists of heavily deformed and low metamorphosed carbonates/limestones (Ori 1989; Doutsos and Piper 1990; Doutsos and Poulimenos 1992).

The age of the fault is unclear. Doutsos and Poulimenos (1992) estimate the age to be in the order of 1.8 m.y. Moretti et al. (2003), however, claim that the fault activity is post-sedimentary, linking the movement to a third extensional phase starting 150-120 000 years ago.
Chapter 3

Characterization of the Doumena Fault Zone

3.1 Introduction to the study area
3.2 Method
3.3 Characterization of the Doumena Fault Zone
   3.3.1 Fault scarp inclination and morphology
   3.3.2 Internal architecture of the fault core
      3.3.2.1 Fault rocks
      3.3.2.2 Fracture sets
      3.3.2.3 Lenses
      3.3.2.4 Spatial distribution of fault rocks and lenses
   3.3.3 Fourier analysis
   3.3.4 Quantification of fault zone components
      3.3.4.1 Fault zone thickness
      3.3.4.2 Lens dimensions
3.4 Fault zone model

The Doumena Fault Zone is part of a series of faults, which delimit the main fault blocks on the southern flank of the Gulf of Corinth rift system. The fault has a displacement in the order of several hundred meters, and is well exposed which offers an excellent opportunity to map the architecture of large-scale block bounding faults.

The objective of this chapter is to provide a qualitative and quantitative description of the architecture of the fault zone, in order to assess the main structural components affecting the fault’s permeability structure. A conceptual model for the fault zone architecture is proposed, based on extensive mapping of the fault surface along with a mathematical analysis of the surface topography. This architectural framework constitutes the fundamental input for the numerical model, which is constructed in the next chapter.
3.1 Introduction to the study area

The Doumena Fault Zone has been studied at a locality situated on the north face of the Prophitis Ilias massif, immediately south of the Doumena village (Fig. 2.2). Here, the fault juxtaposes limestones of the Pindos nappe in the footwall with poorly consolidated clastics of the Kerpini series in the hanging-wall (Fig. 3.1) (Flotté and Sorel 2001). The locality displays an excellent exposure of a part of the Doumena Fault Zone, extending over an area of several thousand square meters. The topography of the surface exposure shows large-scale undulations in both the strike and dip directions. The exposed fault surface has been interpreted to represent a part of the core of the Doumena Fault Zone (e.g. Solheim 2002; Bastesen 2005).

Figure 3.1: Overview picture of the study area showing the exposed fault surface and the rocks constituting the footwall and hanging wall of the Doumena Fault Zone. The rectangle shows the locality where the field work was carried out. The arrow indicates the direction of movement along the fault.

3.2 Method

In order to provide a quantitative description of the architecture of the Doumena Fault Zone, mapping has been performed on two scales: (1) mapping of the fault surface morphology and (2) mapping of the internal structure of individual structural features. The mapping was carried out to (i) quantify the large-scale geometries on the fault surface and identify spatial geometric variations, and (ii) identify different types of structural features (e.g. lenses and fault rocks) along with their spatial distribution.
The surface mapping was performed by establishing a grid of thin strings parallel to the strike and dip of the fault (Fig. 3.2). A total of 9 strike parallel and 2 dip-parallel grid lines were included. The gridlines were carefully positioned in such a way that topographic highs and topographic lows were captured. The dip-parallel (down-dip trending) gridline located farthest to the east was chosen as the reference level. The orientations of all gridlines were measured, as well as the vertical distance between each profile and the reference profile at the point of intersection. The sample data were then acquired by working systematically along these gridlines, recording the required information. The variables measured at each sample point were strike and dip of the surface, horizontal distance from the reference line and height between the gridline and the ground. The orientation data (strike and dip) were measured with a Silva Ranger compass using the right-hand rule. Measures of length and height were carried out by using a measurement tape. The data collected along the gridlines were subsequently transformed into individual topographic profiles (Fig. 3.3, 3.4), which form the basis for creating a surface map of the exposed fault surface.

Figure 3.2: Photography of the exposed surface of the Doumena Fault Zone. The thin lines indicate the position of the grid established across the fault surface. The reference line is the dip parallel line farthest to the east (2). The black arrow points out the direction of movement.
Mapping of individual structural features was done by collecting additional data on fractures (e.g. type, distribution and interaction) and the pattern of amalgamating slip planes. These structural sample data were then superimposed onto the surface map, allowing identification of rock lenses of varying geometry and dimension. The most distinct rock lenses were mapped more thoroughly by recording the internal fracture pattern and composition, along with measurements on length, width and thickness. Subsequently, a structural map showing the outline of individual rock lenses was compiled (Fig. 3.5).

The possibility of any periodic character of the undulating topography has been investigated. The topographic profiles, generated from the surface mapping, were studied by means of Fourier analysis. The method of Fourier analysis transforms any signal in either time or space into the frequency domain, allowing search for any characteristic periodicity. Characteristic frequencies appear as strong peaks in the resulting frequency plot, and may easily be converted to wavelength.

### 3.3 Characterization of the Doumena Fault Zone

#### 3.3.1 Fault scarp inclination and fault core morphology

The dip-parallel topographic profiles (Fig. 3.3) show the irregular, non-planar geometry of the exposed fault surface observed in this direction. Apparent from these profiles are some large-scale variations in the average fault scarp inclination. The lowermost part has an average inclination of around 55°. The middle section shows a wider scatter in the data with an average dip angle of 40°. In the uppermost part, the fault surface has an average inclination of 50°. Based on this difference in inclination, the outcrop is divided into three zones; zone A, zone B and zone C (Fig. 3.3).

The profiles also reveal some differences in the surface morphology in the dip direction (Fig. 3.3). Zone A (the lowermost part) comprises multiple parallel slip surfaces with a planar geometry. In contrast, zone B (middle section) is characterized by an undulating topography in both dip and strike directions (Figs. 3.3 and 3.4), where the surface is made up of several amalgamating sub-parallel slip planes. This network of anastomosing slip planes define stacked rock lenses (Fig. 3.5). In addition, it can be seen from the interpretation of the profiles in zone B (Figs. 3.3, 3.4)
that the geometry of the core-footwall damage zone boundary roughly resembles the topography, i.e. the contact between fault rocks and partly deformed host rock in the figure. In zone C (uppermost part), the fault surface exhibits mostly intact rock permeated by shear fractures. It is more difficult to distinguish individual rock lenses, though some slip planes are identified.

Figure 3.3: Topographic profiles that are oriented parallel to the dip direction of the fault. The profiles 2 and 3 are constructed based on data collected along the dip-parallel gridlines in Figure 3.2. The location of profile 1 is marked in the compiled structural map (Fig. 3.5). Notice the irregularity in these surface traces. The profiles extend through zones A-C which is discussed in the text. Figure is from Bastesen (2005).
Figure 3.4: Topographic profiles that are oriented parallel to the strike direction of the fault. The profiles are constructed based on data collected along the strike parallel gridlines in Figure 3.2. The profiles are located in zone B. Note the undulating topography and different geometries along the profiles. Figure is from Bastesen (2005).
Figure 3.5: Structural map of the fault surface in zone B. The coloured lines show the outline of the major lenses. Figure is from Bastesen (2005).
3.3.2 Internal architecture of the fault core

Based on the above geometric sub-division of the fault zone, the most characteristic components contributing to the overall fault architecture will be described. It should be noted that zone B is aerially the most extensive and has the best continuous exposures. This zone has therefore received more attention than zones A and C.

3.3.2.1 Fault rocks

The description of fault rocks is based on Bastesen (2005), who has identified four main types, i.e. indurated grain-supported breccia, indurated matrix-supported breccia, unconsolidated grain-supported breccia and fault gouge.

The indurated grain-supported breccia consists of clasts (~30%), grains (~45%) and matrix (~25%). The clast sizes are in the range 1-10 mm, whereas the matrix fragment size varies between 0.05 mm and 0.1 mm. The distribution of the clasts, grains and matrix for the indurated matrix-supported breccia is ~10%, ~65% and ~25%, respectively. In the unconsolidated grain-supported breccia, clasts ranging between 1-20 mm constitute 60% of the total volume, while grains with a size of 0.5-1 mm dominate the remaining volume.

The unconsolidated grain-supported breccia is expected to have higher porosity than the two previously described breccias, due to local clusters of voids up to 2 mm in diameter (Fig. 3.6). Common for all the fault rock types is that the fragment size of the fault rock matrix is at least 2 orders of magnitude larger than the grain size of the host rock. This is an important observation concerning the petrophysical properties of the fault rocks and the host rock.

Fault rocks are mainly found in zone A and in association with the lenses occurring in zones B and C (described in 3.3.2.3). In zone A, the volume of deformed rocks mainly constitutes unconsolidated grain-supported breccia with a cumulative thickness of 3 m or more. In zone B (and locally in zone C), the lenses are to a large extent comprised of fault rocks, i.e. indurated grain supported breccia and indurated matrix supported breccia. Fault gouge is only found locally in small amounts within shear fractures.
3.3.2.2 Fracture sets

The fractures present in the core of the Doumena fault zone are described according to the terminology proposed by Petit (1987). Five main fracture sets have been identified (Fig. 3.7); Y-shears, Ridel shears (R-shears), antithetic Ridel-shears (R’-shears), P-shears and T-fractures (mode I). The Y-shears indicate the main slip plane orientation, whereas the other fracture sets have preferred orientation relative to the Y-shears. The orientations of these fractures sets are mainly parallel/sub-parallel to the strike of the Y-shears. The main difference between the sets relate to the dip angle of the fractures. In addition to these five fracture sets, a fracture set (mode I) trending sub-parallel to the slip direction is recognized.

In zone A, mainly parallel Y-shears delimiting thin sheets of fault rock are found. The average dip is 55°. Zone B contains all the identified fracture sets. The fractures interact by linking up to form rock lenses (see 3.3.2.3). The average dip of
the Y-shears in this zone is 38°, whereas the P-shears and R-shears dip 34° and 54°, respectively. The R'-shears dip on average 75° antithetic to the other fractures and the tension fractures are close to vertical. In zone C, only Y-shears, R-shears and P-shears are identified, with an average dip of 48° for the Y-shears. Similar to zone B, the Y-shears, R-shears and P-shears link up to form rock lenses.

Fractures in carbonate rocks are generally thought to contribute to increased permeability. The effect of fractures on permeability depends partly on fracture aperture. Figure 3.8 shows a close up of a R'-shear fracture where the fracture is represented by the blue seam. The aperture varies between 0.1-0.6 millimetres, with an average of 0.25 millimetres. No further analysis on variations in fracture aperture along single fractures, individual fracture sets or between different fracture sets were performed.

Figure 3.7: The geometric relationship between the fracture sets. The Y-shear indicates the main orientation of the fault plane.

Figure 3.8: Thin-section photography of an antithetic Riedel-shear fracture. The fracture void is represented by the blue seam running obliquely across the thin-section photo. The area illustrated is around 4 by 5 millimetres. Photos are provided by Bastesen.
3.3.2.3 Lenses
The undulating geometry of the fault surface in zone B to a large extent reflects the occurrence of rock lenses with different geometry and dimensions (figure 3.5). The observed lenses can occur on a variety of scales as indicated by the irregularity along the profiles (Figs. 3.3 and 3.4). For instance, some of the topographic highs in figures 3.3 and 3.4 correspond to major rock lenses that are bounded by amalgamating sub-parallel shear fractures. Furthermore, additional networks of shear fractures can represent boundaries that define smaller lenses within the major rock lenses. Thus, a hierarchy of lenses with large variability in dimensions and geometry exist along the exposed Doumena Fault Zone.

1st order lenses represent the largest on the scale of observation. These may be superimposed by higher order lenses, with dimensions less than those of 1st order. The largest of the mapped 1st order lenses in zone B is around 20 m in the strike direction (width) and 40 m in the dip direction (length) (Figure 3.5, 3.9). In general, 1st order lenses in zone B varies from 20-40 m in length and have widths in the order of 10-20 m (Figure 3.9). The corresponding dimensions of the superimposed 2nd order are 2-20 m (length) and 1-12 m (width). The ratios between length and width (Fig. 3.15) coincides remarkably for the two data sets, with a sample coefficient of determination (R²) value of 0.7161 and 0.6627, respectively, the number of samples (N) being 7 and 14. This corresponds to a level of confidence of ~99%. It appears to be a ratio of 2:1 between the length and the width for both the 1st and 2nd order lenses.

The thickness of the lenses is more difficult to assess, due to a general lack of cross-sectional exposures. However, some thickness estimates suggest that 1st order lenses do not exceed 3 m, whereas 2nd order lenses have a thickness of less than 1 m. In order to provide an estimate of the length versus thickness ratio, the thickness was calculated from the observed curvature, assuming a symmetric shape. This gives an estimated length-thickness ratio of approximately 30:1.

A closer investigation of the internal architecture of some of the larger lenses (1st and 2nd order) in zone B and zone C, reveals that the lenses can be subdivided into three main types, type I, type II and type III lenses. The classification is based on how the shear fractures interact to delimit the lenses, as well as the internal characteristics of the lenses (e.g. fractures and rock composition).
Figure 3.9: Scatter plot of length vs. width for 1\textsuperscript{st} and 2\textsuperscript{nd} order lenses in zone B. Large circles represent 1\textsuperscript{st} order lenses, and small circles represent 2\textsuperscript{nd} order lenses. The red and green lines mark the regression line respectively and the black line marks the regression line for all the points. The $R^2$ values are 0.7161, 0.6627 and 0.8622 respectively.

Type I lenses are defined by R-shears, P-shears and Y-shears that link up to define lenses. The lenses are bounded on top by Y-shears, while R-shears and P-shears constitute the main part of the basal boundary (Fig. 3.10). Internally, the lenses consist of fractured host rock, where the fractures are mainly R-shears and P-shears that can define higher order lenses (Fig. 3.10). The amount of slip on the fractures is small.

Figure 3.10: Illustration of the external and internal geometry a type I lens.
Type II lenses are also delimited by well developed R-shears, P-shears and Y-shears. Y-shears comprise the roof and floor bounding slip planes. The up-dip boundary of the lenses is defined by P-shears splaying upwards from the base Y-shears, amalgamating with the top side Y-shears (Fig. 3.11). Similarly, R-shears mark the down-dip termination of the rock lenses splaying downwards from the top side Y-shears, amalgamating with the base Y-shears (Fig. 3.11). R'-shears pervade the rock volume between the Y-shears whereas T-fractures cut through the top of the lenses (Fig. 3.11). The rock lenses are mainly composed of brecciated rock, where the bulk volume of breccia corresponds to the previously described indurated and grain-supported breccia. Higher order lenses are also common within lenses of type II (Fig. 3.11).

*Figure 3.11: Illustration of the external (right) and internal geometry (left) of a type II lens. Figure is from Bastesen (2005).*
Type III lenses (Fig. 3.12) are defined by sub-parallel Y-shears bounding thin sheet like rock lenses of breccia. The breccia in these lenses contains a larger amount of fine-grained material than the type II lenses, corresponding to the indurated matrix-supported breccia. There are no internal shear fractures defining higher order lenses within these rock lenses. The upper bounding surfaces of the lenses are often striated.

The dimensions of the lenses presented above are related to the type II lenses. The dimensions of type I and type III lenses are less constrained, although some data provide rough estimates. 1st order type I lenses are characterized by internal P-shears, which have resulted in a pattern of stacked lenses that have individual width-length ratios of approximately 1:1. Unfortunately, we have not been able to assess any correlation between the axes for the type III lenses. The thickness of lenses of type I appear to be comparable to the thickness of lenses of type II, whereas type III lenses appear to be thinner and more elongate than type I and type II lenses.

Figure 3.12: Photography of a type III lens illustrating its external geometry, delineated with the yellow line. Notice from the fresh cut the slip plane defining the basal boundary of the lens.
3.3.2.4 Spatial distribution of the lenses and fault rocks

Based on the mapping of the fault rocks, fractures and lenses it appears to be a clear relation between the distribution of these structures and the zonation (zone A-C). The distribution of the three types of lenses seems to depend on the position in the down-dip direction. There is little or no change in the distribution of lenses laterally along the outcrop.

Type I lenses mainly occur in zone C close to the transition between zone C and zone B. Here, the 1st order lenses are characterized by internal P-shears, which have resulted in a pattern of stacked lenses. These lenses appear to have a smaller length-width ratio than type II and type III lenses. Type II 1st order lenses are common in zone B and, in particular, in the upper half of this zone. The type III lenses are less common, but are roughly located in the lower half of zone B. There is no sharp transition separating the occurrence of the type II and III lenses. A progressive flattening and stretching of the rock lenses in the direction of movement is observed in the down-dip direction, along with increased internal shattering.

The transition between zone B and zone A is also characterized by a change in style of deformation. Whereas zone B is dominated by lenses, zone A is characterized by a lack of lenses. Instead, zone A is characterized by multiple parallel slip planes dipping on average 55°, delimiting sheets of thick incohesive breccia. This breccia apparently exhibits high porosity.

Based on the spatial variations in the inclination, internal geometry and deformation style along the Doumena Fault Zone surface profile, a conceptual model of the fault architecture is proposed, that accounts for the main observations. The surface profile has dip variations that reflect a ramp-flat-ramp geometry, where zone C, zone B and zone A represent the upper ramp, the flat and the lower ramp, respectively. The stacked lenses (type I) occurring at the transition between zone C and B are associated with numerous P-shears. This is interpreted to reflect deformation in an area of local ‘compression’, which may coincide with deformation within a restraining bend. On the contrary, the deformation products in zone A (e.g. incohesive porous breccia) more likely resemble a deformation product formed under local tension, indicative of deformation in a releasing bend. This model thus accounts for spatial variations in deformation intensity and style mainly as a function of the (local) configuration of the overall master fault geometry.
3.3.3 Fourier analysis

The undulating topography observed in zone B is easily recognized in the sample data shown by the different profiles (Fig. 3.3, 3.4). A mathematical approach, the method of Fourier analysis, has been applied to investigate whether there is any periodicity in the observed undulations. The amplitude signal measured along the grid lines (Fig. 3.3, 3.4, 3.13) is transformed into the frequency domain by an FFT-algorithm and the output is investigated for any characteristic wavelengths. Ideally, assuming that the mechanism driving the deformation is periodic, an ordering of the lenses would be reflected in a Fourier analysis.

The MatLab software was used to perform the calculations required. The workflow can be summarized as follows (Appendix I):

- Generate an input vector containing the amplitude data. According to the Nyquist theorem, the sampling frequency should be at least twice the minimum resolution. It is important that the sample points are equally spaced, otherwise the theory supporting these steps is not valid.
- Transform the data into the frequency domain. The mean value of the amplitude signal must be adjusted to zero before executing the transformation.
- Plot the result in terms of wavelength.

![Figure 3.13: Amplitude measurements collected along one of the dip-parallel profiles.](image)
Generally, there should be a strong indication of an underlying periodic mechanism in order for a Fourier decomposition to be fruitful. The result from the profile sample data shown in figure 3.13 is illustrated by figure 3.14. There is a peak around 42 meters, fitting well with our observations on the topography, otherwise little information is revealed. This is somewhat not surprising, given the coarse sampling intervals (0.5m) and the short sampling array (85m). The length of the sampling array should be around ten times the largest wavelength one tries to capture in order to provide acceptable error bounds (Berntsen pers.com.). This narrows the interval of reliable wavelengths to between one and five meters. A higher level of detail may be obtained by increasing the level of detail in the sample data. However, considering faults, heterogeneities in lithology and stress pattern are likely to weaken a potential periodic mechanism, causing the level of noise in the sample data to overprint any characteristic frequencies.

3.3.4. Quantification of fault zone components

3.3.4.1 Fault zone thickness

Although parts of the fault zone are exposed in two directions, cross-sections in the third dimension perpendicular to the fault zone are rare. This complicates the task of determining the thickness of the fault core and the damage zone.

A few incised ravines constitute the sample data for the footwall damage zone. Here, shear fractures related to the movement on the fault can be observed at least
15 meters into the footwall (Bastesen 2005). The damage zone of the hanging wall is buried beneath tens of metres of scree, which prevents any measurements. Furthermore, there are no complete cross-sections through the fault core that can provide reliable and statistically sound thickness estimates. The maximum amplitude observed along the fault surface is around 3 metres, which provides a minimum estimate for the fault core thickness.

The lack of quantitative field data calls for some assumptions to be made regarding the thickness of the fault zone components, i.e. footwall damage zone, fault core and hanging wall damage zone. Studies have shown that fault core thickness and damage zone width increases with increased displacement (e.g. Hull 1988; Knott et al. 1996; Beach et al. 1998; Sperrevik et al. 2002). However, these empirical relationships show that core thickness and damage zone width can vary with several orders of magnitude for a given displacement. Thus, estimates of fault zone dimensions from such relationships are associated with large uncertainties.

A comparison with a fault zone dimension study carried out on the Helike Fault Zone (Micarelli et al. 2003) seems more appropriate as this fault cuts through the same lithologies and has similar throw as the Doumena Fault Zone (Ghisetti et al. 2001; Micarelli et al. 2003). The Helike Fault Zone is located c. 4 km south of Aigion (Fig. 2.2). Micarelli et al. (2003) estimated the damage zone around the Helike Fault Zone to be in the order of 60-80 m. According to Micarelli et al. (2003), the fracture distribution in the limestone is widespread, but decrease away from the fault plane. In the conglomerates, however, the strain is absorbed along discrete slip planes, affecting only the closest few centimetres of the host rock. They also distinguish between an intensely deformed damage zone and a weakly deformed damage zone. The intensely deformed footwall damage zone is around 10 metres, while the weakly deformed footwall damage zone has a thickness of approximately 15 metres. In addition, they find that the hanging wall damage zone for the Pirgaki Fault Zone, located 4km north of the Helike Fault Zone and with a similar throw, is typically 1.5 times wider than the footwall damage zone of the Helike Fault Zone.

The fault core thickness estimate obtained by Micarelli et al. (2003) for the Helike Fault Zone (~4m) is adopted for the Doumena Fault Zone. This is in accordance with our observations of a core thickness of at least 3 metres. The footwall damage zone is set to 10 metres, corresponding to the intensely deformed damage zone of the Helike Fault Zone and coinciding with the average of our
observations. The hanging wall damage zone is assumed to be 1.5 times wider than the footwall damage zone. It is further assumed an exponential decay in fracture frequency in the damage zones based on the Micarelli results.

3.3.4.2 Lens dimensions

From the data in Figure 3.9 it can be seen that the 1st and 2nd order lenses in zone B exhibit a 2:1 ratio between the length (dip-direction) and width (strike-direction). This ratio seems to be valid for most of the type II lenses occurring in zone B. Data on the dimensions of type I and type III lenses are sparse, and the ratios as indicated in the previous description are associated with some uncertainty. However, a few measurements suggest that type I lenses have a ratio of 1:1, whereas type III lenses have approximately the same ratio as the type II lenses.

Lindanger (2003) conducted an extensive study on the dimensions of lenses occurring in extensional fault zones in different lithologies, and found a typical 1:9:10 ratio between the thickness, the length perpendicular to the slip direction and the length parallel to the slip direction. The length-width data for the type I lenses are in accordance with Lindanger’s results, thus her results are considered appropriate for the type I lenses.

The thickness distribution of the lenses is, however, less constrained. An estimate of the thickness was calculated from the observed curvature, assuming a symmetric shape. Combining these estimates with the length data gives an estimated length-thickness ratio of approximately 30:1 for the type II lenses. A few measurements indicate that there are no major differences in thickness between type I and type II lenses, and accordingly, they are assumed to have comparable thicknesses. Type III, however, seems to be slightly thinner. These results differ somewhat from the results of Lindanger (2003) who found a relationship between length and thickness close to 10:1. The reason for this may be the assumption on symmetry or simply that there is a different correlation ratio for the lenses present along the Doumena Fault Zone surface.
3.4 Fault zone model

This chapter has focused on a qualitative and quantitative description of the main structural components that constitute the architecture of the Doumena Fault Zone. The descriptive fault zone model that has been developed forms the basis for construction of the numerical fault model in the next chapter.

The main characteristics of the Doumena Fault Zone are (Fig. 3.15):

1. There are pronounced variations in topography across the exposed fault surface. Systematic variations in dips indicate a fault surface with a ramp-flat-ramp geometry.

2. The fault core in the lower ramp (zone A) is characterized by multiple parallel slip planes, dipping on average 55° and delimiting sheets of incohesive breccia. The breccia of the lower ramp fault core is observed to possess a very high porosity.

3. The flat (zone B) possesses a core composed of lenses, where two main types are distinguished. Type II lenses are located mainly in the upper half of the flat. They display significant internal fracturing and are composed of brecciated rock. These fractures are believed to increase the permeability in the fault core, especially the T-fractures. The type III lenses present in the lower part of the flat do not show sign of any internal fractures and consist of breccia with greater matrix content than the type I lenses. The fragment size of the fault rock matrix is at least 2 orders of magnitude larger than the fragment size of the host rock matrix. In addition, the overall geometry of this part of the fault core roughly follows the observed undulating topography.

4. The upper ramp (zone C) is also characterized by the development of lenses, but these lenses typically consist of fractured host rock. These fractures increase the permeability.

5. The total core thickness is estimated to be around 4 metres. The footwall damage zone is estimated to be 10 m, whereas the hanging wall damage zone is inferred to be 1.5 times the width of the footwall damage zone. An exponential increase in deformation intensity towards the fault core is inferred.
6. A 30:15:1 ratio is found for the length-width-thickness of the type II lenses in zone B. The type III lenses have similar length-width, but are slightly thinner. The results of Lindanger (2003) is considered appropriate for the type I lenses.

Figure 3.15: Diagram showing a summary of the main observations along the Doumena Fault Zone. Figure is from Bastesen (2005).
Chapter 4

Fault zone modelling

4.1 Model assumptions

4.2 The fine scale geologic model
   4.2.1 Preparing the input data
   4.2.2 Modelling the fault surface
   4.2.3 Generating the fault core and damage zone boundaries
   4.2.4 Designing the modelling grid
   4.2.5 Populating the grid by the use of facies modelling

4.3 Petrophysical properties
   4.3.1 Effect of the fracture sets on permeability
      4.3.1.1 Representing fractures as a permeable media
      4.3.1.2 Hydraulic aperture of the fracture sets
      4.3.1.3 Permeability estimate for the fracture sets
      4.3.1.4 Effect of fracture orientations on the permeability
   4.3.2 Permeability distribution in the lenses
      4.3.2.1 Model setup
      4.3.2.2 Upscaling algorithm and choice on boundary conditions
      4.3.2.3 Results
      4.3.2.4 Sources of uncertainty
   4.3.3 Permeability distribution in the fine scale geologic model

4.4 Simulation scale model
   4.4.1 Permeability representation and upscaling
   4.4.2 Coarse modelling grid
   4.4.3 Simulation style grid – Direct sampling from modelling grid
   4.4.4 Simulation style grid – Utilizing a transfer grid

4.5 Exporting the model to Eclipse

Based on the qualitative and quantitative description of the Doumena Fault Zone, a numerical fault zone model was constructed. Irap RMS, a reservoir modelling software supplied by Roxar, was chosen as platform. Novel use of the options
available in Irap RMS for sedimentary facies modelling allowed construction of the fault zone model. More specifically, the fault zone has been modelled as a volume and populated stochastically with structural features using the principles commonly employed for sedimentary facies modelling.

There is no textbook solution on how to build a numerical fault zone model. Whatever approach is chosen will be afflicted with errors, due to both software limitations and the simplifications/approximations employed when describing structural heterogeneities in a modelling context. It is my opinion, however, that numerical modelling is necessary in order to gain increased insight into the flow pattern of fault zones.

The objective of this chapter is bipartite; i) to build a fine scale geological model capturing the heterogeneity of the fault zone and ii) design a suitable simulation grid with upcaled petrophysical properties.

The aspect of grid design and upscaling is dealt with in some detail, as the performance of the coarse simulation scale models relative to the fine scale geological model are significantly influenced by the choices that are made here. The flow properties of the fine scale geological model compared to different coarse simulation scale models based on the fine scale geological model will be investigated in the next chapter.

### 4.1 Model assumptions

When modelling physical problems, a lower limit of critical heterogeneity in the model needs be defined. A physical problem can always be refined in terms of scale, all the way down to the molecular scale, but there is a limit as to what can be captured and realistically dealt with in a numerical model. Therefore, in this numerical representation the fracture sets described in the previous chapter are assumed to represent the smallest structural heterogeneities of significant importance to fluid flow. Individual fractures cannot be included explicitly in the fine scale geologic model. The effect on fluid flow of the different fracture sets, therefore, has to be included implicitly by means of the petrophysical parameters.
4.2 The fine scale geologic model

The spatial variability in petrophysical properties of the Doumena Fault Zone is related to the strain distribution. In the previous chapter, a conceptual model for the architecture of the Doumena Fault Zone was established, providing information of the distribution of structural features, i.e. fault rocks and lenses, displaying deformation of comparable intensity. In this section the facies modelling concept is utilized to build a fine scale geologic model with lenses and fault rocks included explicitly as outlined by the architectural model. The workflow is shown in figure 4.1. The resulting 3D facies parameter will constrain the large scale petrophysical variability in the subsequent petrophysical modelling.

*Figure 4.1:* Flow diagram showing the main steps when the building the fine scale geologic model. The starting point is the field observations as described in chapter 3. The collected raw-data are prepared and made compatible with Irap RMS input formats. The next step, aside from importing the structural data into Irap RMS, involves construction of the surfaces bounding the fault zone components, i.e. hanging wall damage zone, core and footwall damage zone. The modelling grid can subsequently be specified separately for the different fault zone components. This facilitates the use of different grid resolutions for different parts of the fault zone, thereby, keeping the total number of grid cells at a minimum. Finally, the grid is populated stochastically with objects assumed to have distinct geometric and petrophysical properties, e.g. lenses, by using the conventional facies modelling option.
4.2.1 Preparing the input data

The coordinate axes in Irap RMS is oriented with the x-axis trending E-W, the y-axis trending N-S and the z-axis vertical. The positive directions is W, N and downwards respectively. The format of the input file is simply the three coordinate values of the data point relative to this coordinate system. The reference line, profile 2, is trending N-S with a plunge of around 40° (Fig. 3.2). The orientation of the profiles in the strike direction are not perpendicular to the reference profile, however, neither are they horizontal. Thus, before the amplitude measurements can be imported into Irap RMS, these deviations have to be corrected, and the points re-expressed in terms of the coordinate system used by Irap RMS. These corrections were performed using elementary trigonometry and MatLab.

The first step is to correct the profiles in the strike direction. The profiles are rotated horizontally until they trend E-W. The amplitude component is corrected by assuming that the sampled surface dips 40°. This is not always the case, but the result still provides a more accurate estimate than the initial profile. Then, the dip-component is removed by rotating the profile in the vertical plane. The algorithm used in MatLab for performing this operation is described in Appendix I. This algorithm was also used to correct some points along the reference profile. This was considered necessary because during field work, the measuring line for the reference profile touched the ground at one point, causing a local change in the gradient of the profile.

The next task is to represent the amplitude measurements of the profiles relative to the coordinate system in Irap RMS. The measured height differences between the reference profile and the E-W trending profiles at the point of intersection are removed by adjusting the amplitude values of the crossing profiles. This ensures that all the amplitude measurements are represented relative to a common global z axis. Subsequently, the surface points are rotated 40° clockwise about the x-axis (Fig 4.2) in order to align them to correct dip-angle. The MatLab algorithm used for this operation is listed in Appendix II.
4.2.2 Modelling the fault surface

With the surface sample points represented according to the coordinate axes used in Irap RMS, the fault surface can be modelled. The data points are imported into the horizons module in Irap RMS, and the surface is mapped using a built-in interpolation algorithm. With the present input data the algorithms generate some unwanted artefacts in areas where there are no data points (Fig 4.3). This is handled by adding additional points along the top and bottom edges of the surface, forcing it to follow a straight line here. This correction is necessary in order to obtain a realistic looking shape on the fault surface. The surface is furthermore extrapolated at the top and bottom edges, assuming that the fault scarp inclination observed in the field, section 3.3.1, is applicable (Fig 4.4). The global B-spline algorithm was chosen for gridding the surfaces, as this yielded the closest resemblance to the “true” fault surface as seen in the field.

Figure 4.2: The figure illustrates the geometrical view implemented in the rotation algorithm. The initial position is given as the sum of a vector in the y-direction and a vector in the z-direction. The two vectors are rotated around the x-axis and projected onto the two coordinate axes. The new coordinate values for the point is simply the sum of the components of the rotated vectors along the two coordinate axes. The contributions from the vectors in the y- and z-direction are shown with coloured lines, green indicates a positive value and red a negative value.
Chapter 4  Fault zone modelling

Figure 4.3: The fault plane mapped with the surface sample points as input (Using the global B-spline algorithm). With no corrections/extra guide points the surface bends in the areas where there is a lack of data points.

Figure 4.4: The fault plane after adding guide points constraining the top and bottom edges. The fault plane is extrapolated in the dip-direction. This is necessary to obtain the desired grid design. Notice that the curvature caused by the insufficient input data is removed.
4.2.3 Generating the fault core and damage zone boundaries

Together with the architectural model of chapter 3, the fault surface is used to create the boundaries between the different fault zone components, i.e. the footwall damage zone, the core and the hanging wall damage zone.

First, the fault surface is smoothed and adjusted vertically, until it barely touches the original fault surface. This corresponds to the core-footwall damage zone boundary. The smoothing step is performed to remove the most distinct undulations, previously shown to represent lenses. The core-hanging wall damage zone boundary is obtained in a similar fashion, adjusted vertically to match the estimated fault core width (c. 4 m). Secondly, the footwall damage zone boundary is created by further smoothing the fault surface, retaining only the large scale curvature of the surface (the ramp-flat-ramp geometry). The surface is then adjusted to the proper depth, corresponding to the assumed thickness of 10 m. Similar operations are performed for the hanging wall damage zone boundary, allowing for the hanging wall damage zone to be 1.5 times wider than the footwall damage zone.

4.2.4 Designing the modelling grid

Having established the bounding surfaces, the modelling grid can be generated. First, one needs to decide on which modelling grid is the most fit for the current problem. Ideally, both the modelling grid and the simulation scale grid should be designed together, in order to minimize the error introduced when upscaling the detailed geological model. In particular, if the simulation scale grid resolution equals the resolution of the fine modelling grid divided by an integral number, there is an exact agreement between the contributing cells and the result cell. However, in this case, such a simulation style grid introduces potential problems when including stratigraphic units in the model. These problems will be addressed later. For the time being, the modelling grid most suitable for representing the fault zone needs to be decided. In Irap RMS there are two principally different grid designs to consider, a pure proportional grid and a grid with constant cell thickness.

A proportional modelling grid has a fixed number of layers between the bounding surfaces, where the number of layers for the hanging wall damage zone, core and footwall damage zone may be specified individually (Fig 4.5). Consequently,
degenerated cells and non-neighbour connections across the bounding surfaces are avoided. The disadvantage of this design is the varying thickness of the grid cells due to variations in the distance between the bounding surfaces, and the non-unidirectionality of the grid cells. This may introduce errors in the petrophysical model if the permeability is anisotropic. This is further explained in section 4.4.1.

Figure 4.5: Uniform proportional grid refined in the fault core. Notice that the orientation and volume of the grid cells varies with this grid design.

The other option, a modelling grid with constant cell thickness, eliminates the problem with cell-thickness variations. This grid design also offers an opportunity to control the orientation of the grid cells, regardless of the geometry of the boundary surfaces, which minimizes introduced errors in the petrophysical model due to an anisotropic permeability. Figure 4.6 shows such a grid, with a dipping plane used as control surface. However, as seen in Figure 4.6, the number of degenerate cells is huge in this grid configuration. It should be noted though, that the number of pinch-outs can be minimized by choosing a control surface following the average curvature.
This, however, destroys the unidirectionality of the grid cells and consequently the advantage of the grid when dealing with an anisotropic permeability.

Based on the above discussion, a uniform proportional grid was chosen. The horizontal dimensions are set to 40 by 90 cells in the N-S and E-W direction, respectively. 30 layers are assigned to the hanging wall damage zone, 20 layers to the core and 20 layers to the footwall damage zone. This ensures a resolution of approximately 2x1x0.5 meters in the damage zones and 2x1x0.1 meters in the core.

Figure 4.6: Uniform grid with constant cell thickness in each zone. The control surface used is a plane dipping 45°. Notice the how the cells are truncated against the zone boundaries.
4.2.5 Populating the grid by the use of facies modelling

The Facies:Composite module in Irap RMS allows population of the modelling grid stochastically with objects belonging to different user defined groups. Each group represents objects with distinct petrophysical properties and is specified with a simple geometric shape and a Gaussian size-distribution. Supplied with additional constraints on orientations, volume fractions, spatial distributions, interactions etc., Irap RMS proposes a distribution of the objects. The Facies:Composite module uses a Monte-Carlo simulation method, a Metropolis-Hastings algorithm with simulated annealing, where the annealing function controls the weight on the constraints during simulation. Originally, this software module is designed to model sedimentary facies. Here, this option is utilized to model 'structural facies'.

In the previous chapter, three types of lenses were identified along with a thick zone of breccia at the bottom of the outcrop. The different types of lenses are defined as separate groups of objects in the model setup, assigned the size and shape identified in section 3.3.2.5. A proper distribution of the different types of lenses in the model is achieved by assigning a probability distribution, e.g. a trend surface, to each group of lenses. This surface has value zero everywhere, except in the area where the lenses occur. In addition, a repulsion function is specified for each group of lenses, with the repulsion ellipsoid equal to the mean size of the lenses. The repulsion intensity is set constant throughout the whole specified ellipsoid. This ensures minimal interaction between the lenses, but the lenses are still allowed to touch. Thus, the qualitative description in chapter 3 is preserved in the model. Figure 4.7 shows the fine scale geologic model with the three types of lenses highlighted. The background is assigned to represent the breccia in zone A, due to its assumed homogeneous petrophysical properties at the model scale.
Figure 4.7: The fine scale geologic model. The distribution of the three types of lenses is highlighted, where the individual lenses appear with different colours. The red layer in the lowermost part represents the unconsolidated breccia in zone A.

4.3 Petrophysical properties

The 3D facies parameter obtained in the facies modelling step (Fig. 4.7) constitutes a key input parameter in the petrophysical modelling. This parameter contains an explicit representation of the distribution of structural features believed to possess distinct petrophysical properties. It was shown in the previous chapter that there was a trend in how the fracture sets distributed within the lenses. The strategy for how to capture the effect of fracturing in the model is to consider small volumes thought to be representative of specific parts of the lenses. These small volumes may be modelled numerically with the fractures included explicitly. The rescaled permeability
values of these volumes are then incorporated in the petrophysical modelling, hence approximately preserving the effect of the fractures.

To isolate the effect of the permeability distribution in subsequent flow simulations, the other petrophysical parameters, e.g. porosity and net to gross, are set constant throughout the entire model. This simplification will of course influence the saturation distribution with time. This aspect and assumptions used to estimate a set of suitable fluid parameters are discussed further in the next chapter.

The primary result of this section is a set of 3D parameters which describes the permeability distribution in the Doumena Fault Zone. A flow diagram for the process of modelling permeability is given in figure 4.8.

Figure 4.8: Flow diagram for modelling permeability. First the representation of single fractures is investigated, with a quality check of the resulting permeability. Fractured rock models are then used to estimate the permeability distribution within the lenses. The observed trend in the permeability of the lenses along with the facies parameter results in a detailed description of the permeability distribution.
4.3.1 Effect of the fracture sets on permeability

4.3.1.1 Representing fractures as a permeable media

The conductivity of a single fracture depends on several factors, e.g. the fracture aperture, surface roughness, contact tortuosity and the fragment size distribution of the material filling or partly filling the fracture. The cumulative effect of these factors may be approximated by using the hydraulic aperture (Renshaw 1995) as a proxy, i.e. the measure of aperture that can be used in the cubic law for fracture flow (Boussinesq equation) to produce the observed volumetric flow rate. The cubic law for fracture flow represents laminar flow in an idealized fracture, i.e. laminar flow between two parallel plates (Fig. 4.9A):

\[ Q = \frac{-a_p^3 \rho g}{12 \mu} \left( \frac{dh}{dL} \right)_f w, \]

where \( Q \) is the flux, \( a_p \) is the hydraulic aperture, \( \rho \) is the fluid density, \( g \) is the acceleration due to gravity, \( \mu \) is the fluid viscosity, \( (dh/dL)_f \) is the hydraulic gradient and \( w \) is the width perpendicular to flow. The cubic law for fracture flow assumes no fluid exchange with the surrounding matrix.

In the cubic law for fracture flow, the resistance to flow is represented by the viscous drag along the fracture walls. This representation of fractures needs be modified by using a model where the void is replaced by a permeable matrix and the resistance to flow is expressed as a permeability tensor (Fig.4.9B). The volumetric flow rate for a tabular body of porous media embedded in an impermeable media is given by:

\[ Q = \frac{-k_f \rho g}{\mu} \left( \frac{dh}{dL} \right)_f a_e w, \]

where \( k_f \) is the permeability and \( a_e \) is the aperture of the porous body and the other parameters is equally defined as in the cubic law for fracture flow. If the volumetric flow rate is the same, the following expression can be derived relating the hydraulic aperture to a permeable media with aperture \( a_e \) and permeability \( k_f \):

\[ a_p = 12 k_f a_e \]
The equivalent porous media representation makes it possible to represent the conductivity of the fractures by utilizing a parameter measurable in the field. That is, the surrounding matrix is still assumed to be impermeable, and we have no measurements on the hydraulic aperture.

![Figure 4.9: Two models for representing flow in fractures. Inset A: The cubic law for fracture flow describes flow between two parallel plates. Inset B: The equivalent porous media model allows flow within the fractures to be described by Darcy’s law. Figure modified from Taylor et al. (1999).](image)

4.3.1.2 Hydraulic aperture of the fracture sets

For high flow rates or for fractures where the aperture is significantly greater than the magnitude of surface roughness, the arithmetic average of the aperture and hydraulic aperture are approximately the same (Witherspoon et al. 1980). Figure 3.9, shows a close up of an antithetic Riedel shear. The surface roughness caused by rock grain size is small compared to the aperture. However, the aperture and the surface roughness caused by the path of joint propagation are of the same order of magnitude. Half the smallest aperture measured in this thin section (c. 0.05mm) is used as a measure of the hydraulic aperture. This estimate for the hydraulic aperture is considered realistic, and is adopted for both the antithetic and the synthetic Riedel shears in the model. The T-fractures are mode I fractures (joints). The fracture aperture is assumed to be larger on average than the fracture aperture for other fracture sets. A hydraulic aperture of 0.25mm is considered to be a reasonable estimate for the T-fractures.
4.3.1.3 Permeability estimate for the fracture sets

Numerical representation of fractures in Irap RMS involves some major simplifications concerning the geometry of the fractures. Irap RMS uses a structured modelling grid of corner point type and the stochastic modelling options available are limited to simple geometries. Thus, the representation of the fractures typically results in a stepped curve characteristic, unless the orientation of the fractures coincides with the grid orientation.

The general rule in reservoir modelling theory is to choose the grid resolution half the size of the smallest objects in the model. This ensures that the connectivity is preserved in the model. The grid resolution of the models replicating fractured rock volumes is set to 1 mm. Consequently, the fracture aperture in the model should be at least 2 mm.

For reasons explained in the section below, the fracture aperture in the model is set to 5 mm. This yields a permeability of ~2.1x10^3 mD for the fracture sets with assumed hydraulic aperture of 0.05 mm. Similar calculations for the T-fractures yield a permeability value of around 2.6x10^5 mD. A typical estimate for the permeability of un-fractured carbonate rock is in the order of 50 mD. With the employed assumptions, there is a permeability contrast of 10^2-10^4 mD between the matrix and the fractures considered significant to flow in the model.

4.3.1.4 Effect of fracture orientations on the permeability

From a physical point of view there should be little difference in conductivity between a horizontal and an inclined fracture over a short distance, given that the applied hydraulic gradient and the physical properties of the two fractures are identical. Does the same apply for the numerical representation? Three cases are investigated, a horizontal fracture, a gentle dipping fracture (16°), and a fracture with a large dip component (38°) (Fig. 4.10). Each case is modelled using fracture apertures of 2, 3, 5, 7 and 10 mm (Fig. 4.11). The permeability values assigned to the grid cells representing the fractures are scaled according to the aperture used in the specific model. The horizontal permeability is then calculated by upscaling the model into a single block. The single phase flow simulation algorithm with sealed boundary conditions is used to upscale the permeability.
Figure 4.10: The sensitivity of the permeability towards the numerical representation is investigated through the three illustrated cases, a horizontal fracture, a fracture dipping 16° and a fracture dipping 38°. Notice that all three fractures are connected entirely to the same model faces.

Figure 4.11: Different fracture apertures are used to investigate the sensitivity of the permeability towards the numerical representation. The figure also shows that the fractures are represented as planar objects.
The results reveal that the effect of the fractures on permeability depends heavily on the choice of numerical representation. Figure 4.12 shows the permeability estimates for the three models. It can be seen that the discrepancy between the “true” permeability (as represented by the horizontal fractures) and the permeability of the two tilted fractures relies on the fracture aperture used and the angle of the fracture. The error increases as the aperture decrease and the deviation in the fracture orientation from the cell tangent direction increase. The reason for setting the fracture aperture equal 5mm in the previous section should be clear from figure 4.12: it minimizes the scaling error. The improvement in accuracy is huge from 2mm to 5mm, but there appear to be less change for apertures greater than this.

Figure 4.12: Calculated horizontal permeability for the three cases. The solid-drawn lines represent the calculated permeability for the fractures using sealed boundary conditions. The black line denotes the permeability for the horizontal fracture. Notice that the calculated permeability remains constant for the different fracture apertures. This reflects that the permeability assigned to the blocks representing the fracture is scaled correctly. This value is inferred to represent the true permeability. The blue and the red line represent the fractures dipping 16° and 38° degrees respectively. The two dipping fractures show improvement in accuracy (approach the horizontal fracture) as the fracture aperture used increases, with the most significant change in the interval from 2mm to 5mm. The dashed blue line represents the permeability calculated for the fracture dipping 16° applying open boundary conditions. Clearly, the sealed boundary conditions give a closer estimate to the true permeability value.
The choice of boundary conditions in the upscaling process can also be justified by figure 4.12. Comparing the two curves for the permeability of the gentle dipping fractures with sealed and open boundary conditions respectively (blue lines) with the “true” permeability (black line), it is evident that the sealed boundary conditions gives the closest approximation.

### 4.3.2 Permeability distribution in the lenses

#### 4.3.2.1 Model setup

The permeability distribution within the lenses is investigated (modelled?) using small obliquely angled boxes (parallelepipeds) with the fracture sets included explicitly. The idea is to replicate the fracture pattern observed at specific sample points in the lenses. The sample points are located along two of the lenses principal axes. This choice of sample points is not by chance: The internal body trends axes of the petrophysical modelling tool coincide with the principal axes of the modelled objects (Fig. 4.13).

![Figure 4.13: Conceptual sketch showing the body trend directions in Irap RMS (red lines). The sample points are positioned along the vertical axis and the body-parallel axis. Figure modified from Irap RMS technical manual.](image)

The parallelepipeds are 10x20x10 centimetres, with the obliquity of axes coinciding with the average orientation of the cell tangents in the fine geologic model. The reason for this odd choice of grid is the definition of principal directions for the permeability in Irap RMS. This is further explained in section 4.4.1. The grid resolution is set to 2x1x1 mm. This ensures a resolution of 1x1 mm in the yz-plane where orientation is different for the fracture sets. The fracture aperture is assigned to be 5 mm, in line with the above findings.
The fracture sets are distributed stochastically in the models by the facies modelling tool. Deciding on the appropriate volume fractions in the facies modelling is a challenge. Section 3.3.2.3 provided a qualitative description of the spatial distribution of the different fracture types within the lenses (Fig. 3.11, 3.12). This information is utilized along with some additional assumptions on frequency of occurrence.

The permeability values used for the fractures were derived in section 4.3.1.3. Heterogeneities with characteristic lengths on the scale of grain size are expected to be adequately accounted for by the permeability mean value assigned to the embedding media. The permeability value for unfractured carbonate, 50 mD, is assigned to the matrix in all cases.

Each model populated with fractures is then coarsened into a single grid block, where the calculated effective permeability provides an estimate for the permeability of the modelled rock volume. Several realizations of each sample point are generated. The average value of the calculated effective permeability’s is used as a final estimate of the permeability for the sample point (Fig 4.14).

![Figure 4.14: The process of determining a permeability distribution for the lenses.](image)

- 55 -
4.3.2.2 Upscaling algorithm and choice on boundary conditions

Irap RMS offers several upscaling algorithms. The single phase flow simulation algorithm is considered the most accurate when upscaling permeability. Information about the calculated effective permeability can be extracted as a diagonal tensor or a full tensor. A more detailed review of the concept of upscaling and the 1-P flow simulation algorithm is presented in section 4.4.1.

If the fine geologic model, into which these values are substituted, had been the simulation scale model, a full tensor representation could be retained, thus preserving the cross-flow terms. However, this is not the case. The fine geologic model will be upscaled and any cross-flow terms in this model will be lost in the process. The reason for this is that the upscaling process only allows for a diagonal tensor permeability input. Consequently, the method yielding a diagonal permeability tensor is adopted.

Figure 4.12 demonstrates that the sealed boundary conditions give the best approximation of the permeability for randomly oriented fractures represented in an orthogonal grid. The grid used for the fractured rock models is not orthogonal. Do the sealed boundary conditions still provide the best approximation? The answer is no. The calculated effective permeability’s for the type II lenses using both sealed and open boundary conditions are presented in table 4.1. It can be seen that the values generally coincide. However, some questionable $k_z$ values, calculated using sealed boundary conditions, appear for the sample points.

More specifically, the $k_z$ values calculated using open boundary conditions is around 17000 mD for the sample points where the high permeable T-fractures are present. The $k_x$ values are close to equal suggesting that both the $k_x$ and the $k_z$ values are correct. This inference can be justified if one considers the orientation of the T-fractures relative the grid axes. The T-fractures lie in the xz-plane in this grid configuration and consequently the permeability in both the x- and z-direction should be close to equal considering the fact that the T-fractures possess the highest permeability.

This does not apply when calculating permeability using the sealed boundary conditions. For sample point F, the calculated $k_z$ value is an order of magnitude higher than the $k_x$ value. In fact, the calculated $k_z$ for the whole volume is of the same order of magnitude as the $k_z$ within the single T-fractures. Thus, this model cannot be adequately upscaled with the sealed boundary conditions.
4.3.2.3 Results

In line with the above discussion, the permeability values calculated with open boundary conditions are adopted for the fractured rock volumes. The average permeability values calculated for each sample point within the type II lenses are listed in Table 4.1. Some observations need be commented on.

The permeability distribution is dominated by the T-fractures whenever present. Consequently, the upper hemisphere of the type II lenses has a very high permeability in the $k_x$ and $k_z$-directions. The best along-body permeability ($k_y$) is found in the lower hemisphere of the lenses where there is an abundance of fracturing subparallel to the $k_y$-direction. Expectedly the centre of the lenses constitutes the low permeable zone of the lenses, due to fewer fractures present here.

The results for the type I and type III lenses show less variability in the calculated permeability since no T-fractures are present, but there is typically higher along-body ($k_y$) permeability than vertical ($k_z$) permeability.

<table>
<thead>
<tr>
<th>Sample point</th>
<th>Sealed boundary conditions</th>
<th>Open boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_x$ (mD)</td>
<td>$k_y$ (mD)</td>
</tr>
<tr>
<td>1</td>
<td>17576</td>
<td>442</td>
</tr>
<tr>
<td>2</td>
<td>16352</td>
<td>161</td>
</tr>
<tr>
<td>3</td>
<td>159</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>580</td>
<td>423</td>
</tr>
<tr>
<td>5</td>
<td>1103</td>
<td>1006</td>
</tr>
<tr>
<td>A</td>
<td>17265</td>
<td>728</td>
</tr>
<tr>
<td>B</td>
<td>17151</td>
<td>302</td>
</tr>
<tr>
<td>C</td>
<td>254</td>
<td>160</td>
</tr>
<tr>
<td>E</td>
<td>257</td>
<td>170</td>
</tr>
<tr>
<td>F</td>
<td>17008</td>
<td>302</td>
</tr>
<tr>
<td>G</td>
<td>17518</td>
<td>783</td>
</tr>
</tbody>
</table>

Table 4.1: Calculated permeability for the sample points along the vertical and along-body principal axes of the lenses. Notice the numbers typed in red. They appear too high compared to the other values. This is a consequence of the grid design and the boundary conditions used in the upscaling algorithm.
4.3.2.4 Sources of uncertainty

The method using fractured rock models for obtaining permeability estimates for the lenses is not straightforward and contains several sources of error.

In natural fracture networks the individual fractures are connected through both direct and indirect couplings. The influence of the fractures on the overall permeability structure depends on both the proportion of directly connected fractures and the fracture aperture. Taylor et al. (1999) shows that when the permeability contrast between the fractures and the surrounding matrix exceeds 6.5 orders of magnitude, all significant flow occurs within the directly connected fractures. In the model there is a permeability difference between the matrix and the fractures of 2-4 orders of magnitude. Consequently, the reduction in the permeability estimate should not be significant. The fractures modelled have characteristic length larger than the size of the fractured rock models. The models therefore fail to include the aspect of fracture connectivity. All the fractures are continuous through the model; consequently permeability is probably overestimated.

The fracture sets are represented as planar objects in the models with different dip angles. The intersection of different fracture types, defined as the grid cells common to crossing fracture objects, may be specified to belong to the fracture type which is considered to possess the highest permeability. This results in an insufficient representation of the fracture interactions. Reference is made to chapter three, where the style of interaction between the fracture sets to delimit lenses was discussed. For example, the R-shears and P-shears typically amalgamate with the Y-shears, not cutting straight through. Again, this probably leads to an overestimation of permeability.

The ratio of fracture volume to matrix volume is different in the model compared to the real rock volume. This result in a reduced contribution to flow for the matrix compared to reality, which has implication for the calculated permeability.

Although the permeability assigned to the grid cells representing the fractures are scaled according to the aperture used in the model, this representation of fractures embedded in a permeable media introduces errors. The reason for this is that the porous media representation allows for a pressure gradient to exist across the fracture. In a “real” fracture the pressure gradient should be zero, and any change in the flux at one part of the boundary is felt along the whole fracture boundary. This
error increases as the fracture apertures increase and as the spacing between the fractures decreases.

Still, this is the best that can be done with the software at hand. It is noteworthy that the task of representing fractures numerically is an area of extensive research, where today the use of unstructured grids garners particular attention.

### 4.3.3 Permeability distribution in the fine scale geologic model

The 3D facies parameter (Fig. 4.7) and the permeability trends apparent from the modelled rock volumes (Table 4.1) are combined in the petrophysical modelling to yield a detailed representation of the permeability distribution in the fine scale geologic model.

Each group of lenses is assigned a mean permeability value corresponding to the low permeable centre of the lenses. The increase in permeability towards the margins of the lenses is added by body trend functions, where the body trend functions are designed to preserve the permeability variations observed from modelled rock volumes (Table 4.1). Figure 4.15 shows the permeability distribution within a single type II lens in the \( k_y \) direction.

The breccia used as background in the facies parameter is assumed to possess a rather uniform permeability at this scale, 2000 mD is assigned for all three directions.

The permeability distribution of the footwall and hanging wall damage zones is implemented as exponentially decaying away from the fault core. This is in agreement with the general discussion in chapter 3.

There are several variogram models available for introducing noise into the modelled permeability distribution. A Gaussian distribution with standard deviation equal 50 mD is selected for the stochastic variability of the permeability throughout the model except for the breccia (200 mD).

The detailed permeability distribution within the fine scale model of the Doumena Fault Zone is illustrated by figures 4.16 and 4.17. Figure 4.16 shows the permeability distribution in the fault core for the three principal directions \( k_x \), \( k_y \) and \( k_z \). Figure 4.17 presents the along fault permeability \( (k_y) \) with the damage zones included. In the next section, this fine scale permeability representation is subject to different upscaling processes.
Figure 4.15: The permeability distribution in the $k_y$ direction for a type II lens. It can be seen that the permeability is lowest in the centre of the lens.

Figure 4.16: The permeability distribution for the fault core in the $k_x$, $k_y$ and $k_z$ directions respectively. Notice the internal variations in the lenses and the high permeable areas where the T-fractures are present.
Figure 4.17: The permeability distribution in the along fault ($k_y$) direction.
4.4 Simulation scale model

Generally the amount of cells in the fine scale geologic models is too large to be handled by a flow simulator. Different upscaling methods are applied to reduce the number of cells and at the same time preserve the effect of the heterogeneity. In this study the fine scale fault model consists of approximately 125,000 cells. This can still be handled by a flow simulator. However, in a full scale reservoir model, the representation of a single fault will not be granted 125,000 cells. Upscaling is therefore needed to bring computing time down to a manageable scale. Two principally different simulation scale grids can be defined: a coarsened modelling grid and a simulation style grid. First, however, the handling of permeability and upscaling routines in Irap RMS must be reviewed.

4.4.1 Permeability representation and upscaling

Darcy’s law states that the fluid velocity (v) is proportional to the applied pressure gradient (∇P), where the factor of proportionality is referred to as the permeability (k).

\[ v = -k \cdot \nabla p \quad (\mu = 1) \]

The equation, however, does not require the applied pressure gradient and the resulting flow to be parallel. The most general linear operator which maps one vector to another is a tensor. Hence, permeability is a tensor. Even though the permeability generally is a full tensor, there is one case where the permeability tensor appears extremely simple: When the principal directions of the permeability tensor coincide with the coordinate axes of the coordinate system in which the permeability tensor is given, the permeability appears diagonal.

In Irap RMS the principal directions of the permeability tensor are aligned with the axes joining the midpoints of each pair of opposite faces in the cells (Fig. 4.17). Consequently, the complete permeability characteristics of the model can be expressed with three 3D parameters, one for each cell tangent direction (k_x, k_y, k_z). This should make it clear why the aspect of grid design is so important. If the grid fails to align approximately with the principal directions of the real permeability, delineated by the bedding plane when modelling sedimentology, the model quality will be reduced.
Several upscaling methods are available in Irap RMS. The single phase flow simulation algorithms are considered the most accurate for upscaling permeability. These algorithms solve the pressure equation, subject to some flow boundary conditions, for the fine scale grid, from which an effective permeability is calculated by substitution into the coarse grid scale flow equation. Information of the calculated effective permeability can then be extracted as a diagonal tensor or a full tensor. There is a fundamental difference between these two methods.

If the flow simulator software handles a full tensor permeability input, a full tensor representation can be retained, thus preserving the cross-flow terms. In other words, complete information of the underlying permeability is included in the upscaled model.

On the other hand, if the calculated permeability is extracted as a diagonal tensor the upscaling process must be carefully evaluated. Recall the definition of the permeability tensor. Only one set of principal directions can be found for the permeability tensor in a given coordinate system. In the fine scale geologic model the principal directions of the permeability are given by the cell tangents. Consequently, if the coarse grid is not aligned with the fine scale grid there is a high possibility for losing information in the upscaling process.

The upscaling volume is defined to be the smallest box containing all the cells with centre nodes within the result cell (Fig. 4.18). If the contributing grid and the result grid are well aligned and the resolution of the contributing grid equals the resolution of the result grid multiplied by an integer, the upscaled permeability is an
accurate estimate. Alternatively, if this is not the case, the contributing area is larger than the result cell. Consequently, the level of detail in the calculated permeability for the result cells is smoothed out.

Two different boundary conditions, i.e. sealed or open boundaries, can be selected for the diagonal 1-P upscaling method. The sealed boundary conditions are implemented in the upscaling calculations through the application of a transmissibility modifier at the boundary of the contributing volume, and correspond to restricting the resulting flow to be parallel to the cell tangent direction for which the permeability is calculated. The open boundary conditions allow unrestricted flow through the boundaries of the upscaling volume.

Generally, the sealed boundary conditions produce a lower bound on the permeability, while the open boundaries produce an upper bound (King and Mansfield 1999). This statement, however, did not apply to the models representing fractured rock volumes. Although these models are fundamentally different from the reservoir models this statement is intended for (depositional environments), it shows that the interpretation of ‘correct’ boundary conditions should be done with care.

Eclipse 100 is used in the subsequent flow simulations. This software can only evaluate a diagonal permeability representation. Therefore, the 1-P flow simulation algorithm extracting the calculated effective permeability as a diagonal permeability tensor must be adopted in the subsequent upscaling of the fine geologic model. This will demonstrate the point just made regarding the choice of upscaling algorithms. The upscaling is performed with open boundaries. It turns out that, similar to the fractured rock models, the sealed boundary conditions lead to some suspiciously high permeability values calculated for the $k_z$ direction.
4.4.2 Coarse modelling grid

The first category of simulation scale grids is simply coarsened modelling grids with vertical and horizontal resolution equal the resolution of the fine modelling grid divided by some integral numbers. With this grid configuration there is a close agreement between the contributing cells and the result cells (Fig. 4.20). In addition, the cell tangents in the contributing grid cells and the result grid cells are approximately aligned (Fig. 4.20). Consequently, the diagonal upscaling algorithm is afflicted with little error.

This, however, does not imply that the upscaled permeability value always is an accurate representation. The quality of the calculated permeability when upscaling between two such grids depends on the coarsening style, i.e. uniform or non-uniform...
coarsening, and the magnitude of the coarsening. That is, there is typically an upper boundary for how coarse the model can be made without smoothing out heterogeneities in the permeability which may be vital for the performance of the coarse model relative the fine scale model. This limit depends on how the coarsening is being performed. Chapter 5 investigates whether any optimal coarsened model can be identified. That is, the least amount of cells without reducing the quality significantly. The cases looked at are: uniform coarsening up to five times, uniform lateral coarsening (the resolution in the vertical direction remains unchanged) up to five times and three non-uniform coarsened grids (2x3x2, 2x4x2 and 3x5x3). An example is given in figure 4.21 where a five time uniformly coarsened proportional grid is superimposed on the fine scale modelling grid along with the resulting upscaled permeability.

Although performing well, considering upscaling issues, this grid design captures the surrounding stratigraphy less satisfactorily. A horizontal stratigraphic unit linked to the fault zone in this grid will possess a zigzag geometry at the top and bottom. This representation may introduce severe errors in multi-phase flow simulations, due to its effect on the flow pattern. For example, say that a thin oil zone is present beneath an impermeable stratigraphic unit represented in this manner. The modelled sweep of the oil zone will probably not result in satisfactorily low residual saturations.

Figure 4.20: Illustration of the relationship between contributing cells and result grid cell. The resolution of the coarse grid equals the resolution of the fine scale grid coarsened by a factor of five. Notice that there is very good agreement in volume and orientation between the contributing grid cells and the resulting grid cell.
Figure 4.21: Example of upscaling permeability between two proportional grids. The fine modelling grid is to the left superimposed the coarse proportional grid. The coarse proportional grid with upscaled permeability values is to the right. The illustrated permeability direction is \((k_y)\), along the fault dip (the longest axis of the cells). Notice the change in the range of the permeability values. This is not surprising considering that all upscaling methods are averaging methods.

4.4.3 Simulation style grid – Direct sampling from the modelling grid

Another option is to design the simulation scale grid separately from the modelling grid. An obliquely angled grid with grid pillars dipping approximately parallel with the main fault trend is defined (Fig. 4.22). In Irap RMS the simulation style grid was created by shifting the top control rectangle laterally relative the bottom control rectangle. The control rectangles have to lie within the zone-bounding surfaces, and the grid will only be defined where the zone boundary surfaces overlap laterally. This grid will correctly capture the surrounding stratigraphy, but results in a severe mismatch with the fine scale modelling grid of the fault zone (Figs. 4.22, 4.23). This has some important implications; i) the area contributing to the upscaling calculations increases, leading to a more pronounced smoothing-out of the upscaled permeability values and ii) the diagonal tensor upscaling algorithm chosen for the upscaling
calculations fails to represent the permeability correctly for the simulation scale grid, since the cell tangents are not parallel for the two grids. Notice that the full tensor method will retain complete information of the underlying permeability and has no problems with this grid configuration.

Figure 4.22: Example of upscaling permeability between a proportional modelling grid and a simulation style grid. The illustrated permeability direction is along the fault dip (the long axis of the cells). The upscaling algorithm used (diagonal tensor method) extracts information of the calculated permeability tensor only in the direction of the three cell tangents. It can be seen from the figure that this results in a likely incorrect permeability for the simulation scale grid. Notice also that the fine scale model is extrapolated in the dip direction compared to figure 4.21. The reason for this is the shape of the simulation scale grid. If the model had not been extrapolated some of the cells in the simulation grid would be assigned a default value and this is more erroneous than the extrapolating operation.
4.4.4 Simulation style grid – Utilizing a transfer grid

If a software capable of handling a full tensor permeability input (e.g. Eclipse 300) is used for the subsequent flow simulations, then the full tensor method can be applied for the upscaling calculations. A potential solution to the smoothening out of the upscaled permeability values observed in the present model is proposed.

The fine scale modelling grid is resampled onto a new straight proportional grid of approximately equal size aligned with the main fault trend. The resampling copies the permeability values from the corresponding cells in the fine scale geologic model. This does not introduce any error, rather it removes the error in the fine scale model caused by the varying orientation of the cells, considering that the calculated permeability from the fractured rock models were performed for a fixed dip angle. The upscaling calculations are then performed on the new straight proportional grid, resulting in an improved accuracy of the calculated permeability due to a reduced amount of contributing grid cells (Fig.4.24).

This method only holds true if the volumes of the cells we are copying between are approximately equal, i.e. the fault zone thickness is constant, and the curvature of the fault is believed not to be of importance to the flow simulations.
Otherwise, this transition may introduce more errors than the direct sampling from the fine scale geologic model.

![Figure 4.24: The correspondence between the contributing grid cells and the result grid cell (black lines) is greatly improved when the curvature in the modelling grid is removed before upscaling. The validity of this operation depends on the properties of the permeability in the fine scale model.](image)

### 4.5 Exporting the model to Eclipse

Irap RMS has a default export option for grids and parameters to GRDECL format - a file format used by Eclipse.

The grid description and the permeability values for the grid cells are included in the exported file. The grid is reduced in size to coincide with the outcrop (Fig. 4.21), i.e. the extrapolated parts are removed. The reason for initially extrapolating the model in the dip direction is the rescaling calculations into the non-matching simulation style grids (Fig. 4.22).

The other petrophysical properties, e.g. porosity and net-to-gross, along with fluid saturations were assigned directly in Eclipse.
Multi-phase flow in fault zones is complex and difficult to predict. In this chapter, a qualitative investigation of the flow properties of the fault zone model is presented. The objective is to identify the potential impact of the modelled structures on fluid flow.

The uncertainty introduced when upscaling the numerical model is highlighted by comparing the performance of the coarsened proportional models to the results obtained for the fine scale model. The comparison emphasizes flow in the fault core, since the fault core constitutes the area with high quality sample data. The Eclipse 100 software is used for the flow simulations.

5.1 Case setup

The simulation is set up as an imbibition process in a water-wet system. That is, the rocks in the fault zone are assumed to be water-wet and the fault zone initially oil-filled (only residual water present). By sustaining a fixed pressure difference between injecting and producing wells, the water is forced through the model displacing the oil. Four water injector wells are positioned in the lowermost part of the model, equally spaced in the lateral direction. The four producing wells are located in the uppermost part, in a similar configuration (Fig. 5.1). All wells are vertical.
A black oil model (the oil is assumed to be composed of a single component) with dead oil (no gas is dissolved in the oil) is used for the simulations. Before executing the simulation runs, the initial state along with the fluid and rock properties needs to be defined.

The initial fluid pressure distribution in the model is calculated by the software, by applying some user defined constraints. These include the pressure at a reference depth, fluid densities, the fluid saturation distribution and capillary forces.

A pressure of 306 bars, at a depth of 1755 m, is assumed for the top of the model. The density of water and oil is set to 1035 kg/m$^3$ and 880 kg/m$^3$, respectively.

The oil-water contact is located above the injecting wells at a depth of 10000 m (Fig. 5.1). It is recognized that this will influence the simulation results compared to initializing the simulation with an entirely oil-saturated model. However, convergence problems during the initial simulation runs prompted the decision to use a partly oil-filled scenario. Oil and water are in buoyant equilibrium initially in the model. This implies that only residual water is present in the oil zone. The initial oil and water saturations are 0.79 and 0.21, respectively, in the oil zone.

Capillary effects are not included in the simulations. Capillary curves are set as constant and equal to zero.

Complete information on the fluid properties (i.e. density, compressibility, volume factors, viscosity, and relative permeability) used in the model can be found in appendix 4. It should be noted that the displacing fluid (water) has the highest viscosity. This avoids fingering effects when the water is forced through the model.

The permeability distribution in the model is shown in figures 4.15, 4.16, 4.17 of section 4.3.4. An important observation is that the permeability increases towards the boundary of the lenses and that along-fault-permeability ($k_y$) is generally lower than the permeability in the two other directions. The other petrophysical parameters, i.e. porosity and net-to-gross, are set constant throughout the whole model, in order to isolate the effect of the permeability. The values used for the mechanical properties of the rock (density and compressibility) are listed in the setup file for the simulation runs in appendix 4.

The fine scale model was subjected to two different flow simulation experiments. In the first case, the entire model was flooded (Fig. 5.1). The injecting wells were set open to flow in the lower half of the hanging wall damage zone. The producing wells were set open to flow in the upper half of the footwall damage zone.
Water was then forced across and along the fault zone. The effective pressure gradient between the injecting and producing wells (distance ~150m) is approximately 5 bars when the difference in depth between the injecting and producing wells are accounted for.

The second experiment only considered the fault core. The damage zones were removed and only the fault core was flooded (Fig. 5.2). The effective pressure gradient is slightly higher in this case. This case was used to compare performance of the coarsened models with the fine scale model.

The results are illustrated in terms of water cut, time of water breakthrough and by snapshots of the saturation distribution. Total time for the simulation run is 100 years.

5.2 Results for the fine scale model

5.2.1 Experiment 1; Damage zones included

The experimental results for the fine scale model are shown in Figure 5.1. It can be seen that the water front initially propagates along the high-permeable breccia zone of the fault core and in the part of the damage zones close to the fault core (0-6 years). When the water front reaches the lenses, especially the type II lenses, the flow pattern becomes more complex (6-29 years). The water quickly sweeps the areas of high permeability, but oil in the low permeable interior of the lenses is bypassed. At the end of the run high oil saturations can still be observed in these parts of the lenses. This is illustrated in Figure 5.2, showing a close-up of the part of the fault zone containing type II lenses. The water front regains a smooth shape when it reaches zone C, possibly due to the lower permeability contrast between the type III lenses and the damage zone (29-41 years). Water breakthrough happens at 45 years. The development after water breakthrough is mainly a continued reduction in oil saturation of already swept areas (45-100 years). It can be seen from the figure that a large part of the hanging wall damage zone remains oil-saturated. This is a possibly a consequence of the well placement. Production profile for the simulation run is showed in figure 5.3.
Figure 5.1: Snapshots of the simulation run for the fine scale model. The development in the saturation distribution is described according to time. Total run time is 100 years. Water cut is also stated after water breakthrough, which occurs at 45 years. The advance of the water front is controlled by the distribution of high permeable rocks (i.e. the breccia in zone...
A, the part of the damage zone close to the fault core and the marginal parts of the lenses. Note in particular the disturbance of the sweep in the central parts of the model (17-41 years). This seems to be caused by the type II lenses present in the fault core. The oil recovery factor at the end of the run is 0.56 and the water cut is 0.84. See color legend for saturation values, 0<s_o<0.81.
Figure 5.2: Snapshots of the simulation run for the part of the fault core, comprising type II lenses. Location is marked on figure 5.1. The development in the saturation distribution is described according to time. Total run time is 100 years. Notice how the water sweep initially bypasses certain areas. These areas seem to correspond to the low permeable interior of the type II lenses. At the end of the run (100 years) the oil saturation is higher in these areas. The colour legend indicates oil-saturation values, 0<s_o<0.81
5.2.2 Experiment 2; Fault core only

To analyze the impact of fault core permeability structure on fluid flow in detail, a separate simulation run was performed on the fault core. The results support the observations made in Experiment 1. Snapshots from this simulation run are presented in figure 5.4. Notice the path taken by the water. This area corresponds closely to the fractured, marginal parts of several lenses, showing that the water preferentially flows along these high permeability pathways. The production profile is given in figure 5.5.
<table>
<thead>
<tr>
<th>Year</th>
<th>Wetness</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>0.001</td>
</tr>
<tr>
<td>34</td>
<td>0.643</td>
</tr>
<tr>
<td>41</td>
<td>0.872</td>
</tr>
<tr>
<td>54</td>
<td>0.943</td>
</tr>
</tbody>
</table>
Figure 5.4: Snapshots of the simulation run for the core of the fine scale model. The development in the saturation distribution is described according to time. Water cut is also stated after water breakthrough (occurring at 29 years). The advance of the water front can be seen to follow the high permeable rocks, i.e. the marginal parts of the lenses. The oil recovery efficiency factor at the end of the run is 0.78 and the water cut is 0.98. See colour legend for saturation values, $0 < s_o < 0.81$.

Figure 5.5: Production profile for the simulation run.
5.3 Results for the coarsened models and comparison with the fine scale model

To evaluate the quality of the coarsened models some quality measures need to be defined. Two properties for the coarse models are compared with the fine scale model; i.e. water breakthrough behaviour and total injected pore volume. Both properties give information on the transport properties of the models. The water breakthrough behaviour gives information about the preservation of the high permeable pathways in the coarse models. Comparison of total injected pore volume reveals whether the average flow rate is matched between the coarse models and the fine scale model. The results obtained show large variations and demonstrate that upscaling is not straightforward. However, some interesting effects are observed.

It can be seen from table 5.1 and figure 5.6 that for the models uniformly coarsened laterally, the vertical coarsening factor has little influence on the performance. There is a close resemblance between the 2x2x2 and 2x2x1 models etc. The exception is the 5x5x5 and 5x5x1 coarsened models. Whether this is an upper limit for the match in performance is hard to tell, since no coarser models are available for comparison at the time of writing. The other non-uniform coarsened models, 2x3x2, 2x4x2 and 3x5x3, display large variations in performance. Interestingly, the model with the least aggradation factor performs the worst.

The 2x4x2 coarsened model and the 3x5x5 coarsened model perform remarkably well, considering the relatively high coarsening factor. If water breakthrough behaviour is the important parameter to preserve in the coarsened model, the 2x4x2 coarsened model should be chosen. This model matches the fine scale model with 1% deviation in time and 8% injected pore volume. The total flow rate at the end of the run is only 8% less than for the fine scale model. On the other hand, if accuracy in the average flow rate is important, the 3x5x3 coarsened model provides a good match. The model only deviates 1% from the fine scale model, although the water breakthrough occurs slightly early.

In summary, for the present model the transport properties of the fine scale model can be satisfactorily captured by upscaled models with significantly fewer cells. The 2x4x2 coarsened model reduces model size from 56.000 cells to 3.500
cells, while the 3x5x3 coarsened model only requires 1372 cells. Both, however, underestimate pvi at WBT.

<table>
<thead>
<tr>
<th>Water breakthrough</th>
<th>Total injected pore volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (yr)</td>
<td>Pvi</td>
</tr>
<tr>
<td>Fine scale model</td>
<td>30</td>
</tr>
<tr>
<td>2x2x1</td>
<td>-11%</td>
</tr>
<tr>
<td>2x2x2</td>
<td>-11%</td>
</tr>
<tr>
<td>3x3x1</td>
<td>37.5%</td>
</tr>
<tr>
<td>3x3x3</td>
<td>27.5%</td>
</tr>
<tr>
<td>4x4x1</td>
<td>41%</td>
</tr>
<tr>
<td>4x4x4</td>
<td>33%</td>
</tr>
<tr>
<td>5x5x1</td>
<td>-41%</td>
</tr>
<tr>
<td>5x5x5</td>
<td>-11%</td>
</tr>
<tr>
<td>2x3x2</td>
<td>33%</td>
</tr>
<tr>
<td>2x4x2</td>
<td>1%</td>
</tr>
<tr>
<td>3x5x3</td>
<td>14.5%</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of the results obtained for the simulation runs on the fault core. The fine scale model is the reference case and the other values are stated in terms of deviation from this reference value. Negative values are in red typing.
Figure 5.6: Graphical representation of the simulation results for experiment 2. It can be seen that the uniformly coarsened models and the models uniformly coarsened in the lateral direction roughly coincides. The exception is the 5x5x5 and 5x5x1 coarsened models. Is there a critical level for this model here? Another observation is that pvi at water break through for all the coarsened models are less than for the fine scale model.
Chapter 6

Conclusions

The objective of this thesis has been to develop a robust method for implementing structural data into a numerical model, as a tool for investigation of fluid flow within fault zones. The method should be flexible and applicable for various types of fault zones and lithologies. Conventional reservoir modelling and flow simulation software was to be applied (Irap RMS and Eclipse). The work was based on outcrop data from a major fault, the Doumena Fault Zone, in Corinth, Greece.

The hierarchy of solutions presented by this method (Fig. 6.1) assumes that faulting affects a volume of rock, and that flow through fault zones is influenced by the spatial distribution of fault zone components with different petrophysical properties. In addition, fault zone components occur on several length scales.

Descriptive fault zone model

A qualitative and quantitative analysis of the exposed Doumena Fault Zone has been performed. Detailed data on surface morphology and the spatial distribution of different fault zone components, e.g. fault rocks, fractures and lenses, was sampled. This structural information was synthesized into a descriptive fault zone model. The main findings are:

- The exposed fault surface displays a ‘mild’ ramp-flat-ramp geometry.
- The lower ramp is characterized by multiple parallel slip planes, delimiting sheets of fault rocks with apparent high porosity and permeability.
- The flat is characterized by an undulating topography and possesses a core composed of lenses of brecciated rock, where two main types are distinguished. The type II lenses are confined to the upper half of the flat and possess significant internal fracturing, which is assumed to increase the permeability. These lenses display a typical 2:1 ratio between length (dip-direction) and width (strike direction).
- The upper ramp is also characterized by lenses, but here the lenses consist of fractured host rock.
Numerical model

The descriptive fault model forms the basis for the numerical model constructed in Irap RMS. The numerical model has been developed by novel use of the principles of sedimentary facies modelling. The wide range in size of the objects modelled (e.g. lenses and fractures) required a hierarchy of models to be used.

The results show that this way of modelling structural features is applicable, but there are several sensitive parameters within the numerical representation and upscaling requires special treatment. Some important observations are:

- When modelling fractures that are not aligned with grid axes, the aperture used in the model will influence the effective permeability calculated during a 1-P flow upscaling process, although the permeability used for the fractures are scaled to the aperture used in the model.
- When upscaling models with high-permeable fractures included explicitly by 1-P flow algorithms, the choice on correct boundary conditions depends on the type of grid. For orthogonal grids the sealed boundary conditions provide the closest approximation. This is in line with Flodin (2004). In the case of oblique angled grids, the open boundary conditions perform best. Here, the use of sealed boundary conditions leads to an overestimate of the permeability, up to an order of magnitude.
- The upscaling module in Irap RMS only allows for a diagonal tensor permeability input. Consequently, if a hierarchy of models is utilized, complete information on the upscaled permeability for a model (generally a full tensor) will not be possible to include in a new upscaling process.

Simulation model

The base-case numerical model, along with a number of coarsened models, were then exported to Eclipse for investigation and comparison of flow properties. Some interesting results emerged:

- The displacing fluid (water) typically favours the high-permeable pathways.
- Models uniformly coarsened in the horizontal directions show little sensitivity towards vertical coarsening, but the horizontal aggradation rate has major effects on the performance relative to the fine scale model.
Some non-uniformly coarsened models perform very well compared to the fine scale model. The ‘best’ results are obtained with a 2x4x2 coarsened model. Deviation in time for water breakthrough is within 1% and total injected pore volume is within 8%. A 3x5x3 coarsened model deviates 14.5% in time to water break through, but only 1% in total injected pore volume. This is quite impressive, considering that the models reduce the number of grid cells with a factor of 16 and 45, respectively.

Concluding remarks

The current work demonstrates that it is fully possible to build numerical models capturing complex architectures in fault zones. The concept and methodology developed can easily be applied to other lithologies, the only prerequisite being that the input parameters are adjusted accordingly.

It is believed that future reservoir planning and reservoir management will, to an increasing degree, require more accurate representation of faults and fault zone architecture in the reservoir and flow simulation models. The methodology developed here provides a tool for further research and improved understanding of flow in fault zones. Implementation of this concept in full-field modelling may be a challenge, but hopefully it may serve as a means of better estimating fault transmissibility factors used in reservoir models.

Although the model developed during this work is an experimental model, optimized for capturing the heterogeneities within fault zones, this concept of modelling is more widely applicable and can be utilised in a more general reservoir modelling context. The principles for capturing of structural heterogeneities on various scales are directly transferable to sedimentary and stratigraphic modelling.

Figure 6.1: Flow diagram summarizing the main steps in this work.
Chapter 6  Conclusions

Nature (Chp.3)

Fracture Model

Sensitivity Comments

Fine Geologic Model

Coarse model Resolution A

Coarse model Resolution B

Coarse model Resolution C

Sensitivity Analysis in Eclipse

Full scale model Sim style grid Direct sampling
Honours: stratigraphy

Full scale model Sim style grid Direct sampling from transfer grid
Honours: both?

Full scale model Coarse mod. grid Resolution C
Honours: fault zone

Flow simulate in Eclipse

Conclusions Modelling (Chp. 4)
Simulation (Chp.5)
References:


Gabrielsen, R. H., A. Braathen, et al. (In prep). "Fault architecture of extensional faults in sedimentary rocks, and the importance of strain-hardening and strain-softening."


Appendix I

The implementation of the Fourier analysis in MatLab:

\[ x = \text{[input points]}; \]
\[ x = x - \text{mean}(x); \quad \% \text{The input vector must have a mean value of zero.} \]
\[ n = \text{length}(x); \quad \% \text{The number of points.} \]
\[ y = \text{fft}(x); \quad \% \text{The fft-function returns the complex Fourier Transform.} \]
\[ \text{Pyy} = y .* \text{conj}(y) / n; \quad \% \text{Pyy contains the magnitude of the elements of } y \text{ in real numbers.} \]
\[ f = 2 \times (0:n/2) / n; \quad \% \text{The frequencies corresponding to the elements in Pyy.} \]
\[ T = 1 ./ f; \quad \% \text{Converting into wavelength. This implies that the order of the elements in both } T \text{ and Pyy must be inverted.} \]
\[ \text{Pyy} = \text{Pyy}(n/2:-1:1); \]
\[ \text{plot}(T,\text{Pyy}); \quad \% \text{Generates a visual output.} \]

The fft-function in MatLab performs the following transformation for a vector of length \( N \):

\[
X(k) = \sum_{j=1}^{N} x(j) \omega_N^{(j-1)(k-1)}
\]

where \( \omega_N = e^{-2\pi i/N} \) is an \( N \)th root of unity (MatLab Technical Manual).
function A = devcor(d,h,t,p)
% Returns a matrix A containing the horisontal E-W striking distance and 
% heigth for an input array (d,h) trending t degrees with a plunge p. The 
% values of d may also be negative, the array is rotated about d=zero. It 
% is assumed that the measured surface has an inclination of 40 degrees 
% and that the deviation from E-W is within 10 degrees.

dnew = d;
hnew = h;
n = length(d);
A = zeros(n,2);

if ((t>=270)&(t<280))
    for i=1:n
        hnew(i)=hnew(i)-dnew(i)*sin((t-270)*2*pi/360)*sin(40*2*pi/360);
    end
    dnew=dnew*cos((t-270)*2*pi/360);
    if p>0
        for i=1:n
            hnew(i)=hnew(i)-dnew(i)*sin(p*2*pi/360)*cos(40*2*pi/360);
        end
        dnew=dnew*cos(p*2*pi/360);
    end
end

if ((t>80)&(t<=90))
    for i=1:n
        hnew(i)=hnew(i)+dnew(i)*sin((90-t)*2*pi/360)*sin(40*2*pi/360);
    end
    dnew=dnew*cos((90-t)*2*pi/360);
    if p>0
        for i=1:n
            hnew(i)=hnew(i)+dnew(i)*sin(p*2*pi/360)*cos(40*2*pi/360);
        end
        dnew=dnew*cos(p*2*pi/360);
    end
end

if ((t>90)&(t<100))
    for i=1:n
        hnew(i)=hnew(i)-dnew(i)*sin((t-90)*2*pi/360)*sin(40*2*pi/360);
    end
    dnew=dnew*cos((t-90)*2*pi/360);
    if p>0
        for i=1:n
            hnew(i)=hnew(i)+dnew(i)*sin(p*2*pi/360)*cos(40*2*pi/360);
        end
    end
end

if ((t>=100)&(t<=110))
    for i=1:n
        hnew(i)=hnew(i)+dnew(i)*sin((110-t)*2*pi/360)*sin(40*2*pi/360);
    end
    dnew=dnew*cos((110-t)*2*pi/360);
end

end


dnew = dnew * cos(p * 2 * pi / 360);
end
end

if ((t > 260) && (t < 270))
   for i = 1:n
      hnew(i) = hnew(i) + dnew(i) * sin((270 - t) * 2 * pi / 360) * sin(40 * 2 * pi / 360);
   end
   dnew = dnew * cos((270 - t) * 2 * pi / 360);
end

if p > 0
   for i = 1:n
      hnew(i) = hnew(i) - dnew(i) * sin(p * 2 * pi / 360) * cos(40 * 2 * pi / 360);
   end
   dnew = dnew * cos(p * 2 * pi / 360);
end

A(1:n,1) = dnew(1:n);
A(1:n,2) = hnew(1:n);
function T = tilt(A,v)
% Rotates a set of points about the x-axis. The matrix A contains the
% points to be rotated. The output matrix T contains the new coordinates for
% the points after a clockwise rotation of v degrees. The angle of rotation
% have to be within [0,90] degrees. The positive direction is defined downwards.
T = A;
b = length(A(:,1));

for i=1:b
  T(i,2) = A(i,2)*cos(v*2*pi/360) - A(i,3)*sin(v*2*pi/360);
  T(i,3) = A(i,2)*sin(v*2*pi/360) + A(i,3)*cos(v*2*pi/360);
end
Appendix III

-- Flow simulation of fault model
-- Author: Henning Nøttveit
-- Updated: 10.06.05

RUNSPEC

TITLE
  Fault Model

DIMENS
-- Basic size of grid
-- x  y  z
   40  70  45 /

-- Phases present
OIL
WATER

-- Units to be used
METRIC

-------------------------------Table dimensions--------------------------------------

EQLDIMS
-- Dimensions of equilibrium tables:
  -- EQLNUM
     1 /

TABDIMS
-- Table dimensions:
  -- #      #      #nodes  #nodes
  satTab  PVTtab satTab  PVTtab
     1     1     15     18 /

WELLDIMS
-- Well dimension data:
  -- max#  max#Conn  max#  max#well
  wells  pr.well  groups  pr.group
     8    70     1     8 /

-------------------------------Simulator options--------------------------------------

NUPCOL
-- # non-linear iterations
    10 /

NSTACK
-- Linear solver stack size:
    300  20 /
START
  1 'JAN' 2005 /

UNIFOUT
-- Instead of producing separate Restart and Summary files for each timestep,
-- these files are amalgamated into a single file of each type.

--NOSIM

GRID
================================================================
NOECHO
-------------------------------------------------
INCLUDE
-- Generates grid from external file
  '111FaultModel407045.GRDECL' /
-------------------------------------------------
----------------------Assigning porosity and permability data-------------------
PORO
-- Each gridblock needs be assigned a value. The simulator starts in (1,1,1), counting
-- fastest in the x-direction followed by the y-direction and slowest in the z-direction.
  126000*0.2 /

NTG
-- Each gridblock needs be assigned a value. The simulator starts in (1,1,1), counting
-- fastest in the x-direction followed by the y-direction and slowest in the z-direction.
  126000*0.2 /

---------------------Requesting outputdata--------------------------------------
INIT
-- Requests output of an INIT file, a summary of data given in GRID, PROPS and
-- REGIONS sections. Included in the GRID section, a file which can be read by the
-- graphics packages is generated, (Resultviewer in Office).

PROPS
================================================================
---------------------Mechanical properties----------------------------------------

-----------------------------Assigning porosity and permability data-------------------

PVTW
-- PVT table for water phase
-- Pref  Bw(Pref)  Cw  viscw(Pref)
  308.2  1.024  4.64E-5  0.42 /

PVDO
-- PVT table for dead oil
-- Pref  Bo(Pref)  Co
  227  1.2600  1.042
ROCK
-- Rock compressibility
-- Pref  Cr(Pref)
  1.0   0.00007 /

DENSITY
-- Fluid density at surface conditions
-- oil  water  gas
  880.0  1035.0  0.75 /

-----------------------------------Saturation tables-----------------------------------

SWFN
-- Watersaturations with related relperm and capillary pressure
-- Sw  Krw  Pcow
  0.200  0.0000  0
  0.254  0.0063  0
  0.308  0.0143  0
  0.363  0.0241  0
  0.417  0.0356  0
  0.471  0.0488  0
  0.525  0.0638  0
  0.579  0.0805  0
  0.633  0.0989  0
  0.688  0.1191  0
  0.742  0.1410  0
  0.796  0.1646  0
  0.850  0.1900  0
  0.900  1.0000  0 /

SOF2
-- Oilsaturations with related relperm values for 2-phase model
-- So  Kro
  0.15  0
  0.20  0.00734
  0.30  0.05104
  0.40  0.13343
  0.50  0.25453
  0.60  0.41432
  0.70  0.61281
  0.80  0.85 /
SOLUTION
================================================================
EQUIL
-- Prescribing equilibrium data
-- Datumdepth  P(Dd)  ow-con.depth  Pcow,ow-con  go-con.depth  Pcgo,go-con
     1755      306    10000       0 /

SUMMARY
================================================================
-- Field and well oil prod rate. Cummulative oil production for field and every well.
  FOPR
  FOPT
  WOPR
  /
  WOPT
  /

-- Field and well water prod rate. Cummulative water production for field and every well.
-- well.
  FWPR
  FWPT
  WWPR
  /
  WWPT
  /

-- Field and well water injection rate. Cummulative water injection for field and every well.
-- well.
  FWIR
  FWIT
  WWIR
  /
  WWIT
  /

-- Instantaneous water cuts for field and every well.
  FWCT
  WWCT
  /

-- Oil in place for field.
  FOIP

-- Water in place for field.
  FWIP

-- Average pressure for field.
  FPR

-- Drainage efficiency for field.
  FOE
-- Well bottom hole pressure.
WBHP
/

SCHEDULE
================================================================

ECHO
-- Requesting output data-----------------------------------------------

RPTRST
-- Controls output to RESTART-File
BASIC=2 NORST=1 / Restart file created at every report step + graphics only

WELSPECS
-- Specifies new wells
-- name   group   i-heel  j-heel  refDepthBHP  prefPhase
'P1'      'OP'       8        3         1*          'OIL'     /
'P2'      'OP'      16       3        1*        'OIL'     /
'P3'      'OP'     24        3        1*         'OIL'     /
'P4'      'OP'     32        3       1*         'OIL'     /
'I1'       'OP'      8       68      1*         'WATER'   /
'I2'       'OP'     16       68       1*         'WATER'   /
'I3'       'OP'     24       68       1*         'WATER'   /
'I4'       'OP'     32       68       1*         'WATER'   /
/

COMPDAT
-- Specifies data for wells
-- name   i-lok   j-lok   k-up   k-low     flag   SatTabNr   transmFact   wellbore
'P1'       8        3      36       44      'OPEN'      2*                                 0.30  /
'P2'     16        3      36       44      'OPEN'      2*                                 0.30  /
'P3'     24        3      36       44      'OPEN'      2*                                 0.30  /
'P4'     32        3      36       44      'OPEN'      2*                                 0.30  /
'I1'       8       68       8       15      'OPEN'      2*                                 0.30  /
'I2'      16       68       8       15      'OPEN'      2*                                 0.30  /
'I3'      24       68       8       15      'OPEN'      2*                                 0.30  /
'I4'      32       68       8       15      'OPEN'      2*                                 0.30  /
/

WCONPROD
-- Control data for production wells
-- flag     control   o-rate       w-rate      g-rate      l-rate   res.fl.vol-rate   BHP
-- name     status   mode   targ-ulim  targ-ulim  targ-ulim  targ-ulim   targ-ulim
'P1'      'OPEN'  'BHP'       1*         4*                                                           300  /
'P2'      'OPEN'  'BHP'       1*         4*                                                           300  /
'P3'      'OPEN'  'BHP'       1*         4*                                                         300  /
'P4'      'OPEN'  'BHP'       1*         4*                                                            300  /
/

WCONINJE
-- Control data for injection wells
-- inject     flag     control   surf.fl.rate res.fl.volrate BHP

-- name    type       status   mode      targ-ulim     targ-ulim     targ-ulim
'I1'    'WATER'  'OPEN'  'BHP'           1*               1*          1450   /
'I2'    'WATER'  'OPEN'  'BHP'           1*               1*          1450   /
'I3'    'WATER'  'OPEN'  'BHP'           1*               1*          1450   /
'I4'    'WATER'  'OPEN'  'BHP'           1*               1*          1450   /

WECON
-- Economical restrictions of the wells
'P1'  /
'P2'  /
'P3'  /
'P4'  /
/

TUNING
-- Sets simulator control parametres
-- TSINIT TSMAXZ
  1      31 / Record1
/ Record2
-- NEWTMX NEWTMN LITMAX LITMIN MXWSIT
  150     1*    200     1*    100 / Record3

---------------------Initial state is now prescribed---------------------------

DATES
1 'JAN' 2106/
/