Centre for Integrated Petroleum Research – Research activities with emphasis on fluid flow in fault zones

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Improving hydrocarbon recovery holds the key to prolong and maximize production from existing oil and gas fields. The economic potential of providing new methods for increased and enhanced oil recovery is significant. It therefore represents a subject of great interest on a corporate as well as national level as it provides means to optimize production and resource management. A key element of IOR and EOR is to understand the geometry, architecture and petrophysical properties of petroleum reservoirs in order to forecast their response to various production strategies through the use of fluid flow simulation tools. The Centre for Integrated Petroleum Research (CIPR) addresses this challenge by providing a platform for cross-disciplinary research into a range of subjects related to understanding and modeling the complexities of subsurface reservoirs and developing new methods for maximizing oil and gas recovery.

Introduction

The fluid flow in heterogeneous, fractured reservoirs, the geometric complexity of the oil- bearing formations, and the non-linear coupling in the flow model represent extremely challenging research tasks. A main goal for the Centre for Integrated Petroleum Research (CIPR) is to integrate geological, physical and chemical modelling with the mathematical tool- and method development which will enable us to improve handling and study of such complex systems.

The initial task of Centre for Integrated Petroleum Research (CIPR) has been to establish a cross-disciplinary petroleum research unit with a broad international network. This first objective has now to a large extent been achieved. The challenge is further to create a research environment where results from basic research can form the basis for improving petroleum technology to ensure best possible economical development of petroleum resources on the continental shelf. An additional goal within this framework is also to support project-oriented research programs.

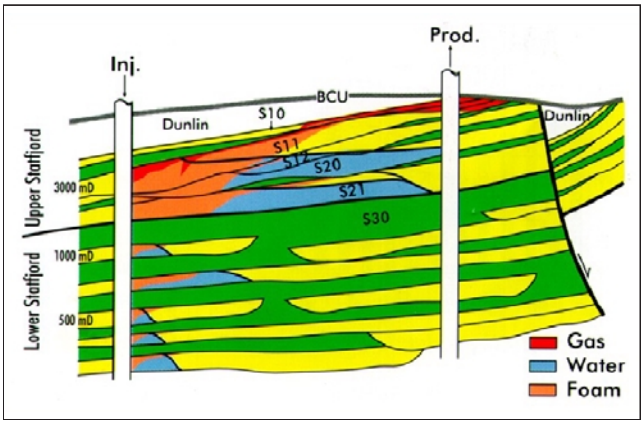

Fig.1. Illustration of WAG injection into a channel sand reservoir.

CIPR Focus on IOR and EOR methods

Improved Oil Recovery (IOR) involves the development of technology that brings oil recovery for operative and future fields up to its theoretical maximum level. For this purpose, the following main research topics have been defined by CIPR:

(i) combine geology, chemistry, physics and mathematics to improve understanding of multiphase flow phenomena in porous media
(ii) develop models and modelling methodologies for heterogeneous reservoirs that provide faster and more reliable reservoir simulations
(iii) contribute to increased oil recovery by improved understanding of oil recovery mechanisms

CIPR is continuously working on improving Enhanced Oil Recovery (EOR) processes like foam for mobility control, Water Alternating Gas injection (WAG) (Fig.1) and Microbial Improved Oil Recovery (MIOR). A

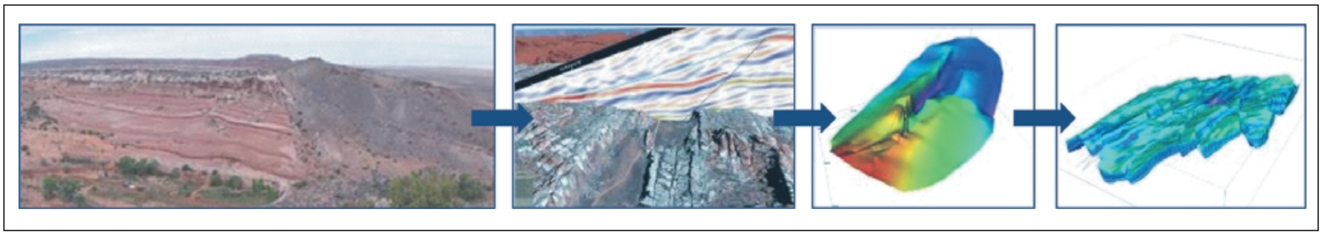

Fig. 2. Illustration of the work process from outcrop to quantitative models.

further, recently discovered, EOR process termed "linked polymer solutions" is also currently evaluated with regard to potential application in North Sea oil reservoirs. It involves the injection of nano-sized coiled polymer particles in order to improve water injection sweep in reservoirs with unfavorable mobility ratios.

Standard reservoir simulation tools are currently not able to include compositional effects in full scale field models. CIPR has, however, been able to develop a method that combines standard Black-Oil reservoir models with compositional modeling in a consistent way. Another modeling contribution from CIPR researchers is a coupling between seismic models and reservoir simulation models. By using these coupled models together with the ensemble Kalman filter technique, one hopes to establish a method that allows continuous model updating with production data and time-lapse (4D) seismic data.

Heterogeneous reservoirs

CIPR has currently a number of students and researchers working on the use of outcrop reservoir analogues as input to reservoir models to investigate the impact of depositional architectures on fluid flow (Fig.2). These studies at present include modeling of turbidite channel systems, coastal plain and shallow marine systems and understanding the impact of delta front clinoforms on fluid flow. Currently, outcrop data is utilized in case studies from producing fields (Niger Delta). A "Lidar" system, which allows 3D digitizing of field outcrops for modeling purposes, has recently been made available to CIPR. The new equipment will provide a means for expanding the already ongoing research into the systematic use of outcrop analogues to understand subsurface reservoir architectures and properties and their influence on reservoir behaviour.

Researchers at CIPR have been involved in several projects involving the use of synthetic models to understand fluid flow response to changing static reservoir parameters. Examples are reservoir heterogeneity in faulted shallow marine systems (SAIGUP), and fault controls on production in different North Sea stratigraphic settings.

The research on heterogeneous and fractured reservoirs is a good example of integration between different disciplines (Fig.3). Modeling and forecasting of fluid flow in fractured reservoirs requires the combination of

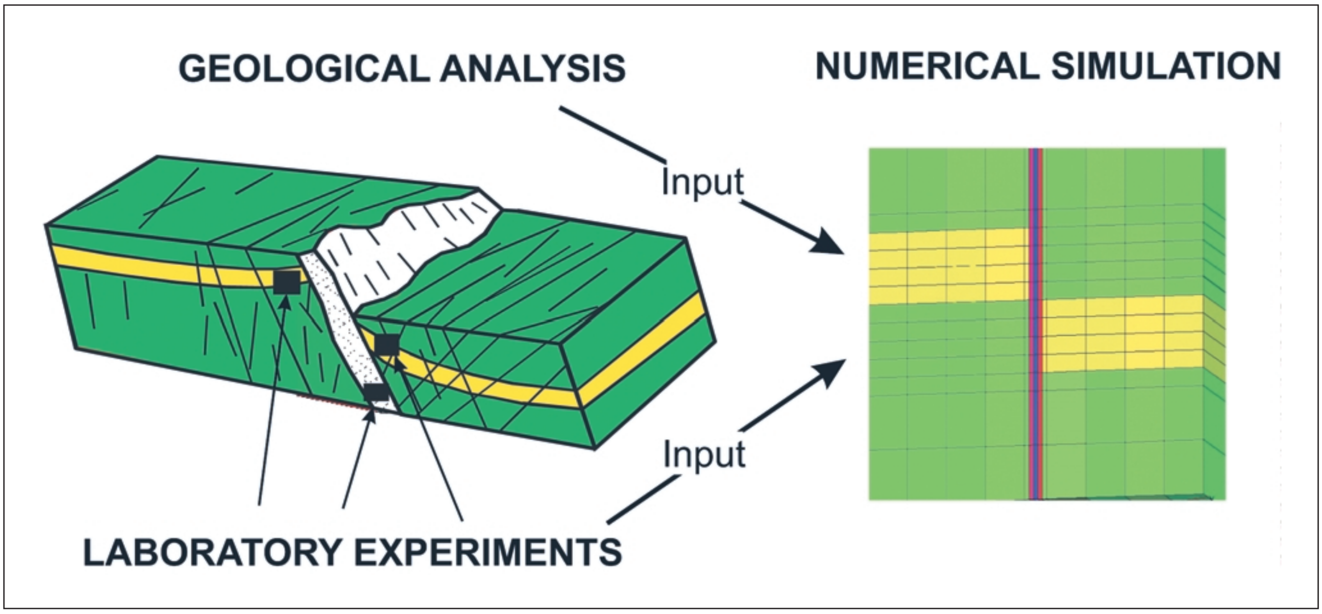

Fig. 3. Diagram illustrating the cross-disciplinary study of faults from geological concept to mathematical model.

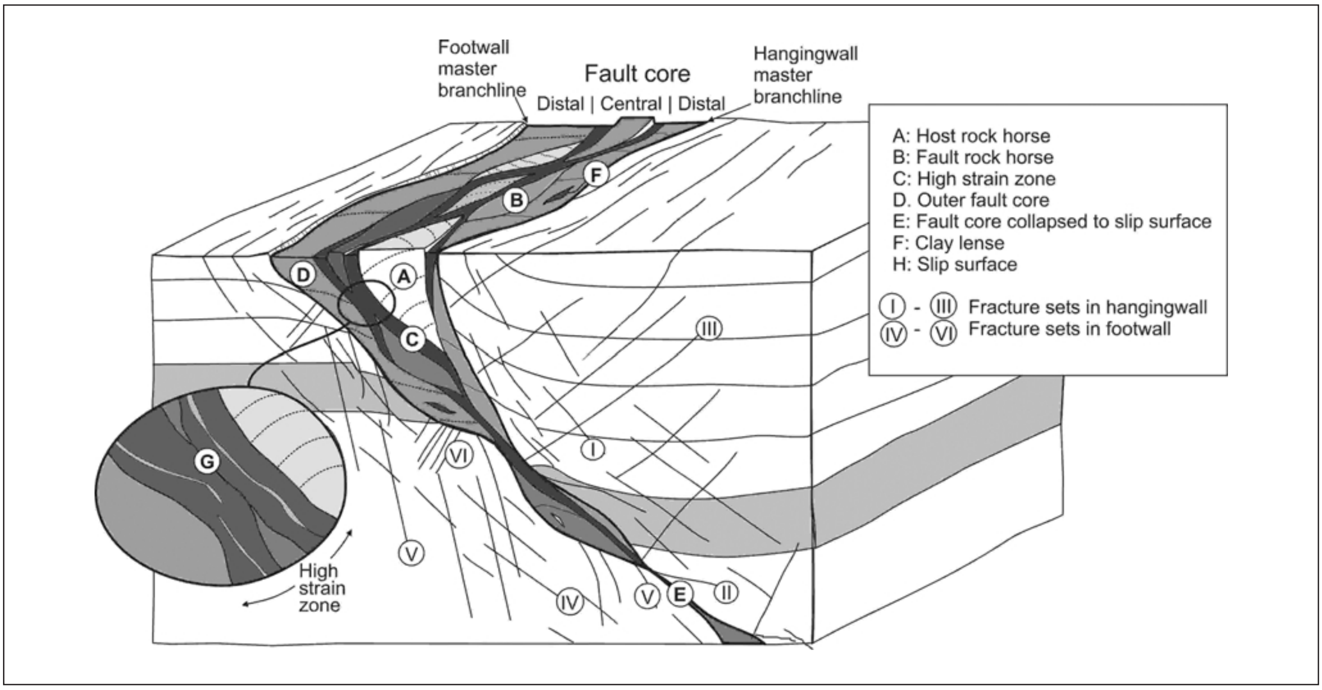

Fig. 4. Generalized sketch showing the main structural features that are associated with deformation around a fault; the fault core, the hanging wall and footwall damage zones. Note the large variation in thickness and architecture of the fault zone (from Gabrielsen et al. submitted).

geological data (architecture and petrophysical property distributions), data from physical flow experiments, and refined mathematical models of the local properties and fluid flow process. In addition to fracture properties this cross-disciplinary activity has moved towards developing a methodology for quantitative description of faults and fault rocks in order to capture and model fluid flow through fault zones.

Structural features of fault zones in reservoirs

Faults play an important role in the distribution of fluids in the subsurface and they may act as barriers or conduits to flow. In a petroleum reservoir context a fault represents a volume of deformed sedimentary rocks (Fig. 4) which can be subdivided into a central core, which has accommodated most of the displacement, and bounding damage zones (e.g., Caine et al. 1996; Gabrielsen et al. submitted). Structural features of the core include fault rocks, smear membranes, lenses of more or less intact host rock and lenses of fault rock within the core. The damage zones on both sides of the fault core may display features such as folds, smaller faults with individual cores, deformation bands, clay- and silt-shear bands (smears), and fractures (e.g., Heynekamp et al. 1999; Clausen et al. 2003; Berg & Skar submitted; Gabrielsen et al. submitted).

The internal architecture of a faulted rock volume and its inherent petrophysical property distribution strongly depend on the microscopic deformation mechanisms. These mechanisms comprise contrasting processes of granular flow (grain boundary sliding) commonly seen in unlithified to poorly lithified sediments (soft rock), versus frictional flow (crushing/ cataclasis/ granulation) that characterise deformation in more lithified rocks (hard rocks). In consequence, faults in loose sediments may actually enhance permeability, whereas faults in more lithified sediments and rocks commonly reduce it.

Studies of faulted porous, poorly consolidated siliciclastic sediments/soft rocks (Heynekamp et al. 1999; Sperrevik et al. 2000; Clausen et al. 2003; Bense et al. 2003) show that these faults consist of a fault core, footwall and hanging wall mixed zones, and a damage zone. The core in poorly lithified rocks usually contains veneers of clay and sand (Fig. 5a) or may contain a continuous membrane of clay smeared into the fault. In contrast, faults in hard, lithified rocks have a fault core that displays a large variance in internal architecture (Fig. 5b,c). Furthermore, it is seldom of uniform thickness and may even be discontinuous. The major components of the fault core in many extensional faults are horses with a lensoid shape (Fig. 5b,c) (Woodcock & Fisher 1986; Cox & Scholz 1988; Cruikshank et al. 1991; Childs et al. 1996; Gabrielsen & Clausen 2001; Lindanger 2003). The horses may consist of undeformed to heavily deformed and fractured protolith that may be stacked together with units that consist entirely of fault rocks.

High-strain zones of different types usually separate the horses (Fig. 4), and may include single slip surfaces

Fig.5. Photographs showing variations in the internal structure of the fault core in faulted sandstone. a) Fault core in poorly consolidated sandstone where the deformation mechanism is granular flow and the core is characterized by sand shears (Photo: A. Braathen), b) Fault core in consolidated sandstone showing two parallel slip surfaces that bound the core. Internal slip surfaces within the core delineate several minor bodies with a lensoid geometry, c) Fault core in consolidated sandstone showing marked variation in thickness, d) Slip zones in consolidated sandstone characterized by networks of cataclastic deformation bands.

(Aydin 1978; Aydin & Johnson 1978; Fossen & Hesthammer 1998; Berg et al. submitted), clay smear (Clausen et al. 2003), and/or slip zones encompassing networks of deformation bands (Fig. 5d) and fault rocks such as gouge and cataclasite (Sibson 1977; Braathen et al. 2004). Fractures also frequently occur in the core and may have originated either during an early stage of deformation of the brittle constituents of the zone, or may represent a later stage of reactivation. Determining what is the case for any particular fault is of great importance, because the pattern of fracture interconnectivity and hence fluid communication in the fault core may be dramatically different for the two. The fault core is usually bounded on either side by two major high-strain zones, which delineate the core from the damage zones.

The permeability structure of the damage zone is strongly dependent on the lithology of the rock that is faulted. A damage zone in sandstone is characterized by deformation bands (Aydin 1978; Aydin & Johnson 1983; Gabrielsen & Koestler 1987; Antonellini & Aydin 1994, 1995), which may decrease the bulk permeability. The opposite is the case within a sequence of mechanically strong rocks with low permeability (e.g. carbonate, chalk) where fractures may enhance permeability (e.g.

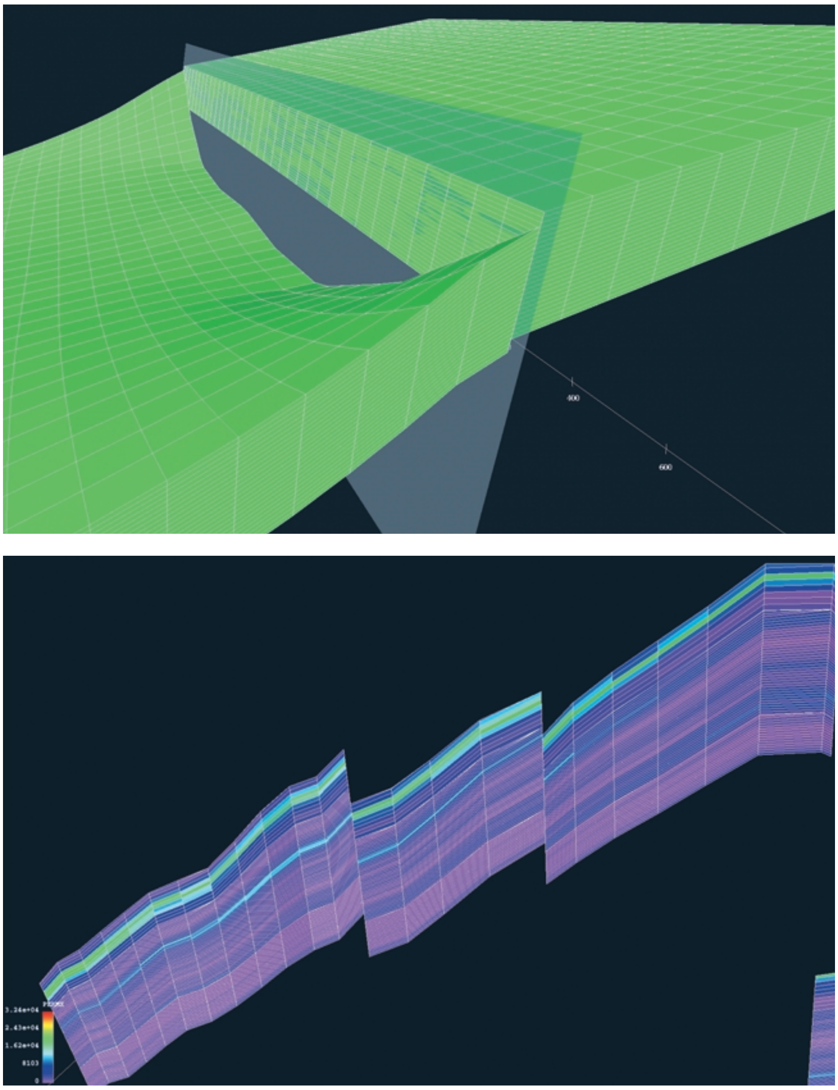

Fig.6. Conventional way of incorporating faults in reservoir models.

Watts 1983; Smith et al. 1990). If clay is present, clay smears strongly affect permeability (Sperrevik et al. 2000; Clausen et al. 2003; Skar et al. submitted). The key parameter, which defines the influence on permeability in the damage zone as such, is the interconnectivity of the fracture system in the zone (e.g., Odling et al. 1999).

Fault modeling; State of the art

When reservoir geology went digital, nearly twenty years ago, the initial goal was to capture the depositional architectures and property distributions which constitute the bulk of any petroleum reservoir. Fluid flow simulators using these geological models for input to forecast reservoir behaviour during production were adapted for this purpose, and over time combined software solutions pairing geological modeling software with simulators have become part and parcel of any serious effort at evaluating subsurface petroleum reservoirs. Despite significant advances in reservoir modeling over the last decade certain basic elements and concepts have essentially remained untouched. Two of these are: 1) An emphasis on sedimentary features and properties, and 2) Representation of faults as simple surfaces along which the modeling grid is offset with no impact on the surrounding rock volume (Fig. 6).

Although faults have all along been recognized as having significant impact on reservoir performance, efforts toward adapting existing modeling software to incorporate tectonic features as observed in nature have been modest. A number of *ad hoc* methods have been developed to include fault impact within the framework of "faults-as-surfaces" provided by the standard industrial modeling tools. Common for these methods is that changes to host rock properties caused by the fault are handled either explicitly in the simulation model transmissibility expression or as transmissibility multipliers across grid cell splits. In this way faults are represented as barriers, baffles or conduits in the simulation model. Quantification of fault transmissibility can be obtained deterministically by history matching of wells, or by using specialized applications on stochastic model realizations (e.g. HAVANA™: Hollund et al. 2002; Juxtaposition™: Knipe 1997a; and TransGen™: Harris et al. 2002). These applications calculate transmissibility distribution across modeled fault surfaces based on various combinations of host rock lithology parameters and fault throw.

Shortcomings of current methods

Although capturing overall impact on reservoir geometry and including transmissibility changes across faults by various proxies, the technical solutions chosen for these applications are restricted by their need to adapt to the established fault modeling conventions. Furthermore they are not employed routinely by modelers as they are considered specialists' tools. In practice, most reservoir engineers still estimate fault transmissibility based on history matching of wells rather than geological data, thereby running the risk of assigning effects caused by a flawed depositional model to fault impact.

When comparing these existing methods for incorporating faults in reservoir models with what is actually observed in nature, as described above, the most striking feature is that the models do not consider faults to have any volumetric extent or influence on the host rock adjacent to them. From a geological perspective, present methods, by including faults only as "membranes", therefore fail to incorporate a number of observable fault-related features which may have a significant influence on fluid flow.

The Fault Facies Project

A solution to these problems needs to be comprehensive in terms of being able to model what is known about fault architecture and properties. It should be based on field studies of faults and their associated properties and provide means to incorporate these into 3D reservoir models. It must also venture to address current 3D modeling software shortcomings, by adapting the software to capture geometries of faulted rock volumes as distinct elements in the modeling grid. For practical purposes (i.e. to ensure that the method is actually used by industrial reservoir model builders), it is also important that the improved method can be easily fitted into existing modeling work-flows.

A viable approach that fulfills these requirements is to adapt existing concepts used for object- based modeling of sedimentary bodies to handle fault and fault-related architectural elements and features (Fig. 7). For this purpose we introduce the concept of "Fault Facies" (Tveranger et al. 2004; Tveranger et al. in press).

A "Fault Facies" is informally defined as any feature or rock body deriving its present properties from tectonic deformation. As the term "facies" is not linked to any specific scale or feature, it allows a high degree of flexibility when building models with varying levels of detail and the amount of input data. The main advantage of the concept of Fault Facies is that it *per se* implies that deformational features have a volumetric extent and impact on rock properties. The use of fault facies thus allows stochastic modeling of tectonized rock volumes as consisting of discrete building blocks with defined dimensions and property ranges related to strain.

Fault facies modeling may provide a practical method for capturing fault impact in reservoirs if the following

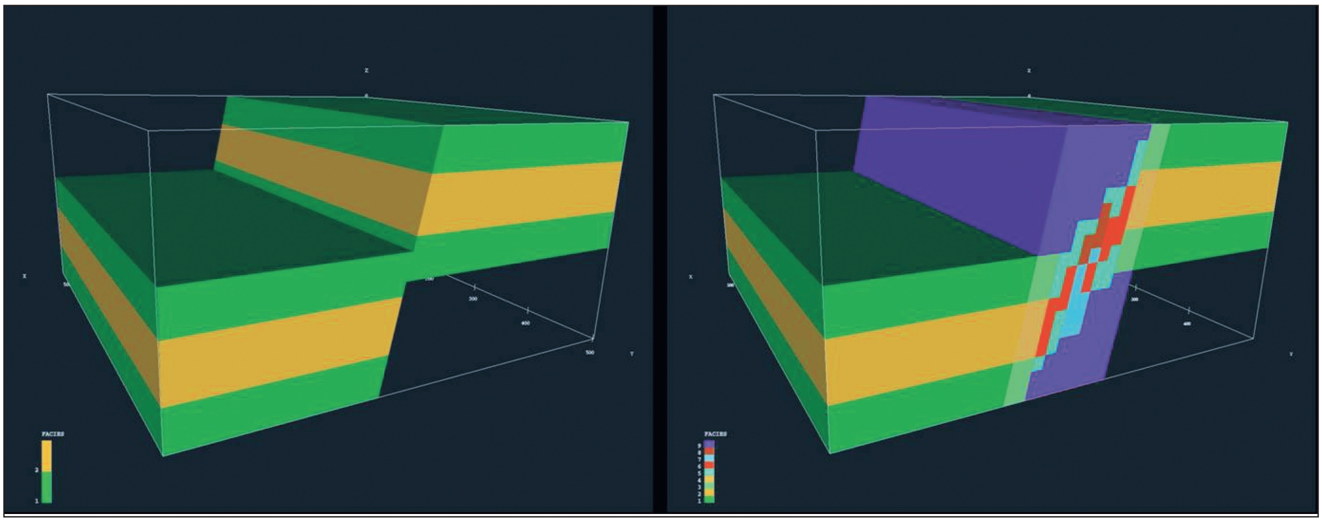

Fig.7. Conventional fault model representation (left) vs. conceptual fault facies model (right). Colours indicate different sedimentary facies and fault facies. See text for discussion.

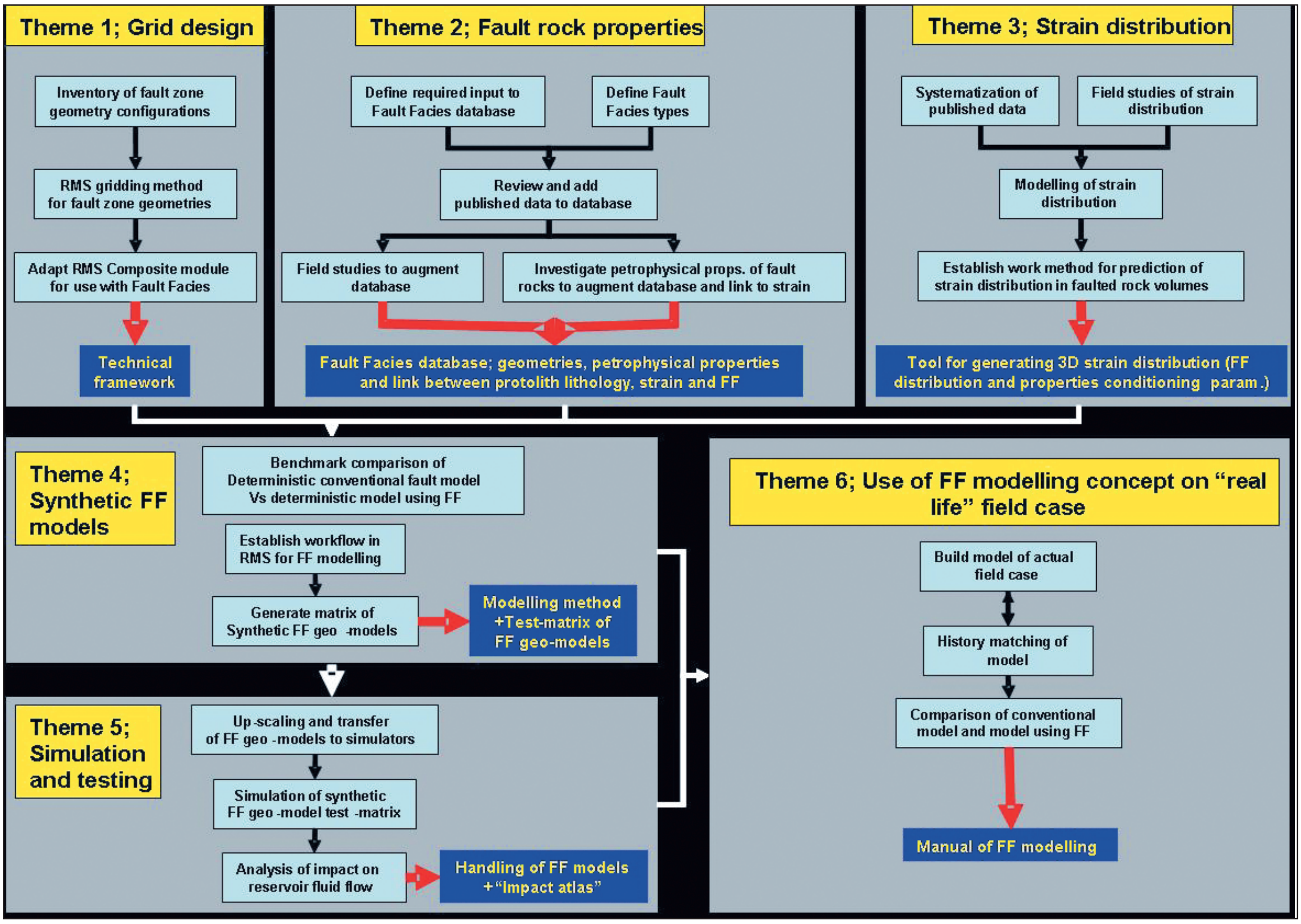

Fig.8. Work-flow diagram for the Fault Facies project.

requirements can be met:

1) The rock volumes affected by deformation can be realistically captured in the modeling grid.
2) Three-dimensional strain fields can be mapped and quantified.
3) Strain in a host-rock produces predictable structures with characteristic sizes, geometries and petrophysical properties related to strain magnitude.

Strain modeling software, using combinations of mapped fault displacements, lithology and the laws of physics, already exist (VISAGETM, FaultEDTM, POLY3D©, a.o.). These tools allow users to model 3D strain distributions in the subsurface, which effectively can be used to outline rock volumes in the reservoir affected by tectonic deformation and serve to condition the distribution of various fault facies in the reservoir.

The link between strain and changes of host rock properties in sedimentary rocks is complex, but has nevertheless been extensively studied (Aydin 1978; Aydin & Johnson 1978; Antonelli & Aydin 1994, 1995; Knott et al. 1996; Beach et al. 1999; Fossen & Hesthammer 1998; Lothe et al. 2002; Ngwenya et al. 2003; Harris et al. 2003; Gabrielsen et al. in press), and a number of empirical relationships relating to fault feature dimensions and properties have already been established (Walsh & Watterson 1987; Cowie et al. 1996; Gillespie et al. 1992; Manzocchi et al. 1999; Shipton et al. 2002; Odling et al. 2004; Berg et al. submitted). However, the practical application of concepts derived from these studies into the realm of reservoir modeling has so far been restricted by the existing methods for representing faults in modeling grids as well as the lack of a comprehensive classification scheme specifically adapted for modeling purposes. In practice this implies that a coherent effort to incorporate these empirical relationships into an object-based modeling context has to be accompanied by an algorithm that allows volumetric gridding of fault zones.

Volumetric gridding of fault zones is not at present part of an industrial modeling tool, but pilot studies (Berg et al. 2004; Skar et al. 2004) performed as part of the strategic university project (SUP) showed the practicability of the concept by using CIPR in-house simulation tool ATHENA (Reme & Øye 1999).

The task of introducing this new modeling concept for faults and their associated deformation zones requires both a modification of existing grid building techniques and re-organization and adaptation of geological information for object based modeling purposes. An interdisciplinary effort involving geologists, mathematicians, reservoir engineers and software programmers is therefore required. The Fault Facies Project represents an interdisciplinary effort involving researchers from CIPR, the Norwegian Computing Center, Roxar Software Solutions and industrial partners which will address these issues. The aim is to take the Fault Facies concept, as outlined above, from invention to practical application as an integral part of standard industrial 3D modeling of hydrocarbon reservoirs.

The project is subdivided into six main themes which will partly be run in conjunction (Fig. 8):

Theme 1. Grid design and software modification
Theme 2. Fault rock properties
Theme 3. 3D strain distribution in fault zones
Theme 4. Build geological models using FF
Theme 5. Up-scaling and flow simulation
Theme 6. Build a full-field model of an actual petroleum reservoir

The first three themes aim to a) generate a workable code for volumetric gridding of faults by using the existing grid codes in IRAP-RMS™ as a starting point, b) establish Fault Facies definitions, Fault Facies properties (geometrical and petrophysical) and their relation to strain distribution, and c) develop strain modeling methods to provide conditioning parameters for spatial distribution of Fault Facies.

Theme 4 to 6 cover the testing and application of concepts derived from Themes 1 to 3. These tests will involve a) building an extensive number of geological models (both synthetic and based on actual observations) to establish a "best practice" for the Fault Facies modeling method, b) establish robust up-scaling techniques and run the geological models in fluid flow simulators (ECLIPSE™ and ATHENA) in order to map fluid flow responses to changes in fault/deformation zone architecture and properties, ultimately providing an "impact atlas" for these features, and c) test the method on a "real life" field case.

Conclusions

Researchers at CIPR are at present involved in a broad range of research activities targeting IOR and EOR. Understanding and modeling reservoir heterogeneity and its impact on reservoir performance is a key element in these studies. The Fault Facies project, targeting existing problems of including the impact of tectonic features on reservoir fluid flow, represents a significant effort in this respect by implementing the use of large multidisciplinary teams to transfer innovative basic research into practical use. As such it represents the idea of integrated petroleum research as stated in CIPRs charter.

References:

Antonellini, M. & Aydin, A. 1994: Effect of faulting on fluid flow in porous sandstones: petrophysical properties. *American Association of Petroleum Geologists Bulletin 78*, 355-377.

Antonellini, M. & A. Aydin, A. 1995: Effect of faulting on fluid flow in porous sandstones: geometry and spatial distribution. *American Association of Petroleum Geologists Bulletin 79*, 642-671.

Aydin, A. 1978: Small faults formed as deformation bands in sandstone. *Pure and applied Geophysics 116*, 913-913.

Aydin, A. & Johnson, A.M. 1978: Development of faults as zones of deformation bands and slip surfaces in sandstone. *Pure and applied Geophysics 116*, 931-942.

Aydin, A. & Johnson, A.M. 1983: Analysis of faulting in porous sandstone. *Journal of Structural Geology 5*, 19-31.

Beach, A., Welbon, A.I., Brockbank, P.J. & McCallum, J.E. 1999: Reservoir damage around faults: outcrop examples from the Suez rift. *Petroleum Geoscience 5*, 109-116.

Bense, V. F., van den Berg, E. H. & van Balen, R.T. 2003: Deformation mechanisms and hydraulic properties of fault zones in unconsolidated sediments; the Roer Valley Rift System, the Netherlands. *Hydrogeology Journal 11*, 319-332.

Berg, S. S. & Skar, T., in press: Damage zone asymmetry of a normal fault zone - outcrop analyses of a segment of the Moab Fault, SE Utah. *Journal of Structural Geology.*

Berg, S.S., Øian, E., Skar, T. & Gabrielsen, R.H. 2004: The architecture of faults and its consequence for fluid flow. *Geologiska Föreningens i Stockholms Förhandlingar 126*, 61-62.

Braathen, A. & Osmundsen, P.T. 2004: Dynamic development of fault rocks in crustal scale detachment: an example from western Norway. *Tectonics 23*, TC4010, 27 p.

Caine, J.S., Evans, J.P. & Forster, C.B. 1996: Fault zone architecture and permeability structure. *Geology 24*, 1025-1028.

Childs, C., Watterson, J. & Walsh, J.J. 1996: A model for the structure and development of fault zones. *Journal of the Geological Society of London 153*, 337-340.

Clausen, J. A., Gabrielsen, R.H., Johnsen, E. & Korstgård, J.A., 2003: Fault architecture and clay smear distribution. Examples from field studies and drained ring-shear experiments. *Norwegian Journal of Geology 83*, 131-146.

Cox, S. J. D. & Scholz, C.H. 1988: On the formation and growth of faults: an experimental study. *Journal of Structural Geology 10*, 413-430.

Cruikshank, K. M., Zhao, G. & Johnson, A.M. 1991: Duplex structures connecting fault segments in Entrada Sandstone. *Journal of Structural Geology 13*, 865-886.

Gabrielsen, R.H. & Koestler, A.G. 1987. Description and structural implications of fractures in late Jurassic sandstones of the Troll Field, northern North Sea. *Norsk Geologisk Tidsskrift 67*, 371-381.

Gabrielsen, R. H. & Clausen, J.A. 2001: Horses and duplexes in extensional regimes: A scale modeling contribution. *In* Koyi, H.A. & Mancktelow, N.S. (eds.), *Tectonic Modeling: A Volume in Honour of Hans Ramberg.* Geological Society of America Memoir 193, 207-220.

Gabrielsen, R.H., Braathen, A., Skar, T., Berg, S.S., Clausen, J.A. & Lindanger, M. (in press): Fault architecture of extensional faults in sedimentary rocks, and the importance of strain-hardening and strain-softening. *Petroleum Geoscience.*

Fossen, H. & Hesthammer, J. 1998: Deformation bands and their significance in porous sandstone reservoirs. *First Break 16*, 21-25.

Harris, D., Yielding, G., Levine, P., Maxwell, G., Rose, P.T. & Nell, P. 2002: Using Shale Gauge Ratio (SGR) to model faults as transmissibility barriers in reservoirs: an example from the Strathspey Field, North Sea. *Petroleum Geoscience 8*, 167-176.

Harris, S.D., McAllister, E., Knipe, R.J. & Odling, N.E. 2003: Predicting three dimensional population characteristics of fault zones: a study using stochastic models. *Journal of Structural Geology 25*, 1281-1299.

Heynekamp, M. R., Goodwin, L.B., Moszley, P.S. & Haneberg, W.C. 1999: Controls on fault-zone architecture in poorly lithified sediments, Rio Grande Rift, New Mexico: Implications for fault-zone permeability and fluid flow. *In* Haneberg, W.C., Mozley, P.S, Moore, C.J. & Goodwin, L.B (eds.), *Faults and Subsurface Fluid Flow in the Shallow Crust.* Washington DC, American Geophysical Union, 113, 27-49.

Hollund, K., Mostad, P., Nielsen, B.F., Holden, L., Gjerde, J., Contursi, M.G., McCann, A.J., Townsend, C. & Sverdrup, E. 2002: Havana – a fault-modelling tool. *Norwegian Petroleum Society Special Publication 11*, 157-171.

Jones, G., Fisher, Q.J. & Knipe, R.J. 1998: Faulting, fault sealing and fluid flow in hydrocarbon reservoirs. *Geological Society of London Special Publication 147*, 319p.

Kim, Y-S, Peacock, D.C.P. & Sanderson, D.J. 2004: Fault damage Zones. *Journal of Structural Geology 26*, 503-517.

Knipe, R.J. 1997a: Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. *AAPG Bulletin 81*, 187-195.

Knipe, R.J., Fisher, Q.J., Jones, G., Clenell, M.R., Faemre, A.B., Harrison, A., Kidd, B., McAllister, E., Perter, J.R. & White, E.A. 1997b: Fault seal analysis: Successful methodologies, application and future direction. *In* Møller-Pedersen. P. & Koestler, A.G. (eds), *Hydrocarbon Seals: Importance for Exploration and production.* Norwegian Petroleum Society Special Publication 7, 15-40.

Knott, S.D., Beach, A., Brockbank, P.J., Lawson Brown, J., McCallum, J.E. & Welbon A.I. 1996: Spatial and mechanical controls on normal fault populations. *Journal of Structural Geology 18*, 359-372.

Lindanger, M. 2003: A study of rock lenses in extensional faults, focusing on factors controlling shapes and dimensions. Master Thesis, Department of Earth Science, University of Bergen, 157 p.

Lothe, A.E., Gabrielsen, R.H., Bjørnevoll Hagen, N. & Larsen, B.T. 2002: The texture of deformation bands: effects on porosity and permeability. *Petroleum Geoscience 8*, 195-207.

Ngwenya, B.T., Kwon, O., Walphick, S.C. & Main, I.G. 2003: Permeability evolution during progressive development of deformation bands in porous sandstones. *Journal of Geophysical Research - Solid Earth 108*, Art. No. 2343.

Reme, H. & Øye, G.Å. 1999: Use of local grid refinement and a Galerkian technique to study secondary migration in fractured and faulted regions. *Computers and Viz. in Science 2*, 153-162.

Sibson, R. H. 1977: Fault rocks and fault mechanisms. *Journal of the Geological Society of London, 133*, 191-213.

Skar, T., Berg, S.S., Braathen, A., Gabrielsen, R.H., Garrido, I. & Øian. E. 2004: Fluid flow in faults – modelling with the Athena simulator. *EAGE Conference proceedings – Fault Seal and Top Seal, September 2003, Montpellier.*

Sperrevik, S., Gillespie, P.A., Fisher, Q.J., Halvorsen, T. & Knipe, R.J. 2002: Empirical estimation of fault rock properties. *In* Koestler, A.G., Hunsdale, R. (eds.), *Hydrocarbon Seal Evaluation.* NPF Special Publication, 11, 109-125.

Tveranger, J., Braathen, A, & Skar, T. 2004: Incorporation of fault zones as volumes in reservoir models. *Bolletino di Geofisica Teoretica et Applicata 45*, 316-318.

Tveranger, J., Braathen, A. & Skar (in press): Incorporation of fault zones as volumes in reservoir models using " Fault Facies". *Geological Society of London Special Publication.*

Watts, N. L. 1983: Microfractures in chalks from the Albuskjell Field, Norwegian sector, North Sea: Possible origin and distribution. *American Association of Petroleum Geologists Bulletin 67*, 201-234.

Woodcock, N. H. & Fisher, M. 1986: Strike-slip duplexes. *Journal of Structural Geology 8*, 725-735.

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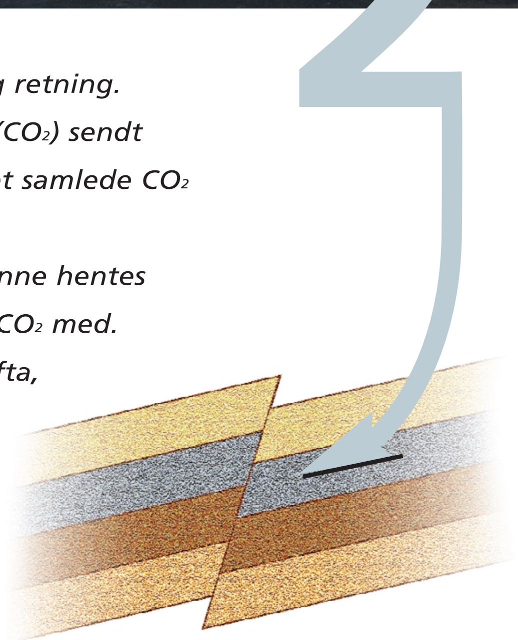

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