Best practice in structural geological analysis

Structural geology is seen too often as the domain of the specialist. Steve Dee,* Brett Freeman, Graham Yielding, Alan Roberts, and Peter Bretan of Badley Geoscience, document the case for routine inclusion of structural geological analysis within company workflows.

Structural analysis is often seen as something that only 'big companies' do, the domain of the technical specialist within a company, or an outsourced service. Yet the increasing awareness of the benefits that structural geology can bring to the E&P workcycle has created a circumstance in which technical software innovation brings specialist tools to the non-specialist.

Application of structural techniques in the search for oil and gas has undoubtedly delivered real value, ever since the initial groundbreaking work on section restoration by Dahlstrom (1969), yet standard workflows to address common problems are often not defined. Commonly this disparity is because structural geology is perceived as a specialist area and companies rely on professional structural geologists, both staff and consultants, to deliver results. Unsurprisingly, in the competitive software market, techniques and workflows have been developed to make structural analysis a 'mainstream' tool for seismic interpreters, geophysicists and geologists. Where do we apply these techniques in the workflow, and where do they deliver real value?

Structural geological analysis is… ?

For many non specialists in the petroleum industry 'geologic structure' is the three-dimensional arrangement of faults and fractures, beds or horizons and intrusions such as salt diapirs, sills, and other igneous features. With the advent of advanced 3D visualization and interpretation systems, the awareness of their geometric interrelationships has undoubtedly increased.

In the mainstream geological literature, however, structural geology is the tool used by geologists to understand the history of deformation, from understanding and interpreting displacements, strains and rates, through to stresses, pressures and temperatures. We define structural geological analysis, at least as far as this basic distinction applies to the E&P industry, as the application of the techniques of structural geology. In other words, structural geological analysis is the practical application of structural geology to the technical challenges of finding and exploiting hydrocarbons.

So what are the main areas in which we can apply structural geological analysis? There are at least four key areas where we believe the techniques of structural geological analysis have been proven to deliver real value:

- Seismic interpretation and QC
- Building representative models of geological structure
- Understanding the impact of geological structure on hydrocarbon migration and accumulation
- Understanding the impact of geological structure on fluid flow during production

Clearly, the same structural geological technique can be applied in many parts of the workflow. For example, during a seismic interpretation you may want to predict palaeobathymetry by backstripping and restoring cross-sections, the aim being to help constrain depositional and erosional analysis (e.g. Kusznir et al 1995, Roberts et al 1998). The classic example would be modelling the amount of erosion at a fault-block crest (Yielding & Roberts 1992). Yet you could use the same general technique to model the burial history of a basin or as part of a workflow to predict heat-flow and horizon temperatures through time (Kusznir et al 2005).

The key here is the understanding of the potential benefits deriving from the application of structural geological techniques to specific problems and their broad application to a number of potential workflows, rather than the common focus on the structural geological technique itself. In this article we will take a look at some selective examples of the application of structural geological techniques using Badleys' TrapTester software as the main tool for structural analysis.

Seismic interpretation and QC

Fault correlation is an area where the structural toolkits available provide immediate impact. For example, correlation of faults is greatly aided by understanding the distribution of displacement on their surfaces (Figure 1). By correlating the throw pattern across a network of faults, it is possible to look for anomalies in the overall pattern that can correspond to areas of missing interpretation, or premature truncation of a fault interpretation (Figure 1c).

Defining fault intersections during interpretation can be problematic. An established technique for analysing fault-fault intersections is to 'slice' the seismic volume parallel to a fault surface, in both the hangingwall and footwall, and interpret intersecting faults directly. An example in Figure 2

**E-mail: stephen@badleys.co.uk, Tel: +44(0)1790 753 472, Web: www.badleys.co.uk.*

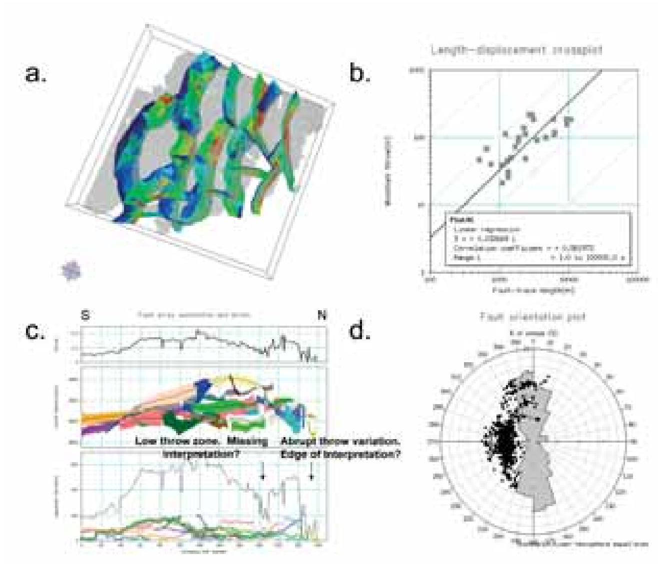

Figure 1 a) *Fault analysis techniques aid interpretation of faults through the systematic application of simple concepts. b) Maximum fault throw normally scales with fault length. Cross-plotting these key attributes for a fault population quickly identifies statistical outliers. Are they due to poor interpretation? c) Fault throws sampled at regular points along the fault plane show that interpretation gaps may exist wherever there are anomalous fault throw patterns (arrowed). d) Simple summary statistics and plots convey a great deal of information on the fault system.*

highlights how complex intersections can be rapidly correlated with horizon interpretation to produce a more robust fault framework interpretation.

Simple tools are a great help in the interpretation of faults on seismic data, yet are commonly not available in interpretation systems. In TrapTester the seamless integration of tools for interpretation and analysis means that even the non-structural geologist can make meaningful judgements that affect the interpretation of the fault system, reliably and rapidly.

Building representative models of geological structure

This is the area where the impact of 3D interpretation and visualization techniques together with the advent of low-cost high-value software tools has greatly benefited the geoscientist. Geological modelling is frequently carried out in two stages. Initially a layer- and fault-based framework is constructed where the main goal is to represent faithfully the 3D geometry of the subsurface geology, as imaged by seismic data. At this stage close attention is paid to the shape, location and connectivity of fault planes. The second stage usually involves cellularisation of the framework to a 3D corner-point geometry and it is here that the detailed sedimentological and physical property attributes are modelled into the structure. The corner point geometry is used because the endpoint of the process is a model that is designed for reservoir-flow solvers.

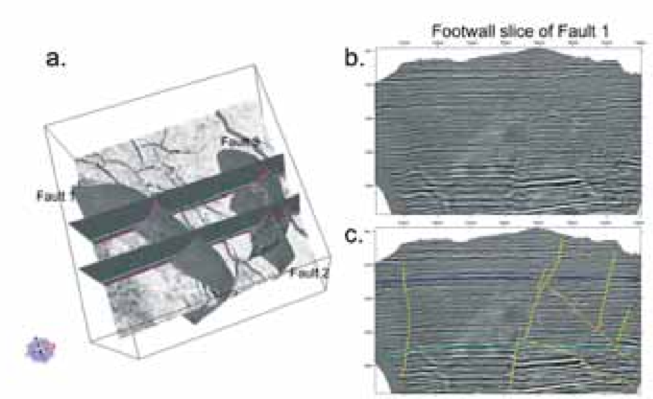

Figure 2 a) *Seismic slicing is a technique whereby the seismic volume is sliced by any arbitrary surface such as an horizon or a fault. b) When applied to faults, slices are made parallel to the fault surface in both the footwall and hangingwall, in this case the footwall of fault 1. c) A number of fault intersections are clearly imaged in the footwall slice of the fault. Slicing not only improves the modelling of fault interrelationships and linkage, but also aids in the definition of fault horizon intersections for accurate mapping of fault juxtapositions.*

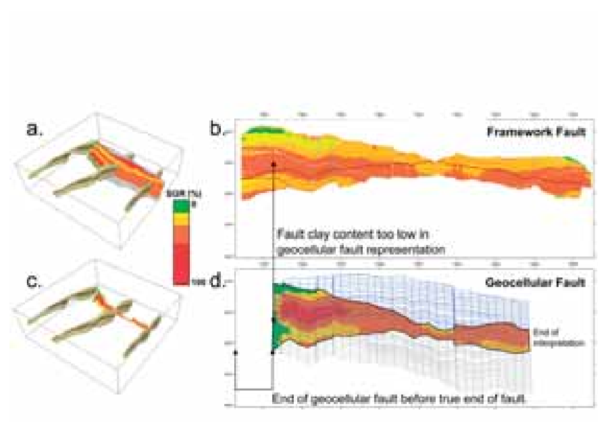

Figure 3 *Comparison of fault attributes calculated in a faulted framework model (a and b) and a geocellular model (c and d). Faults are colour coded for shale gouge ratio, a proxy for the clay content of the fault zone. Whilst there is a good overall correspondence in the shale gouge ratio values calculated from the framework and geocellular models, the description of the fault in the geocellular model is compromised in that it neither has the same vertical property extent, nor the same lateral extent – it tips-out too soon.*

The most effective place to assess the geometrical impact of the faults is in the framework model but the best property information is in the cellular model. Since cellularization can severely degrade the quality of the structural model in terms of the numbers of faults, their shapes, locations, layer connectivity and displacement, an unmeasurable uncertainty is introduced into the modelling process. For example truncation of faults in cellular models (Figure 3) can lead to an underestimate of the potential for fault baffles within the reservoir model. In the illustrated example the geocellular fault reaches its tip 500 m short of the interpreted tip for the framework fault!

Building the faulted framework model in the real data domain, prior to compromising the detail of the fault model through the limitations of geocellular modelling, is a starting point for more effective analysis of the impact of faults on migration and flow.

Understanding the impact of geologic structure on hydrocarbon migration and accumulation

Understanding fault seal and trap integrity are key requirements for many geoscientists and the quantitative methodology has been described in a number of previous papers (e.g. Yielding 2002, Bretan et al 2003).

Another example in this particular area of structural analysis is the potential impact of the in-situ stress on fault stability. Faults that are closer to reactivation within the current stress system are more likely to be permeable and conductive to hydrocarbons. To assess this potential risk we can use a new methodology which will compute the pore pressure increase required to force the fault into reactivation and display this value onto the fault surface itself (Figure 4). The smaller the pore pressure increase required, the closer the fault is to reactivation. This analysis is relatively quick since it only requires a definition of the fault surface and constraint on the in-situ stress system.

Reservoir filling and trap analysis can now be integrated within a single workflow. In collaboration with the Permedia Research Group, we have developed a workflow for the inclusion of fault properties from TrapTester within reservoir filling models (Figure 5) in Permedia Research Groups MPath software. The model is defined as a dense, regular, 2D or 3D grid of properties. Faults are introduced directly into the model by their capillary properties at the appropriate grid cell. Petroleum

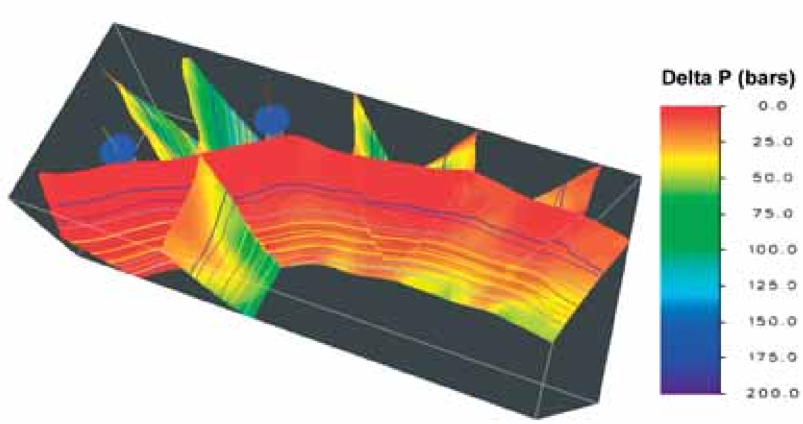

Figure 4 *The change in fluid pressure required to reactivate a fault can be mapped on the fault surface with a knowledge of the in situ stress system, pore pressure system and fault geometry. Faults with red colours require only a small pore pressure increase to reactivate and may be more transmissive to migrating, or leaking, hydrocarbons.*

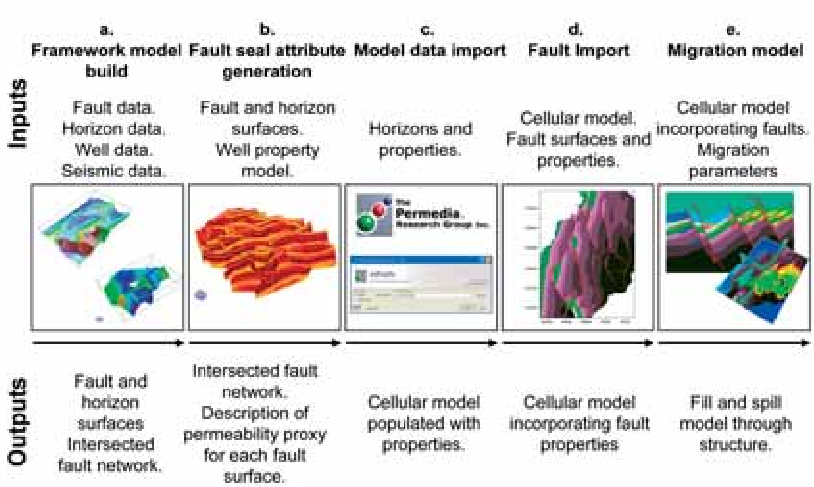

Figure 5 *Workflow to derive fault-controlled fill and spill through a field modelled using TrapTester and MPath. Fault attributes and the fault horizon framework and attributes exported from TrapTester form the basis of a realisation that incorporates the threshold pressure properties of the fault network within the percolation model.*

fluids are introduced at pre-specified locations and are free to move according to the balance of the local water pressures, petroleum buoyancies and resistive capillary pressures. Fault properties can vary laterally and vertically so that complex fault behaviour can be modelled (Figure 6a). Hydrocarbons migrate through the faulted network as a result of fill and spill. Key to understanding the distribution of hydrocarbons is an understanding of the migration pathways as affected by the fault barriers (Figure 6b).

Understanding the impact of geological structure on fluid flow

Fault properties for reservoir simulation have been available for some time within commercial software such as TransGen, a product of the Dublin-based Fault Analysis Group (Manzocchi et al. 1999, 2002). Workflows integrate the property information available in the reservoir model, with the geometry of the fault plane, to derive realistic transmissibility multipliers based on fault zone composition and thickness (Figure 7). Realistic modelling of fault properties in dynamic reservoir modelling offers the potential to understand the impact of faults on hydrocarbon producton in a true production timescale, identifying those faults that may be acting as barriers in a production sense, and helping constrain development scenarios.

Evaluating the impact of faults and fractures on fluid flow using cellular reservoir models and reservoir simulators is hampered by the difficulty of adequately defining the entire fault and fracture network e.g. the spatial distribution, orientation and type or mode of fracturing. The application of fractal-based methods enables the extraction of fault and fracture population information from seismic and well data (Gillespie et al. 1993; Yielding et al. 1996), but does not easily define the spatial aspects of faults and fractures throughout the reservoir. The slip distributions on faults that are likely to have exerted a significant control are not considered and rock mechanics are ignored in the generation of a fault model at a scale below that resolvable by seismic data.

Recent advances in the application of elastic dislocation (ED) theory to the modelling of faulted geological structures have led to the development of a new method for the prediction and mapping of fracture permeability and areas of enhanced reservoir productivity (Bourne & Willemse 2001, Bourne et al. 2001). Elastic dislocation theory, widely used (for many years past) by seismologists and geologists to model surface deformation following earthquake rupture (e.g. Healy et al. 2004), has recently been extended to analyse sets of faults mapped on seismic reflection profiles, in order to predict the density, location and orientation of sub-seismic-

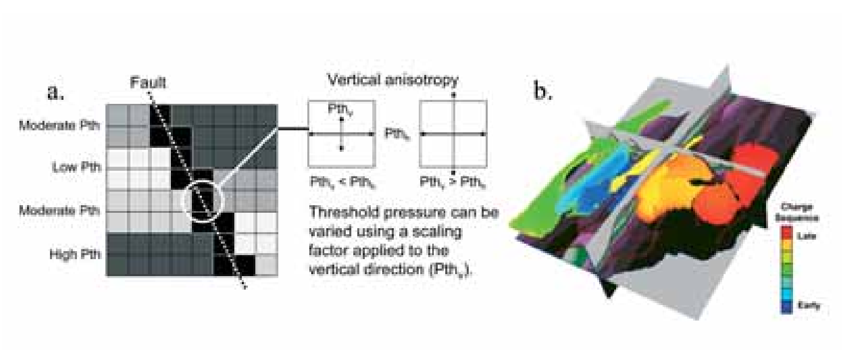

Figure 6 a)*The high-resolution MPath cellular model incorporates faults explicitly, Faults have lateral and vertical permeability and capillary properties. This allows description of the lateral and vertical flow within the fault zone. b) A realisation of fill and spill for one fill scenario in the Gullfaks field from the North Sea. Fill and spill are controlled by low capillary pressure windows on the fault plane.*

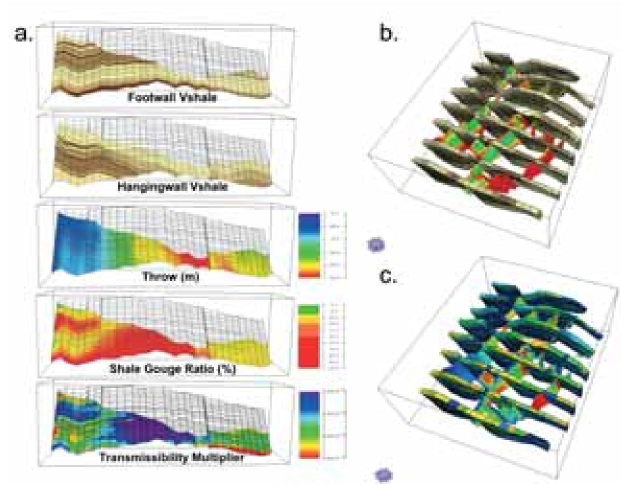

Figure 7 *Fault properties for reservoir simulation. a) Description of the flow properties of the fault requires a description of the fault geometry and Vshale in the footwall and hangingwall of the fault. Transmissibility multipliers are calculated from the fault zone composition represented by shale gouge ratio and the thickness of the fault zone calculated from throw. b) Example reservoir model with Vshale parameters in the cellular model and corresponding Shale Gouge Ratio values on the faults. c) Transmissibiity multipliers on fault planes with permeability in the cellular grid.*

scale faults. This has been implemented as part of the structural analysis workflow within the FaultED module of TrapTester (Figure 8).

Structural analysis delivers

There are obviously many more opportunities, beyond those illustrated here, for deriving benefit from structural geological analysis. There are also many more applications of technology from a wide variety of vendors and service companies than have been covered in this article. We have, however, tried to set out a broader context within which to consider the benefits of structural geological analysis, and why the focus clearly needs to be on the problem to be solved rather than the methodology applied.

Key to the inclusion of structural analysis software within the generic workflow are a seamless integration of the techniques available and a ready exchange of data between the various established software packages. Any structural toolkit has to provide data in a form that can be readily used in other applications within the workflow. Badleys have formed links with other vendors, notably Midland Valley Exploration, the Permedia Research Group, IFP and Landmark Graphics, in order to achieve this.

A good example of this increased cooperation amongst the specialist structural service companies and software vendors are recent efforts by Badleys and Midland Valley Exploration to enhance the fault-seal workflow, by including the fourth dimension, time. Combining the tools for advanced fault-seal analysis in Badleys TrapTester, with the advanced restoration capability of MVE's 3Dmove, the present-day structure can be restored to an earlier stage in the deformation sequence, and the fault-seal potential at that time analysed. Badleys and MVE, working together, have created a unique solution to the problem of defining the seal potential of subsurface faults in the geological past.

The inclusion of structural analysis in more generic E&P workflows requires collaboration with other specialist vendors in order to enhance the joint workflow, taking the analysis beyond the capability of any single discipline on its own. For example Badleys and the Permedia Research Group have been working together to include fault properties from TrapTester within Permedia's MPath migration modelling software. By focusing on its own areas of expertise, each company adds benefit to the workflow.

The future of structural analysis within company workflows is assured to a greater or lesser extent by the continued use of specialists. However, its real value lies in routine application. Structural analysis provides the solution to countless day to day problems in the E&P industry and as such, should be in the hands of the generalist as well as the specialist.

Acknowledgements

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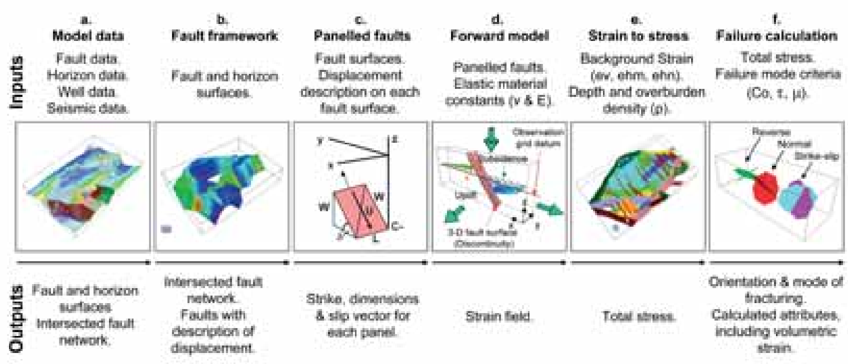

Figure 8 Prediction of small-scale fractures and faults is possible using geomechanically-based methods such as elastic dislocation modelling. Within TrapTester, elastic dislocation modelling is implemented in a straightforward workflow allowing prediction of fracture failure mode, orientation and density using the subsurface model data as input.

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