

Industrial structural geology: principles, techniques and integration: an introduction

NICHOLAS J. RICHARDSON^{1*}, FRANCIS L. RICHARDS²,
STEPHEN J. RIPPINGTON³, CLARE E. BOND⁴ & ROBERT W. WILSON⁵

¹*Oil & Gas Authority, Atholl House, 86–88 Guild Street, Aberdeen AB11 6AR, UK*

²*Chevron Energy Technology Company, Chevron House,
Hill of Rubislaw, Aberdeen AB15 6XL, UK*

³*ARKeX LTD, Newton House, Cambridge CB4 0WZ, UK*

⁴*Department of Geology and Petroleum Geology, University of Aberdeen,
School of Geosciences, King's College, Aberdeen AB24 3UE, UK*

⁵*BP Exploration, Chertsey Road, Sunbury-on-Thames, Middlesex TW16 7LN, UK*

**Corresponding author (e-mail: dr.nick.richardson@gmail.com)*

Abstract: This volume explores how structural geology can be applied to industrial activities. It includes case studies that exhibit the state of the art and provides an overview of current and future trends in structural geology. The constituent papers cover a wide range of topics, including regional tectonics; trap and prospect definition; fault, fold and fracture analysis; seal analysis; interpretation of geophysical, borehole, core and outcrop data. The volume demonstrates how structural concepts ultimately create value and how academic institutions, specialist consultants and operating companies work together at a variety of scales and in varied geological settings to explore for and produce natural resources for the economic benefit of society.

Structural geology is a fundamental component of natural resource industries such as the petroleum, mining and hydrogeology sectors, and the application of structural workflows to these businesses has a far-reaching economic impact. This volume focuses on a series of case studies and workflows that are largely derived from the oil and gas industry; however, the underlying principles and techniques are broadly applicable to any industry where subsurface resources can be delineated, quantified and extracted, or where industrial products must be stored underground. The papers within this volume are contributions from workers based in academic institutions, specialist consultancies and operating companies, demonstrating the variety of organizations contributing to the industrial structural geological ecosystem and the development of techniques. Structural techniques have routine application at every scale, from remotely sensed data acquired by satellite observation right down to thin-section analysis. The most common industrial applications of structural geology are to the interpretation of seismic data and borehole-derived data to define the geometries of petroleum and mineral deposits in order to ultimately quantify resources and determine safe and economic methods

of extraction. However, a rigorous structural framework is also required at multiple scales to aid with other subsurface disciplines such as drilling engineering (borehole stability), petroleum systems modelling (fluid/migration pathways, thermal history) and sedimentology (sediment routing, provenance).

Although industry builds upon classical structural principles and techniques, many of the workflows in industry have developed rapidly over the last two decades, taking advantage of novel, high-cost datasets, such as marine 3D seismic and well data from deep, challenging-to-access zones of the Earth's crust, including high-pressure and high-temperature domains. Often this industrial data result in a unique view of the subsurface, which can be of both scientific importance and potential economic significance to society. Whilst structural geology is only one of a number of techniques applied in the petroleum industry, it is one of the fundamental components of risk and volume analysis, which provides the geoscientific bedrock for economic assessments in the exploration and production business. The work of Rose (2001) provides an excellent introduction to the analysis and dynamics of the petroleum industry, the framework

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within which E&P investments should be made, and the technical work that underpins decision making.

Industrial structural principles

Structural traps are by far the most significant type of hydrocarbon accumulation in terms of volumetric contribution to the global oil and gas reserve base. Adequate delineation of structural surfaces and the stratigraphic horizons they interact with is essential to both robust pre-drill assessments of prospective resource ranges (together with the associated chances of encountering hydrocarbons), and to predictions of the dynamic behaviour of reservoirs in a production context.

Once a petroleum play has been defined, mapping of potential containers consisting of reservoir–seal pairs and folds/faults must be carried out in order to establish the location and size of these traps. This is most commonly achieved using seismic images of the subsurface, which are, by their very nature, an imperfect geophysical representation of geology and are, therefore, open to a variety of interpretations. In a unique study of the variability that can result from interpretation by different individuals and groups of such datasets, **Richards *et al.* (2015)** expose the need for careful assessment of the validity of subsurface interpretations in order to mitigate the chances of exploration well failures. Even if mapped traps are valid, uncertainties in the interpretations and the data from which they are derived will result in a range of possible volume outcomes and, by extension, estimates of the economic value of individual prospects. The authors outline some simple screening methods that may be used to test structural interpretation quality, so that potential problem areas can be identified and subjected to more rigorous analysis.

Subsequent to the mapping of a valid trap (or alternate scenarios of the same trap), it is necessary to evaluate seal integrity across all of its bounding surfaces. In structural traps, this commonly involves a fault seal component, which will involve consideration of juxtapositions between permeable/impermeable stratigraphic units, plus entrained material along fault planes, and inferences of the hydraulic properties of these interfaces and fluid phases within the system. **Yielding (2015)** outlines the principles behind fault seal assessments in structural traps, which are a key element in establishing hydrocarbon column heights in exploration and production workflows. Given that column height variability is commonly the single biggest contributor to volumetric (and therefore economic) uncertainty, much of the technical effort required in prospect assessment should be directed towards seal assessment and trap-fill.

More holistic assessments of structural geometries require integrating an understanding of the kinematic evolution of folds, faults and fractures, and the mechanical behaviour of deforming rocks. Folding and faulting in the Earth's crust results in the formation of associated fractures that play a significant role in allowing migration of fluids from hydrocarbon source kitchens into traps. **Cosgrove (2015)** reviews the broad variety of folds that can develop within compressional regimes, and outlines how an understanding of the variability in timing and spatial distribution of the associated fractures is fundamental to assessments of fluid migration pathways and history that are required for petroleum system models.

Whilst consideration of the impact of structure on hydrocarbon trapping and migration is relatively common, **MacKay (2015)** considers the converse situation where variations in hydrocarbon generation and pore fluid pressure impact the evolution of the gross structural system. Theoretical considerations of pore pressure-related stress changes, linked to source rock distribution and maturation, may have the potential for significant feedbacks into contractional tectonic regimes, as illustrated by the example of the Canadian Rockies.

Industry techniques and workflows

Structural interpretations rely on a broad array of different data types, acquired at different scales of observation, and whilst it is important to integrate as many techniques as possible into interpretational workflows, industrial workers frequently do not have the luxury of access to complete or ideal, multi-faceted datasets. **Bond *et al.* (2015)** assess the impact of applying different techniques to the same dataset on interpretational outcomes, using synthetically generated borehole and seismic data from a common geological model. The general message is that regardless of data type and density, the chances of a worker generating a valid interpretation are greatly enhanced by considering the geological evolution of structures during the interpretation process. Surprisingly, seismic interpreters in this study tended to perform less well than interpreters using borehole data alone, despite having access to a 'complete' image of the subsurface. This indicates that there is a risk with ever-improving seismic imaging that the geological reasoning process can be shut down by workers who 'map what they see' and impose the bias of their past experience onto the data, rather than using thought processes that test and establish the geological evolution of structures during the interpretation workflow.

Techniques involving data derived from exploratory wells are described by **Blenkinsop *et al.***

(2015) and Murray (2015). The former paper focuses on a novel, unified technique for obtaining structural data such as planes, lineations, fold hinges, shear zones, fractures and faults from oriented drill cores, which are expensive to acquire but, where available, should be utilized fully as a source of structural information. Techniques such as this, derived initially from the minerals industry, are becoming increasingly important to the petroleum industry. Murray (2015) outlines a method where fractures and other features can be characterized in the absence of core, using images obtained down the borehole. Correctly describing fracture populations is of crucial importance to the evaluation of hydrocarbon reservoirs in basement rocks, but has other industrial applications in groundwater modelling and nuclear waste disposal schemes.

Outcrop studies can be used to bridge the gap between core- and well-scale observations of fractures and the scale of an entire field, since fractures are below the resolution of seismic data. Pless *et al.* (2015) describe the construction of three-dimensional models of fracture systems using terrestrial laser scanning of outcrops, supplemented by remote sensing and line-sampling workflows in order to derive fracture densities, orientations and dimensions. This technique is illustrated by application to the Scottish Highlands, which are potentially analogous to nearby offshore fields that have basement reservoirs.

Structural integration and case studies from industry

The final section of the volume is a collection of case studies applied to regional-, field- and reservoir-scale industrial structural problems. At the regional scale, Morley (2015) considers the intracratonic rift basins of Thailand and how their atypical structural evolution and configuration have controlled trap styles, reservoir depositional systems and the maturation and migration history within these basins. These basins have undergone multiple phases of rifting and inversion, with a complex stress regime against the background of rapid plate boundary changes, and prevalent low-angle normal fault development, all of which have combined to have an impact on the prospectivity of the petroleum systems.

Regional-scale studies of this kind can often be greatly enhanced through careful application of gravity and magnetic data in order to delineate the gross distribution of crustal types, which are crucial for modelling source rock presence and maturity as well as the distribution of major structural highs. Such techniques add particular value in situations where seismic imaging is problematic (e.g. in the

presence of salt and volcanics) or where seismic data acquisition is complicated or coverage is sparse. Rippington *et al.* (2015) apply gravity and magnetic methods to the Faroe–Shetland Basin where deep, basement structures beneath a volcanic succession have an important control on the overlying hydrocarbon-bearing traps. Within this basin lies the giant Clair oil field, which has been a challenging development of a fractured basement reservoir. Ogilvie *et al.* (2015) describe the importance of the application of structural geological techniques not just to the regional setting and reservoir characterization of this field, but also to the safe and efficient execution of drilling activities through a complex overburden and reservoir section.

The dynamic behaviour of reservoirs during production can also be understood and predicted better using a number of structural techniques. Wood *et al.* (2015) describe an integrated study where seismic and outcrop resolution datasets were combined to construct a geocellular model to simulate the flow behaviour of oil within a reservoir under depletion. The structural and stratigraphic resolution of the model was shown to have a significant impact on the modelled production history of the reservoir, primarily as a result of the degree to which cross-fault reservoir juxtaposition and permeability is represented, and underscores the importance of capturing sufficiently detailed and realistic structural complexity within dynamic models.

In fields that rely primarily upon fracture permeability, correct prediction of fracture densities and permeabilities is vital to correct well placement, which can have a significant impact upon production rates, and overall oil or gas recovery. Freeman *et al.* (2015) illustrate this by way of the novel application of geomechanical modelling techniques to the Gorm Field in the Danish sector of the southern North Sea. They have developed an elastic dislocation model in which strains are calculated using the observed geometry of seismically interpreted surfaces, and constrained by image log data from well penetrations, in order to forward model the location, density and orientation of fractures within the reservoir. The application of such techniques could become invaluable in predicting fracture populations in exploration and unconventional resource scenarios, using readily available seismic data and their interpretations.

An alternative method for fracture prediction using structural restorations and forward models of geomechanical deformation is described by Bergbauer & Maerten (2015). Using the example of the Hoton gas field in the southern North Sea, they demonstrate how successful exploitation of unconventional reservoirs can be enabled through this approach, thus unlocking previously uneconomic resources.

Conclusion

This volume demonstrates the value of structural geological techniques to resource industries, and particularly to petroleum exploration and production. It showcases a variety of workflows, and demonstrates the broad applicability of structural principles at all scales and stages of the E&P lifecycle. Structural geology has played, and will continue to play, a fundamental role in resource discovery, economic extraction and safe operations for many decades to come.

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