Fold and thrust belts: structural style, evolution and exploration – an introduction

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Abstract: The outer parts of collision mountain belts are commonly represented by fold and thrust belts. Many of the key concepts in the structural geology of fold and thrust belts have origins in ancient orogens such as the Appalachians and Caledonian chains of Europe, together with the Alps. Impetus in thrust belt research then came from the desire to exploit geological resources that reside in the subsurface, especially arising from hydrocarbon exploration in the foothills of the Canadian Cordillera in the 1960s and 1970s. Notwithstanding decades of exploitation, continental fold and thrust belts are still estimated to hold reserves of 700 billion barrels of oil equivalent. But exploration will focus increasingly on small, hard-to-resolve structures. Basic geological understanding remains as important today as it did for the pioneering explorers in the Canadian foothills. It is a theme that runs throughout this Special Publication.

For many, the key advances in understanding thrust systems arise from hydrocarbon exploration in the foothills of the Canadian Cordillera, as exemplified by landmark papers by petroleum geologists (e.g. Bally et al. 1966; Dahlstrom 1969, 1970). Thus, although many of the key concepts in the structural geology of fold and thrust belts have earlier origins in other orogens, the impetus has come from the desire to exploit geological resources that reside in the subsurface. The significance of continental fold and thrust belts as hosts for hydrocarbons is reviewed by Cooper (2007). Roeder (2010) estimates that globally these systems hold known reserves of 700 billion barrels of oil equivalent. However, both authors recognize that very large fields are unlikely to be found so that exploration will focus increasingly on small, hard-to-resolve structures.

Exploration in continental thrust belts is complex. Terrain is commonly inaccessible, making seismic acquisition exceptionally problematic, compounded by additional uncertainties emanating from complex near-surface geology, weathering profiles and topography that create substantial challenges for seismic processing. Therefore, the quality of subsurface imaging can be much poorer than, for example, of submarine rift basins. Many approaches to reducing the resultant uncertainties in forecasting subsurface structure use theory and models of structural behaviours to understand structural style and its evolution.

The simple styles of thin-skinned tectonics deduced for the foothills of the Canadian Cordillera are just part of a spectrum of deformation styles by which the continental crust can deform during contractional tectonics (as noted for example by Ramsay 1980; Coward 1983; Butler & Mazzoli 2006).

From: Hammerstein, J. A., Di Cuia, R., Cottam, M. A., Zamora, G. & Butler, R. W. H. (eds) 2020. *Fold and Thrust Belts: Structural Style, Evolution and Exploration*. Geological Society, London, Special Publications, **490**, 1–8.
First published online July 31, 2020, https://doi.org/10.1144/SP490-2020-81

Pre-existing structures controlling the styles of crustal-scale deformation, and the variable role of detachment surfaces within, and at the base of, sedimentary successions, can generate complex structures that evolve in different ways. Orogenic contraction can involve complex sequences of thrust-sheet emplacement and the formations of arrays of subsidiary faults that impact on the assessment of petroleum prospectivity in different ways. Significant challenges remain in down-scaling descriptions of fold and thrust structures to forecast deformation on the reservoir scale (e.g. Butler *et al.* 2018).

The papers in this Special Publication represent the latest endeavour to collect together the current state of academic understanding of these systems together with their significance for petroleum exploration. Over the years there have been many attempts to collate research addressing contractional tectonics in general and specifically the structure of fold and thrust belts. However, these have only rarely brought together research from the diverse communities – not only those who develop interpretational methods and tools for constructing cross-sections and associated visualizations to forecast subsurface structure but also those who apply and test these ideas in natural settings – essentially through drilling. But there are exceptions: the compilation of papers that brought together researchers and explorers include ‘Thrust tectonics and hydrocarbon systems’ (McClay 2004), ‘Oil and gas in compressional belts’ (Needham *et al.* 2004), ‘Thrust belts and foreland basins’ (Lacombe *et al.* 2007), and ‘Hydrocarbons in contraction belts’ (Goffey *et al.* 2010).

In the past decade there have been significant developments in structural methodologies that complement well-established techniques in geometric cross-section construction and restoration. Simultaneously, advanced acquisition technologies are helping to reduce uncertainties in the characterization and evaluation of subsurface structures and reservoirs. New technologies and approaches are helping to advance understanding of fold and thrust belts, not only opening new exploration opportunities in these systems but also in making hydrocarbon production more efficient. The insights and workflows developed by the oil and gas sector in characterizing and forecasting the subsurface in structurally complex settings are assisting other industrial applications, including waste storage. These insights may also help to forecast and mitigate earthquake hazards in tectonically active settings.

It is evident from the papers in this Special Publication that fold and thrust belts are far from simple structures displayed in idealized models, with a number of controls that need to be considered in order to fully understand them. Specifically, pre-orogenic architecture, basement interactions, sedimentation and mechanical properties of stratigraphy, all play roles in the evolution of a convergent system. Natural fold–thrust structures can show substantial variations in their geometry along their lengths, meaning that insights gained in one area may not apply to another even in the same fold–thrust belt.

The 19 papers collected here are divided into four sections. The first section presents six papers examining modelling techniques and general methods used to understand the mechanisms and controls on the evolution of fold and thrust belts, and to evaluate potential petroleum systems. There follow papers on a variety of case studies which are grouped here into three regions: Europe, Asia–Pacific and the Middle East. Collectively they show how multidisciplinary approaches are essential for reducing uncertainty in the deductions of structural evolution. The papers use a variety of observations, from outcrop and the subsurface, allied with remote imaging both from satellites and seismically. Thermal and stratigraphic data are used to assess geological histories. Insights are gained from modelling, both using analogue materials and numerical methods. But to appreciate the diversity of potential structures, insights come from understanding different natural examples, and from revisiting areas again using legacy data informed by new ideas. The various locations of case studies and other examples used in this Special Publication are shown on Figure 1. Ideas, models and interpretations of fold–thrust belts are evolving; assessing whether their application leads to better exploration outcomes remains for the future.

About this volume

Modelling of fold and thrust belts and petroleum systems

The first papers examine general issues in understanding fold–thrust belts. One way to investigate structural evolution is through the use of deformation experiments on analogue materials, an approach pioneered by Henry Cadell towards the end of the nineteenth century. **Butler *et al.* (2020)** review Cadell’s results and motivations that sprung from fieldwork in the NW Highlands of Scotland. This study of historical scientific investigation, using Cadell’s original field notes and commentary, informs a discussion of uncertainties and biases that can result from using analogue experiments to assist interpretation of the subsurface in the natural world.

As Cadell showed, deformation styles are highly sensitive to the mechanical properties of the material. **Hughes (2020)** explores this notion through computational methods, applying discrete element modelling to see how strain is distributed in folding and faulting. These models demonstrate that ‘weak’ rocks form folds with distributed strain so that

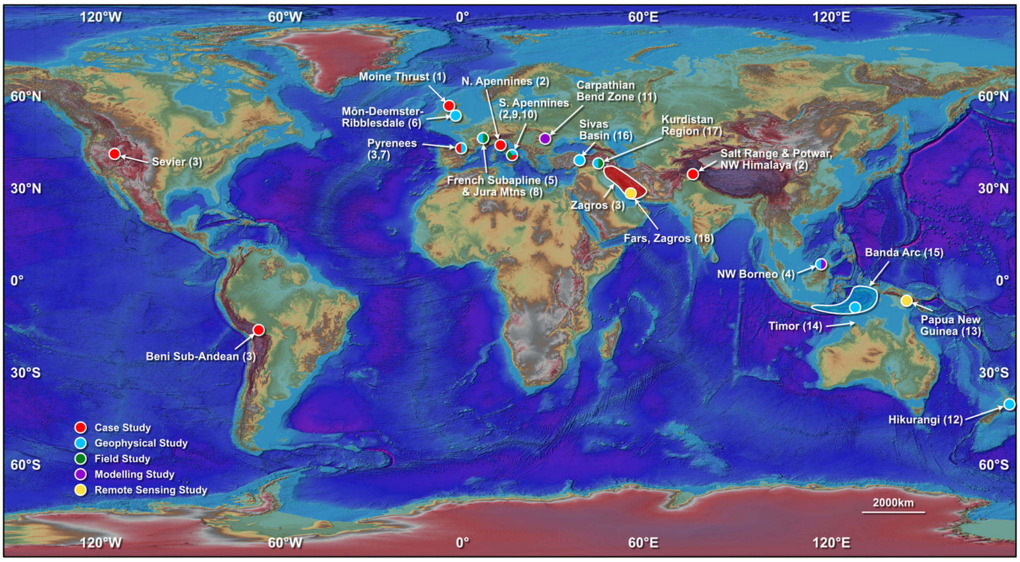

Fig. 1. Global digital elevation model (DEM) showing locations of studies presented in this volume. Associated paper and type of study indicated by number and marker colour respectively. Field studies include those involving sample collection for laboratory analysis. (1) Butler *et al.*; (2) Butler; (3) Kendall *et al.*; (4) Grant; (5) Muirhead *et al.*; (6) Pharaoh *et al.*; (7) García-Sen *et al.*; (8) Malz *et al.*; (9) Pace *et al.*; (10) Casabianca *et al.*; (11) Tamas *et al.*; (12) McArthur *et al.*; (13) Ollarves *et al.*; (14) Duran *et al.*; (15) Baillie *et al.*; (16) Legeay *et al.*; (17) Tozer *et al.*; (18) Ginés *et al.* Elevation data courtesy of NASA.

layer thicknesses become heterogeneous with deformation. In contrast rock sequences with moderate strength fold with flexural slip and therefore form concentric structures with better preservation of layer thickness. With stronger strain-weakening properties the propensity of rocks to deform through the formation of faults increases.

In addition to the mechanical properties of the stratigraphy, sedimentation and the syn-kinematic strata can have a strong influence over the structural style of emergent fold and thrust belts. With examples from the Apennines and Himalayas, **Butler (2019)** illustrates how the rate of syn-kinematic sedimentation relative to thrust displacement rate controls whether thrusts are imbricate-dominated or allochthon-prone. Here it is demonstrated that high sedimentation rates, relative to displacement, appear to generate imbricate systems with ramp-dominated geometries, in contrast to regions of little sedimentation where thrust allochthons are emplaced. Furthermore, lateral and temporal variations in sedimentation rate can cause the structural style to evolve, and as such it is likely that emergent thrust systems will demonstrate complex deformation activities.

Source-rock distribution, pre-orogenic architecture and its interaction with the orogenic processes, and mechanical stratigraphy are fundamental in the evolution of a petroleum system. With these factors in mind, **Kendall *et al.* (2019)** examine how a petroleum tectonic analysis can be used as an effective method of evaluating the orogenic processes of fold and thrust belts containing organic-rich intervals. Examples from the Zagros, Pyrenees, Sevier and Beni Sub-Andean demonstrate the role of flexural and dynamics processes, wedge taper kinematics, mechanical stratigraphy, source-rock distribution and inherited architecture can either create or destroy a petroleum system.

When considering multiple hydrocarbon prospects, readily usable tools for evaluating the petroleum system are critical for exploration and development of drilling programmes. **Grant (2020)** proposes an empirical 1D growth model that presents a method of evaluating the geo-history and trap integrity of a growing toe thrust structure. Giving due reference to the more simplistic nature of this approach and critical assumptions used, Grant argues that this model can provide a quick assessment of the geo-history. These representative results can then be tested against well data and have potential for the evaluation of neighbouring structures.

Understanding the thermal history of a system is fundamental to hydrocarbon exploration and can test different predictions of thrust belt evolution (e.g. Deville & Sassi 2005; Aldega *et al.* 2017). **Muirhead *et al.* (2019)** discuss the use of Raman spectroscopy in determining the thermal maturation of carbonaceous sediments. Previously utilized for metamorphic samples exceeding 270°C, the authors show that Raman spectroscopy can be an effective thermal marker for temperatures down to 75°C. Raman data from the Bornes region of the French Sub-Alpine chain are compared with published vitrinite reflectance and thermal modelling data, and critically is shown to be consistent. The authors argue that Raman spectroscopy may therefore be considered a quick and effective tool for lithological analysis of samples with a geological temperature of less than 300°C. As this temperature window is aligned with the oil and gas generation window, the method represents a powerful tool for testing models of structural evolution in fold and thrust belts, and calibrating models of hydrocarbon generation in sedimentary basins.

Europe

Crustal strength plays a key role in the evolution of fold and thrust belts. **Pharaoh *et al.* (2019)** examine seismic data from the Môn-Deemster-Ribblesdale fold–thrust belt, the Variscan inversion of the Bowland Basin, in order to develop a detailed model for the structural evolution. Significantly, a region of weak crust located between rigid massifs to the north and south is identified as the key control for the evolution of the Bowland Basin and Môn-Deemster-Ribblesdale fold and thrust belt. Subsequent inversion was focused on reactivated older structures.

García-Senz *et al.* (2019) examine the role of contrasting crustal strength in the Cantabrian–Pyrenean Orogen. The authors here present five crustal-scale balanced and restored cross-sections based on field data, published seismic data and new gravity and magnetic models. Here it is postulated that the presence of an exhumed mantle body, suggested by gravity and magnetic data, acts as a rigid buttress for weaker continental material to be thrust outwards and upwards during Alpine collision. This process resulted in the formation of two triangular crustal zones at the boundaries of the exhumed mantle body.

As well as crustal strength it is essential to consider the control pre-existing structures can have on the evolution of a fold and thrust belt. **Malz *et al.* (2019)** provide a detailed analysis of the Late Miocene Mandach Thrust, easternmost Jura Mountains (Northern Switzerland). The construction, restoration and forward modelling of eight cross-sections, constrained by depth-migrated 2D seismic data and geological maps indicate predominantly thin-skinned thrust tectonics. Along-strike variation in thrusting style is controlled by pre-existing structures, specifically the change in relief of the mechanical basement beneath the thrust. Additional along-strike changes are associated with local activation of secondary detachment and lateral sedimentary facies changes. The authors also postulate that variation in recorded shortening of individual sections may relate to currently unidentified transfer structures.

Pace *et al.* (2020) reappraise vintage data from the Southern Apennines thrust belt, Southern Italy, with modern techniques to determine the remaining hydrocarbon potential of an existing oil field. Revisiting legacy data with more up-to-date knowledge of the geological framework, structural style and geophysical characteristics, as well as better understanding of tight-fractured carbonate reservoirs allowed for reappraisal of the abandoned Benevento Field. Identification of new prospective structures demonstrate similarities with other discoveries along the same structural trend. Structural reconstruction suggest that these newly identified structures are related to Pliocene positive inversion of pre-existing Permian–Triassic half grabens, and therefore the structural evolution of the Apulian thrust belt is consistent with a basement-involved inversion tectonics model.

Casabianca *et al.* (2020) examine the role of pre-existing extensional structures and how they have controlled the development of the Maiella anticline: a fold and thrust belt-related structure in the Southern Apennines, Italy. When discussing the potential evolutionary models for the region the authors examine the implications for the size and distribution of reservoir elements for hydrocarbon exploration. With data for this study primarily coming from field observations and well bore data, the authors also raise the question of how their conclusions might have differed if this were purely based on a seismic dataset. The authors conclude that observation of syn-sedimentary normal faults within the structure may not have been observed, with negative consequences for general understanding as well as hydrocarbon exploration. This highlights the need for an integrated approach, including field observations where possible, to capture the full story of these complex systems.

The presence of salt can have detrimental effects on subsurface imaging. In such instances scaled analogue modelling can inform interpretation. **Tămaș *et al.* (2019)** present the results of two scaled analogue models in an attempt to understand the Mid-Miocene tectonic evolution, structural geometries and effects of penetrative strain for the Diapir Fold Zone, Eastern Carpathian Bend, Romania. Poor seismic quality due to the presence of salt has led to contrasting structure models for this complex system. A combination of digital image correlation techniques and digital elevation-model analysis were used to aid interpretation of layer parallel compaction, thickening, fault propagation and reactivation history. The structural style of the models is characterized by sub-salt duplex structures overlain by wide supra-salt detachment folds with steep limbs, which are considered comparable to structures observed in the Diapir Fold Zone. Whilst the authors acknowledge that the way penetrative strain affects analogue models and nature is different, they show how penetrative strain may be temporally and spatial distributed in such systems.

Asia–Pacific

The third section of the volume presents four papers discussing fold and thrust belts in Asia–Pacific.

With an integrated study utilizing gravity, bathymetry and 2D seismic data **McArthur *et al.* (2019)** examine the structural and stratigraphic variation in the southern regions of the Hikurangi subduction wedge, North Island, New Zealand. The authors demonstrate that whilst longitudinal variation of accommodation and sediment distribution styles exists, a broad inboard-to-outboard subdivision is observed. The study highlights the variable style of sedimentation across the margin and the role of underlying structures for the development of distinctive types of accommodation, sediment flux and stratigraphic evolution. It is concluded that lateral and longitudinal variation in structure and sedimentation is key to exploiting such regions for frontier hydrocarbon exploration.

Poor geophysical imaging and preservation of syn-kinematic stratigraphy of study areas leads to alternative approaches being adopted. **Ollarves *et al.* (2019)** present a morphotectonic analysis of the surface expressions of folded structures in order to assess the folding style and sequence of the Western Papua New Guinea Highlands. Folds were initially characterized by shape, aspect ratio and symmetry. Fold front sinuosity and karst development observations allow for relative ages to be assessed and drainage network analyses were used to refine these ages. These analyses highlighted common characteristics associated with particular structural styles, such that the folds could be grouped according to their likely evolution.

Two papers in this section interpret the broadband BandaSeis 2D seismic survey. Interpretations from **Martinez Duran *et al.* (2019)** describe structural and tectonic features, not previously reported, of the Timor Orogen, whilst **Baillie *et al.* (2020)** consider more regional observations. The complex collision of the Eurasia, Australia and Pacific plates resulted in a distinctive horseshoe morphology, that has been associated with Late Jurassic rifting and breakup of East Gondwana (e.g. Longley *et al.* 2002; Hall 2012). The authors describe how the fold and thrust belts change in size, shape and degree of basement reactivation around the Banda Arc.

Middle East

With typically excellent outcrop exposure, coupled with large volumes of known hydrocarbon reserves, regions such as the Zagros Mountains have presented geologists with prime opportunities to understand the evolution of fold and thrust belts and their relationship with hydrocarbon generation, migration and trapping. The final section of this volume brings three papers discussing fold and thrust belts in the Middle-East region.

With a combination of field studies and interpretation of seismic data, **Legeay *et al.* (2019)** construct a series of regional cross-sections to constrain the structure and evolution of the Sivas Basin, central–eastern Anatolia, Turkey. Critically, the authors consider the influence syn-orogenic salt has had on the structural style and lateral variability of a fold and thrust belt.

Tozer *et al.* (2019) consider vertical movements associated with fold and thrust belts presenting a case study from the Kurdistan region of Northern Iraq. The authors demonstrate how a combination of 1D subsidence analysis of well data, construction of cross-sections incorporating a common structural datum and vitrinite-reflectance data can be used to assess the subsidence, uplift and erosion of the region. When considering the uplift history, the importance of considering the regional context is indicated; when a structural datum from a regional cross-section is employed an additional 0.9 km of basement-involved uplift is calculated. Significantly, it is suggested that this additional basement-involved uplift maybe the explanation for unsuccessful hydrocarbon exploration in parts of the region.

When regions of interest are inaccessible it is necessary to utilize alternative methodologies. **Ginés *et al.* (2019)** examine how remote sensing methods can be used to good effect in regions such as the Zagros Mountains, Iran. Given the climatic conditions, excellent exposure and ever improving resolution of satellite imagery, geological features exposed at the surface can be evaluated in great detail. By combining optical data, digital elevation models and InSAR data it is possible to take structural measurements and map lithologies and make predictions for the subsurface geology. The authors demonstrate the interaction between sedimentary cover and basement structures and how variation in structural style can be observed in the region. Further analysis of longitudinal river profiles was used to indicate the existence of basement faults.

Concluding remarks

It is evident from the papers in this Special Publication that fold and thrust belts are far from simple structures. Specifically, pre-orogenic architecture, basement interactions, sedimentation and mechanical properties of stratigraphy, all play a critical part on the evolution of a convergent system. Failure to incorporate these natural variations and complexities when building structural understanding can lead to significant problems when forecasting the subsurface to develop prospects for hydrocarbons and other resources.

Lateral and longitudinal variation in characteristics of fold–thrust belts are commonly reported and need to be thoroughly assessed, especially when considering the significant hydrocarbon potential of such regions. With technological advancement there is not only the possibility of collecting new, higher quality data, but also to re-examine legacy data. Utilizing scaled physical, numerical and empirical models can inform our interpretation of real data but it is critical that we do not rely on any one model or realization as a definitive solution. They form part of a spectrum of possible solutions. Recognizing diversity is key. Even in this digital age of 'big data', good field observations and critical interpretation remain essential.

Acknowledgements The editors would like to sincerely thank all those involved with the production of this Special Publication. We are extremely grateful to the many authors that have taken the time to prepare and present their research for inclusion in this volume. We would also like to thank Jürgen Adam, Patrice Baby, Sabina Bigi, Kyle Bland, Caroline Burberry, Nestor Cardozo, John Cosgrove, Peter DeCelles, Tim Dooley, Oscar Fernandez, Lawrence Gill, Paul Griffiths, Rosalind King, Hemin Koyi, Piotr Krzywiec, Olivier Lacombe, Richard Law, Gianreto Manatschal, Jon Mosar, Paolo Pace, James Rigg, Alberto Riva, Nicola Scarselli, Oliver Schenk, Ian Sharp, Juan I. Soto, Richard Swarbrick, Stefano Tavani, Peter Turner, Robert Wilson, Nigel Woodcock, Jonny Wu and other anonymous reviewers who have given generously their time and effort to help shape the papers; it is greatly appreciated. Sincere thanks are given for the help and patience provided by Bethan Phillips, Tamzin Anderson and Samuel Lickiss at the Geological Society of London.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author contributions **JAH**: conceptualization (equal), writing – original draft (equal); **RDC**: conceptualization (equal), writing – original draft (equal); **MAC**: conceptualization (equal), writing – original draft (equal); **GZ**: conceptualization (equal), writing – original draft (equal); **RWHB**: conceptualization (equal), writing – original draft (equal).

Data availability statement Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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