Journal of Structural Geology 114 (2018) 251–273

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Interpreting structural geometry in fold-thrust belts: Why style matters

Robert W.H. Butler[a,*], Clare E. Bond[a], Mark A. Cooper[a,b], Hannah Watkins[a]

[a] Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, Aberdeen, AB24 3UE, United Kingdom
[b] Sherwood Geoconsulting Inc, Suite 304, 1235 17th Ave SW, Calgary, Alberta, T2T 0C2, Canada

ARTICLE INFO

Keywords:
Thrust belts
Folding
Interpretation uncertainty
Fold thrust structures

ABSTRACT

Structural interpretation in fold-thrust belts has become reliant on a few idealized geometric models (i.e. fault-bend, fault-propagation and detachment folding) and their quantitative methods for section construction and validation.

We couple historical review with selected outcrops to show that there is a substantially greater range of solutions available for interpreting the geometry and evolution of thrust belt structures than implied by these idealized models.

Examples are documented, and lessons drawn, from comparing structural interpretations developed in the foothills of the Canadian Rockies with those in the Western Alps. Both show a range of structural geometries with regional variations that reflect variations in the pre-kinematic stratigraphic template. Locally, fold-thrust development can localize on pre-existing structures. Thus consideration of the precursor geology is essential for structural interpretation. Using a case study from the Papuan Fold Belt we show that even with seismic data, assessing the role of basement in structural development can be uncertain.

The idealized models offer only a narrow range of possible geometries for constructing cross-sections and developing structural understanding in fold-thrust systems. Failure to consider alternatives, and the inherent interpretation uncertainty, has biased understanding of thrust systems leading in turn to over-optimistic risk assessment and repeated drilling surprises.

1. Introduction

This paper takes a critical look at existing fold-thrust models and interpretation strategies in fold and thrust belts. Our premise is that the tendency to use a narrow range of idealized "structural styles" for the relationships between folds and thrusts is an important source of interpretational bias that can impede understanding of structural geometry. Our motivation comes from the repeated failure of many of these existing models to forecast the structural complexity encountered in the subsurface when hydrocarbon prospects are drilled. Perhaps unsurprisingly, these failures are rarely publicised – but there are a few.

In mid 2005, Shell Nigeria drilled well Alpha-1X into an anticline in the deep-water fold belt of the Niger Delta. The well was planned on the basis of idealized fold-thrust models, such as those presented by Shaw et al. (2005), including a single thrust fault across which a multilayer of sandstones and mudrocks had been displaced. This type of multilayer together with the significant inferred fault displacement implied that clay should have been smeared along the thrust (Yielding et al., 1997), hopefully supporting much of the oil column. As Kostenko et al. (2008) report, the Alpha-1X well passed through a tract of rock with a range of bedding dips indicative of structural complexity – overturned, folded and faulted beds (Fig. 1). The oil column in the anticline was significantly smaller than hoped. Kostenko et al. (2008) infer that this outcome is because oil migration pathways exist in the fold forelimb, through the folded sandstone-mudstone multilayer. Therefore, no single thrust surface with smeared clay could have acted as a lateral seal. The structural complexities encountered in well Alpha-1X exceed those predicted from the idealized fold-thrust models.

A fundamental problem with subsurface interpretation of fold-thrust structures is the inherent ambiguity in seismic imaging – especially in the steep forelimbs of folds and in the footwalls to thrusts. The data used to interpret the fold in deep-water Niger delta was industry-standard 3D seismic. However, in many onshore settings, especially young or active fold-thrust systems, these inherent imaging problems are exacerbated by the prohibitive cost and issues of acquisition of 3D seismic data and the consequent reliance on 2D profiles. Consider the Agogo structure in the outer fold belt of Papua New Guinea. Hill et al. (2010) interpreted this in terms of a stack of simple thrust ramps of relatively low displacement. The higher anticline, in the hangingwall of the Agogo Thrust, was penetrated by three wells. The 2D seismic imaging

* Corresponding author.
E-mail address: rob.butler@abdn.ac.uk (R.W.H. Butler).

https://doi.org/10.1016/j.jsg.2018.06.019
Received 29 August 2017; Received in revised form 15 June 2018; Accepted 20 June 2018
Available online 23 June 2018
0191-8141/

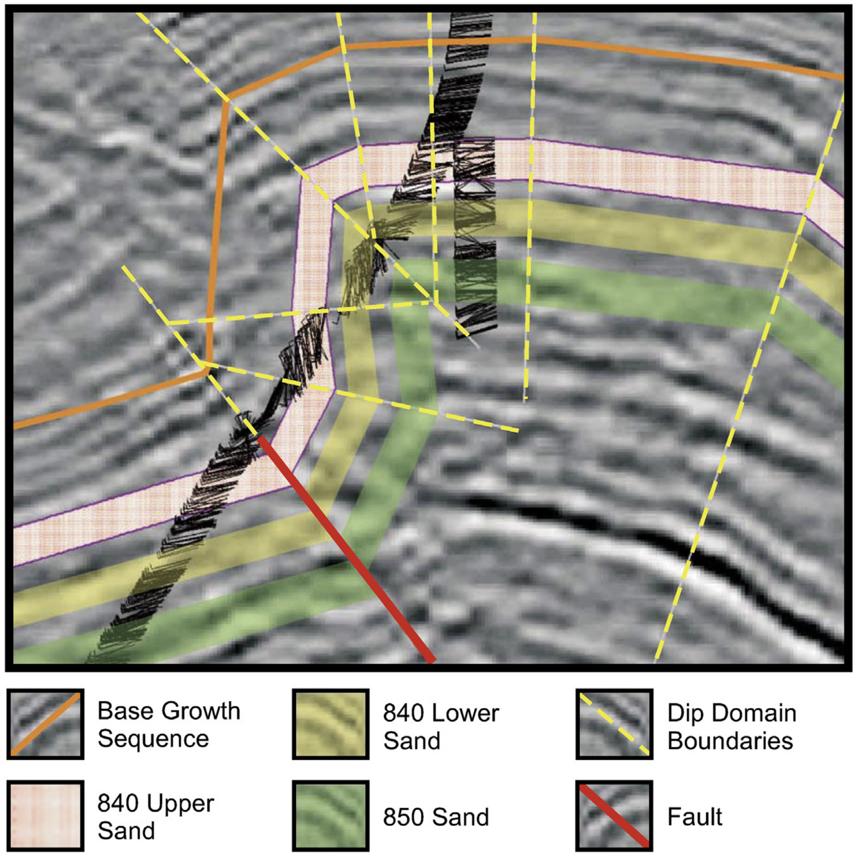

Fig. 1. Kostenko et al.'s (2008) post-drill interpretation of the Alpha structure, deep-water Niger delta showing the folded forelimb. Note that their inferred continuity of stratigraphic units cross-cuts the structure of seismic reflectors indicating problems with the seismic imaging.

appears to be excellent – with good reflector continuity, even in the footwall to the Agogo Thrust. This footwall was targeted for further exploration drilling (Parish, 2015). Three sidetrack wells from an existing well (ADT2) were drilled. Rather than encounter sub-horizontal bedding and a simple reservoir structure, all three sidetrack wells crossed steeply dipping and faulted strata (Fig. 2). While this significantly increased the volumes of reservoir in the footwall to the Agogo Thrust, the structural complexity was entirely unexpected. Indeed it is entirely incompatible with the reflector geometries apparently imaged in the seismic data used to plan the wells. So even apparently good-quality 2D seismic imaging need not guarantee success in structural interpretation.

The two case studies described above, together with others (e.g. Cooper et al., 2004; Heidmann et al., 2017), indicate that the predominance of a rather narrow range of idealized geometries used in structural interpretations of thrust systems limits interpretation and causes anchoring bias (Bond, 2015). There are many reviews of these idealized models (e.g. Shaw et al., 2005; Groshong et al., 2012; Brandes and Tanner, 2014; and references therein) and it is not our intention to duplicate them here. Rather we note that in general the interpretation of fold-thrust structures is under-constrained and the use of a few simplified models of fold-thrust relationships to the exclusion of other, more complex patterns may lead to an under-estimate of structural risks associated with subsurface exploration. We concentrate on two key issues. The first is the geometry of individual fold-thrust structures such as those targeted in the deep-water Niger Delta and the Papuan fold belt. The second is the role of basement involvement in thrust systems, which in turn impacts not only on the assessment of tectonic detachments at depth but also on the geometry and mechanical properties of the stratigraphic template incorporated into the structures.

There is a vast literature on thrust systems and many case studies on the relationships between folds and thrusts. Rather than provide broad geographical coverage, we compare interpretative approaches adopted in the Canadian Rocky Mountain foothills with those in the Western Alps. These places are historically important for developing geometric understanding of fold-thrust belts, as reviewed briefly below. We also consider models for basement involvement in thrust belts that draw on examples from the Rockies and the Papuan thrust belt where the topic has significant importance for hydrocarbon exploration. The general issue for these applications is to identify not only where the hydrocarbons are located but also how they migrated there. The specific lessons learned from these case studies have broader impact for the general understanding of fold-thrust belts.

2. Thrust localisation and structural styles: historical perspectives

Understanding the development of ideas through the history of research can assist in identifying origins of community bias in interpretation. Many approaches to understanding fold-thrust relationships, especially through the development of geometrically quantitative methods, date back just a very few decades. But the geometry and kinematic evolution of fold-thrust systems, their impact on both structural style and the mechanics of thrust belts, have been investigated since the 1880s (e.g. Brandes and Tanner, 2014). One of the motivations for Cadell's (1888) "experiments in mountain building" was to challenge Heim's (1878) model from the Swiss Alps – that thrusts localised at a late stage in the folding process that created nappes (Fig. 3a). Cadell showed that thrusts can grow (propagate) without significant folding of strata (Fig. 3b). These insights directly influenced the construction of cross-sections through the Moine Thrust Belt in the 1880s. The idealized structure, showing multiple imbricate stacks as used by Peach et al. (1907), is illustrated in Fig. 3c.