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Research paper

# The importance of missing strain in Deep Water Fold and Thrust Belts

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ABSTRACT

Deep water fold and thrust belts (DWFTBs) are sedimentary wedges that accommodate plate-scale deformation on both active and passive continental margins. Internally, these wedges consist of individual structures that strongly influence sediment dispersal, bathymetry and fluid migration. Most DWFTB studies investigate basin- and intra-wedge- scale processes using seismic reflection profiles, yet are inherently limited by seismic resolution. Of critical importance is strain distribution and its accommodation on discrete faults compared to distributed deformation. Recent studies have considered strain distribution by investigating regional reflection DWFTBs profiles within coupled systems, which contain down-dip compression and up-dip extension. There is broad agreement of a mis-balance in compression versus extension, with ~5% excess in the latter associated with horizontal compaction, yet this remains unproven.

Using two exceptionally well exposed outcrops in the Spanish Pyrenees we consider deformation of DWFTB at a scale comparable to, and beyond, seismic resolution for the first time. By coupling outcrop observations (decametre to hectometre scale) with a re-evaluation of seismic profiles from the Orange Basin, South Africa, which contains one of the best imaged DWFTBs globally, we provide a unique insight into the deformation from metre to margin scale. Our observations reveal hitherto unrecognised second order structures that account for the majority of the previously recognised missing strain. This re-evaluation implies that ~5% missing strain should be accounted for in all DWFTBs, therefore existing studies using restorations of the sediment wedge will have underestimated crustal shortening in active margins, or sedimentary shortening in gravity driven systems by this amount. In contrast to previous studies, our observations imply that the majority of this strain is accommodated on discrete fault surfaces and this can explain the occurrence and location of a range of intra-wedge processes that are intimately linked to structures including sediment dispersal, fluid migration pathways and reservoir compartmentalisation.



## 1. Introduction

Deep Water Fold and Thrust Belts (DWFTBs) occur on continental margins globally and are a consequence of the contraction of sedimentary sequences that are decoupled from underlying stratigraphy or basement by a décollement horizon (Rowan et al., 2004; Morley et al., 2011). The driving force that induces the contraction can occur either at a crustal scale, as is the case in an accretionary prism on an active margin (Type II; Morley et al., 2011), or within the decoupled sedimentary sequence as a consequence of gravitational processes, on an Atlantic-style passive margin (Type I: Morley et al., 2011). Regardless of the setting, processes that are intimately linked to the resulting deformation span the margin-scale geometry of the fold and thrust belts including critical taper angle (e.g. Dahlen et al., 1984), the structural configuration and stratigraphic fill of associated sedimentary basins (Morley, 2007; Fillon et al., 2013) and the role of fluids that migrate through them (Saffer and Bekins, 2001). Quantifying the strain distribution across a DWFTB is therefore fundamental to understand these processes.

An entire DWFTB system comprises three domains: an up-dip extensional domain, a down-dip contractional domain and a transitional domain in-between (Krueger and Gilbert, 2009). An essential technique applied to understanding DWFTBs, and the

*Abbreviations:* DWFTBs, Deep water fold thrust belt.

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distribution of strain across these three domains, is the kinematic restoration of stratigraphic sequences. This is commonly based upon interpretation of an increasing number of seismic reflection profiles covering DWFTBs. Conceptually shortening across the entire system should balance, however, recent studies document a 5–10% imbalance between extensional and contractional domains in favour of extension (Fig. 1) and outline the importance of this value on our understanding the evolution of DWFTB systems (de Vera et al., 2010; Butler and Paton, 2010; Dalton et al., 2015). This 5–10% imbalance is calculated assuming the contraction due to the recorded missing strain component is distributed in both the extensional and contractional domains as per Dalton et al. (2015). This imbalance is implicit from the initiation of growth and throughout the growth of the structure as seen in Fig. 1.

Although many of these recent studies have considered coupled extension and compressional systems, the same principles are as applicable to accretionary prisms as they are to passive margins. In the latter, for example, an accurate quantification of compression is important for both plate kinematic predictions as well as basin fill architecture in a range of settings including Sinu-Jacinto offshore Columbia, Barbados Ridge and Taiwan (Biju-Duval et al., 1982; Davis et al., 1983; Robertson and Burke, 1989; Toto and Kellogg, 1992; Vinnels et al., 2010). In certain settings where there is a complex interplay of accretionary prism and gravity collapse processes occurring (e.g. NW Borneo), differentiating between the two processes is essential to understanding the whole system evolution (Franke et al., 2008; Hesse et al., 2010; King et al., 2010).

Central to any analysis of a DWFTB, be it accretionary prism or gravity induced, is this mismatch in strain. In this study we couple field observations with seismic reflection examples of the extensional portion of DWFTB's to investigate this question. Through the identification of previously unrecorded contractional features present within the extensional domain we reconsider how strain is distributed across the system and discuss how this influences our current understanding of the associated processes.

## 2. Quantification of sub-seismic scale strain

As most studies of DWFTBs are based upon seismic reflection profile analysis, an obvious limitation to quantifying the missing strain component in such profiles is the issue of how much strain is accommodated at a sub-seismic scale. Previous work in extensional settings has highlighted and quantified the potential impact of sub-seismic deformation on terms of both hydrocarbon exploration and production (Wood et al., 2015a, 2015b). Here we address the issue of sub-seismic deformation in DWFTBs by considering two well exposed outcrops in the Spanish Pyrenees that reveal as yet undocumented deformation across three orders of magnitude. The first is a decametre scale example in Laspuña (Fig. 2). The second investigates a larger (hectometre) scale example at Armeña, Spain (Fig. 2).

### 2.1. Case study 1; decametre scale; Laspuña

A distinctive set of multiphase growth faults detaching onto a basal detachment is observed in the cliff section immediately to the west of the village of Laspuña. The syn-kinematic growth packages in the top of the normal faults seen in the cliff are indicative of the extensional domain of a DWFTB. This DWFTB is located on the then uplifting, north-eastern flank of the Ainsa Basin (Pickering and Bayliss, 2009) in the Spanish Pyrenees (Fig. 2).

The stratigraphy that is deformed by the DWFTB comprises marls and fine sand slope deposits (Dreyer et al., 1999) and are of Early Ypresian age (Pickering and Corregidor, 2005). The slope sediments present at Laspuña were depositing whilst the Peña Montañesa, Cotiella and La Fueba thrusts systems were active (Muñoz et al., 2013). The DWFTB presently sits structurally below these thrust faults (Fig. 2), the slope was generally stable allowing deposition of successions of muddy sediments. The active tectonic system and a mud dominated semi-lithified slope provided the ideal conditions for gravitational collapse to occur. During phases of tectonic activity on the surrounding thrust systems stable paleoslopes were uplifted and became mobilized, forming mass transport complexes (Dakin et al., 2012). At Laspuña, failure of the slope did not result in mass transport remobilisation, but resulted in the formation of growth faults, indicative of multiple phases of extension and syn-deposition, shifting sediments south west downslope into the Ainsa Basin. This difference in deformation may be as a result of smaller uplift events occurring over a longer time period allowing a slower readjustment of surface slope geometry or an effect of the presence of an underlying slip horizon making DWFTB formation more practical than outright slope failure.

The cliff section, in which the DWFTB is observed, is divided into four packages (1–4, bottom to top) based upon their lithology and internal geometry. The lowest package (Package 1, Figs. 3 and 4) is composed of a largely undeformed dark grey succession of more

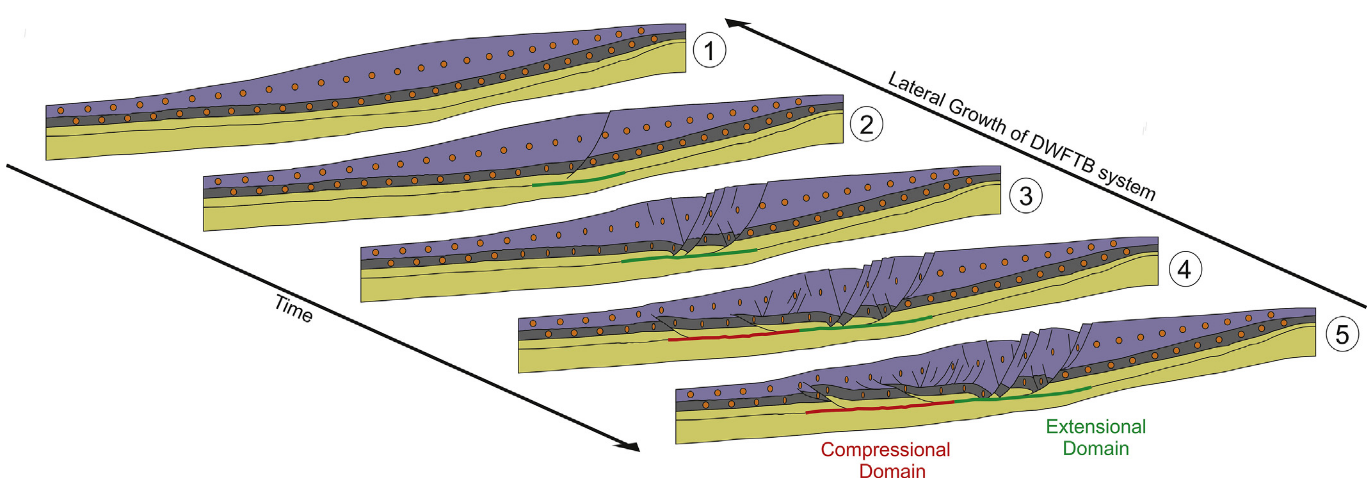


**Fig. 1.** Conceptual model for the growth of a DWFTB in both space and time indicating the missing strain component is not explained by lateral deformation elsewhere along the margin, Dalton et al. (2015). The location of extensional and compressional domains are also shown along with Orange circles representing the lateral compaction of sediments in the wedge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)