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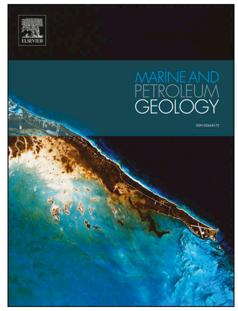

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The importance of missing strain in Deep Water Fold and Thrust Belts

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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., 2012) and the role of fluids that migrate through them (Saffer et al., 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 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 (Figure 1) and outline the importance of this value on our understanding the evolution of DWFTB systems (de Vera et al., 2010; Butler & 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 Figure 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 et al., 1989; Toto et al., 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 (Figure 2). The second investigates a larger (hectometre) scale example at Armeña, Spain (Figure 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 & Bayliss, 2009) in the Spanish Pyrenees (Figure 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 & 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 (Figure 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 paleo-slopes 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, Figures 3 & 4) is composed of a largely undeformed dark grey succession of more organically rich concordantly layered marls. Package 2 is defined by a sequence of light grey/brown muds with thin inter-beds of fine sands, which become thicker and more numerous towards the top of the cliff. Within this package a set of west dipping listric normal faults with throws of 8 – 15 m is observed. Striae on the fault planes indicate a westerly displacement of material into the Ainsa Basin. These faults detach onto a common décollement (Décollement 1) along the upper surface of Package 1 (Figure 3); this is the extensional domain of the DWFTB. The top of Package 2 is truncated by a distinctive planar, gently west dipping fault surface, Décollement 2 (Figure 4). Above this is Package 3 which comprises a chaotic package of folded and faulted, muds and sands. This is topped by Package 4, a succession of dark grey planar concordant laminated beds. Packages 3 and 4 contain a set of evenly spaced thrust faults with displacements of up to 40 m, which detach onto Décollement 2 (Figures 4 & 5 b). These potentially form part of the contractional domain of a distal, later DWFTB for which the up-dip continuity does not crop-out.

The scale of the DWFTB systems present at Laspuña offers the opportunity to observe the internal

structure of the fault blocks and in particular minor structures formed during deposition and deformation (Figure 5). Restorations of DWFTBs imply the preservation of pre-kinematic bedding within the fault blocks. However, we observe that significant internal deformation is present within the extensional and compressional blocks. Within the extensional fault blocks we observe multiple thrust features with throws of 0.2- 3 m as well as significant folding (Figure 5 a). This smaller scale deformation is present equally in the contractional domain in Packages 3 & 4 which show smaller scale thrust faults with throws of 0.5-1 m and folding, in between larger thrusts (Figure 5 b). These smaller scale contractional features (< 5 m throw) are largely unresolvable at the outcrop scale (Figure 4), yet detailed analysis reveals that many of these surfaces that appear undeformed at outcrop scale contain kinematic indicators that show significant internal compression (Figure 5).

These two sections in the Laspuña DWFTB system illustrate that not only does deformation occur at a range of scales, but more importantly, there is evidence of compression within the extensional domain. Such deformation has not been demonstrated before and is therefore not accounted for in current DWFTB restorations. To understand the impact of these smaller scale contractional structures on a restoration we present two interpretations of the same section (Figure 3). The first interpretation (Figure 6 a) is equivalent to existing DWFTB sections and does not incorporate these smaller contractional structures (i.e. equivalent to these structures being below observable resolution). While the second interpretation (Figure 6 b) is a detailed interpretation across the section including contractional features. It can be seen in Figure 6 b that the contractional features are isolated within single fault blocks and are thus not pre-existing deformation features. Both interpretations use the same distinct dark grey pre-kinematic bed that is present throughout the collapse (Figure 5 a). Slickensides on fault planes indicate this section is within 10^{o} of the transport direction, making it viable for restoration (Price, 1981). We then restore both sections to a pre-deformed geometry and calculate the extensional strain when the small scale contractions are ignored compared to when they are accounted for (Table 1).

In Table 1 the significance of contractional features becomes clear, with the measurement of total displacement being 11-14 m less. The difference recorded in the total amount of strain ranges from 4.6 - 5.9 % implying these sediments would be ~ 5% more compressed than expected. These figures are comparable with the missing strain component identified in seismic examples in Dalton et al. (2015) of ~ 5

% and thus may offer an explanation for the observed miss-balance.

The Laspuña section is clearly small scale and therefore the validity of scaling these observations to larger examples is critical if we want to consider margin scale (> 60 km long) DWFTBs. To address this we consider a larger (4 km wide) DWFTB that crops-out approximately 25 km to the north-east of Laspuña at Armeña (Figure 2) as this allows us to observe whether similar contractional structures are present in larger systems.

2.2 Case Study 2; Hectometre Scale; Armeña

The gravity driven, growth fault system at Armeña, Huesca, Spain (Figure 2) has been described by McClay et al., (2004), Lopez-Mir et al., (2014, 2015) and Tavani et al. (2015). This growth fault forms part of the Cotiella extension system that formed in the Coniacian to Early Santonian during a post-rifting thermal subsidence phase of basin evolution (Vergés et al., 2002). It comprises three listric growth faults traversing a 14 km section orientated NE-SW (Lopez-Mir et al., 2015, Figure 2). The best exposed of these three growth faults is the 4 km wide cliff section above the Refugio d'Armeña (Figure 7) referred to as the Armeña growth fault (Lopez-Mir et al., 2014). Extension initiated in the Coniacian and continued into the Early Santonian depositing up to 3 km of syn-kinematic carbonates and calcarenites which diverge towards the southwest, within the hanging wall of the controlling listric normal fault indicating a north easterly extension (Lopez-Mir et al., 2014). They are deposited above a pre-kinematic Upper Cenomanian to Turonian limestone succession (McClay et al., 2004). This overlies Late Triassic shales and evaporites that crops out at the northern end of the cliff section (Figure 8). The top of this Triassic sequence also forms the detachment horizon for all three growth faults.

The collapse structure at Laspuña implies that the most likely location for contractional features in extensional fault blocks is within the pre-kinematic sequence. Figure 8 shows the pre-kinematic Upper Cenomanian to Turonian limestone succession. The more competent limestones have better preserved bedding than the more mobile muds at Laspuña and so do not show the same amount of ductile deformation. Within these limestones multiple brittle contractional structures are present throughout, the largest being a ~100 m displacement thrust on the north-eastern flank (Figure 8). Multiple (10+) smaller intra-layer thrusts with throws of less than 10 m are also observed throughout the cliff. The orientation of these contractional features are consistent with a south-west to north-east transport direction (as indicated by striae on fault surfaces) and is therefore not related to the later phase of north east to south-west inversion. Despite later inversion Tavani et al. (2015) affirms syn-kinematic fracturing has been well preserved. Folding of beds in the hanging wall of the thrust and the orientation of the throw are incompatible with the orientation of the inversion event.

Restorations of the three normal faults in Lopez-Mir et al. (2014), reveal a total extension of 8.1 km over 13.9 km. Assuming a missing strain component of 5 % (Dalton et al., 2015) is compensated for by second order structures, compressive features totalling ~650 m should be present over the three faults, with ~215 m displacement being accommodated within the Armeña growth fault, assuming an equal distribution. The observation of a ~60 m displacement thrust and multiple smaller displacement (~10 m) contractional structures is in agreement with that prediction. From this we would suggest that 5 % of measured extension is compensated by second order structures which should be prevalent in the extensional portion of DWFTBs.

The observation that 5 % of the recorded extensional deformation is accommodated by smaller scale features in Armeña concurs with the observations made at Laspuña which are consistent with a scale invariant relationship. We now consider if these features are similarly present on margin-scale DWFTBs imaged on seismic reflection profiles.

3. Application to seismic scale; Orange Basin

We choose a DWFTB within the Orange Basin (Figure 9), offshore South Africa and Namibia, because the geological evolution of the margin has been well established (Gerrard & Smith, 1982, Brown et al., 1995, Mohammed et al., 2015) and DWFTBs are a well-documented and common feature found throughout the basin (Muntingh & Brown, 1993, Paton et al., 2008, Peel et al., 2014, Dalton et al., 2016). Restorations of these DWFTBs have been undertaken by de Vera et al. (2010), Butler & Paton (2010) and Dalton et al. (2015), all of which identified a shortfall in contractional features versus extensional. This imbalance, ~5%

(Dalton et al., 2015), is equivalent to the 5% of strain recorded in the contractional features within the extensional domain of the DWFTB at Laspuña. Our field observations would suggest that contractional structures should be present within the larger extensional structures observed in the data presented by Dalton et al. (2015) although predict that they would be close to seismic resolution.

Our observations from Laspuña and Armeña suggest if these smaller contractional features are present, they are most likely to form in the pre-kinematic horizons towards the base of normal fault blocks. These portions of the collapse structures are frequently unresolvable, especially in more mature parts of the system where multiple phases of collapse have occurred and been overprinted. To overcome this difficulty we select a portion of an extensional domain (Figure 10 a, see Figure 9 for location) which contains later, more distal, normal faults and where seismic imaging is good.The reflections in the upper part of the collapse (Figure 10 a, light blue and yellow horizons) are broadly parallel and faulted in several places. The base of this package is picked by a high amplitude reflection (just below the blue horizon), which is the well documented Tertiary unconformity (Paton et al., 2008). The reflections beneath the unconformity have a shallow dip towards the south west, with multiple upper reflections truncating against the Tertiary unconformity heading progressively north east. These reflections are discontinuous in their horizontal extent and are broken by steeply dipping discontinuities that extend through the package. This style of response appears throughout the remainder of the section till the base where a number of broadly horizontal continuous reflections are present. The discontinuous packages represent Late Cretaceous sediments rotated by normal faults within the extensional domain. The termination of the discontinuous reflections defines the location of normal faults. The continuous reflections are beneath the horizon on which these faults detach and are thus undeformed.

At the scale of the regional section (Figure 9), previous restorations of the 156 km long section (de Vera et al., 2010; Butler & Paton, 2010) interpreted that the reflections are continuous between normal faults implying no internal deformation (Figure 10 c). However, when we consider these apparently low strain areas in more detail we observe that reflections are not parallel and show truncation and localised repetition of reflections that are best explained by the presence of thrust faults (Figure 10 b). These structures are most prevalent in pre-kinematic horizons at the base of fault blocks, as our observations at Laspuña and Armeña predict.

We choose two pre-kinematic horizons affected by these second order thrust faults as well as a number of higher horizons to make two interpretations. We apply the same method as at Laspuña and undertake one restoration that ignores contractional features (Figure 10 c) and a second (Figure 10 d) that accounts for the contractional features. The interpretation of the 1st order extensional faults remains the same for both. This allows us to isolate the effects of including the contractional features in the restoration.

The results of the restorations (Table 2) show a marked increase in displacement down the length of the normal faults and thus through time. This reveals these faults have an extended growth history with multiple phases of deformation. Table 2 shows a difference of 4-5% between the interpretations including and excluding contractional features. This implies that 5% of the strain created by extension is compensated for within the extensional domain itself.

Discussion

Recognizing the missing strain

Recent analyses of DWFTBs involving gravity collapse broadly agree that there is an imbalance between extensional and contractional domains in favour of extension of ~ 5% (de Vera et al., 2010; Butler and Paton et al., 2010). Dalton et al., 2015 went further to look at a set of parallel lines (Figure 1) through a single collapse finding a consistent imbalance throughout, concluding the missing strain component is not an effect of out of plane movement but a crucial part of the growth mechanism. They suggested the imbalance represents a phase of strain hardening through compaction of more distal sediments relative to the primary normal fault. This phase predates the formation of down-dip thrusts, seismically resolvable as the contractional domain. It is this strain hardening phase which we have investigated. The missing strain component is likely to be near or below seismic resolution and should therefore be represented in field examples of DWFTB's.

The previously unpublished field location at Laspuña, whilst limited in extent displays many of the same features that we observe in seismic examples of extensional domains in DWFTBs. These include 1st order listric normal growth faults, a detachment surface above a relatively undeformed package and a separate overlying contractional domain composing imbricated thrusts. This implies a potential scalability in these structures that offers us an analogue to study the internal architecture of larger systems. The key observation from the Laspuña system (Figure 5), is the occurrence of 2nd order contractional features, present within both the extensional and compressional faulted blocks**.** This is contrary to seismic interpretation of thrust and normal fault blocks, which implies the preservation of pre-kinematic bedding. This both resolves the calculated missing strain component and suggests it is distributed across the entire structure and not limited to the contractional domain.

The results of the restoration of the seismic sections with and without contractional structures imply that 5% of the strain created by the extension is compensated for through contraction in the extensional domain itself. This would imply results of restorations of the entire DWFTB that do not account for this contraction will produce missing strain components over the entire structure of 5%. This is highly comparable with the results of restorations undertaken at Laspuña and by de Vera et al. (2010) and Dalton et al. (2015). We conclude therefore that the contractional features interpreted in the Orange Basin are genuine rather than being artefacts of seismic processing.

Figure 11 shows a possible growth mechanism for DWFTBs showing how these contractional structures grow throughout the development of the collapse structure. This explains the observation made in Dalton et al. (2015) that notes the outer fringes of DWFTBs commonly lack a down-dip contractional domain, as the extensional strain created by the displacement of the normal faults is entirely compensated for internally (Figure 1). We suggest this contraction is a necessary stage in the development of collapse structures and continues throughout their deformation history

Given the dimensions of most DWFTBs (>100 km) it is unreasonable to expect restorations to include this level of detail. Indeed, such structures are only imaged in our dataset because of the high fidelity nature of our profiles where as in many examples the resolution of the data would preclude such analysis. We therefore suggest that when undertaking restorations of shale detached DWFTBs an internal shortening factor of 5% of the total strain produced through sub-seismic resolution deformation be implemented over the total length of the collapse.

Application of missing strain to gravity collapse and accretionary prisms

We consider that this 5% missing strain has important consequences for understanding the tectonic, structural, stratigraphic and fluid evolution of DWFTBs regardless of the driving mechanisms that induces them. As this estimate of the missing strain is sub-seismic and is predicted to be prevalent throughout a collapse structure it should be applicable in both compressional and extensional components of DWFTBs.

The critical taper model (Davis et al., 1983; Dahlen, 1984) describes the evolution of accretionary prisms and thrust belts as a self-similar wedge of sediment that is at Coulomb failure through the system and is often applied in a whole system context e.g. the critical taper angle between surface and the basal surface and its evolution in response to plate convergence rates, sedimentation rates, exhumation and climate (Willet et al., 2003; Roe et al., 2006; Stolar et al., 2006; Simpson, 2010; Fillon et al., 2013; von Hagke et al., 2014) In addition, a number of studies consider the internal geometry of the wedge, and the individual structures that interact through the fold and thrust belt. Our results imply that an additional, and unrecognized 5%, should be accounted for in such studies. We acknowledge that this may be within the errors of the analysis, however of particular note are studies in Niger and Baram Deltas and the Nankai Trough (Bangs et al., 2004; Bilotti and Shaw, 2005; Morley, 2009) that have coupled seismic reflection derived interpretation and restorations to understand bulk deformation and shortening amounts in a critical taper context. A further example is the analysis of the broader Sabah system, NW Borneo in which evaluating the role of tectonic versus gravity driven deformation is critical both to the DWFTB and regional tectonic evolution (Kin et al., 2010). In such settings, where estimated shortening is low, in the order of ~ 1.8%, the sub-seismic deformation that we observe could play a significant role.

Although our focus here has been on the structural analysis, the quantification of a 5% missing strain will influence our understanding of the syn-kinematic evolution of sedimentary basins associated with DWFTBs. It is well established that in these settings there is an intimate link between the controlling structures, the accommodation space and the associated sedimentary basin fill. This is a consequence of the development of anticlines that act as transverse barriers to sediment moving down slope and the intervening synclines that not only control bathymetry and sediment distribution but can also influence the location of sand prone fairways and mass-transport complexes (McGilvery and Cook, 2003; Paton et al., 2007; Deville et al., 2015; Ortiz-Karpf et al., 2015). Our calculation of 5% missing strain is across an entire system and may therefore have a significant impact on specific structures, and sedimentary basins within a system. This agrees with the findings of Spikings et al. (2015) who conclude that the misinterpretation of structural features in sedimentary systems can lead to considerable underestimates of sediment volume and architecture.

A direct consequence of this missing 5 % is that estimates of porosity and permeability of sediments within DWFTBs would be considerably less than previously predicted. This alters our understanding of the formation of these structures implying that prior to the translation of strain down-dip and thus the formation of a contractional domain a period of compaction and "strain hardening" must occur first. Most of the contractional structures persist in a single fault block towards the centre as opposed to being equally distributed amongst the blocks. This is possibly a feature of the local lithology being more prone to failure than the sediments in surrounding blocks. Internal variations in lithology may provide the opportunity for the formation of multiple higher slip horizons within fault blocks allowing DWFTBs with multiple detachments to form as described previously (Totterdell & Krassay, 2003; Rowan et al. 2004; Corredor et al., 2005; Briggs et al. 2006). This process could produce vertical segmentation of normal fault blocks allowing for anomalous fault throws down a fault plane where higher throws may be recorded nearer the top of some faults as in Robson et al. (2016). This would add considerable uncertainty to the interpretation of the inner working of individual fault bounded blocks.

As a final consideration, faults within DWFTBs influence the location and migration of fluids through the system. The presence of water plays a major role in the dynamic evolution of accretionary prisms (Casey and Vrolijik, 1992; Saffer and Bekins, 1998) by increasing pore pressure and thereby altering the failure criterion at which Coulomb failure occurs, and by association the critical taper of systems. It is well established that faults play a critical role in localising fluid migration pathways and locations of future failure (Saffer and Bekins, 1998, 2001; Klaucke et al., 2016). In their study of Four Way Closure Ridge, offshore SW Taiwan, Klaucke et al. (2016) specifically discuss that water and methane (which subsequently feed Bottom Simulating Reflectors (BSRs)) exploit relatively permeable fault zones but note that these are poorly imaged. Permeability is dynamic over time (Maltman et al., 1997; Bolton and Maltman, 1998) as well as laterally variable (Maltman, 1998; Bolton et al., 1999) this potentially gives us a mechanism for internal

shortening. Small scale contraction occurs where the fluid pressure drops and so local shortening occurs (i.e. the décollement locks). Sliding and extension occurs in areas where higher fluid pressures are maintained along the décollement horizon. Our observations highlight the importance of considering a range of fault sizes that are likely to be present in DWFTBs whether seismically resolvable or not and may all play a role in fluid migration through the system. The presence of hydrocarbon fluids is equally important in DWFTBs, although of course, much of the interest is in predicting areas in which it is retained rather than expulsed.

At the 2016 Tectonic Studies Group conference it was stated "it is not the faults that industry is interested in but the white spaces in-between" (Peel pers comm, 2016) this statement perhaps most validates the outcome of this study. When we consider the white space between 1st order structures, we find a set of 2nd order structures precisely where our drilling targets are. Whilst previous research (Morley et al., 2011; Futalan et al., 2012) indicates reservoirs are present in these areas we caution that reservoir intervals may be more structurally compartmentalised with lower permeabilities than predicted.

Conclusion

Through combining field observations from exceptionally well-exposed outcrops with high fidelity seismic observations we are able to, for the first time, consider DWFTB deformation from the metre scale to the margin scale. Regardless of the scale of observation, we observe hitherto unrecognised compressional fault structures that are at a second order in scale compared to the principal structures. As our structural restorations suggest that they can account for ~5% of the overall strain irrespective of scale; we propose that this accounts for the missing strain that has been identified in previous studies but remained poorly understood. We conclude that the majority of this missing strain is accommodated on discrete faults rather than as distributed deformation as previous models invoke.

As our model for the evolution of these second order structures is scale invariant we propose that this 5% additional shortening is applicable to all DWFTBs and should be accounted for when shortening estimates are calculated in both active and passive margins. Furthermore, individual faults are important within an intra-wedge setting as they can control sedimentation, localise the position of fluid migration (brine or hydrocarbon), modify bathymetry and compartmentalise reservoir intervals. Yet often these processes are identified without an association with a visible fault structure in the seismic reflection data. Our conclusion, and resulting model, that these second order structures are discrete faults that are close to, or often beyond seismic resolution, provides a method for determining if these intra-wedge processes are indeed controlled by structures that are not necessarily resolvable in seismic data.

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Figure Captions

Figure 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.

Figure 2: Location and geological map of the two areas used in this study along with a cross-section through the three faults in the Cotiella extension system; with the upper map displaying the location of both areas, adapted from Lopez-Mir et al. (2014); and the lower zoomed in map of the study area beneath Laspuña indicating the location of Figure 3, 4 and 5b. The cross section extends to the end of the Pena Montanessa thrust just off the edge of the geological map.

Figure 3: Image and interpretation of the 240 m long cliff section in the valley beneath Laspuña. Faults are indicated in red, DWFTB package in orange, undeformed sub-detachment horizon in blue. For location see Figure 2.

Figure 4: View of the valley beneath Laspuña showing the stratigraphy that overlies that observed in Figure 3.. Faults are indicated in red, DWFTB package in orange, undeformed sub-detachment horizon in blue,

chaotic package in green, planar concordant laminated beds in black. Also marked is the location Figure

5a. For location of profile see Figure 2.

Figure 5: Interpreted and uninterpreted image of cliff sections seen from base of the cliff showing: a) the compaction of beds within normal fault blocks, b) the contraction of beds within thrust fault blocks. The purple horizon is the horizon used for the restoration. See Figures 3 and 4 for location.

Figure 6: Two different interpretations of the section in Figure 3; a) based upon what is observed from the opposite side of the valley where only large scale structures can be intrerpreted, b) interpretation based upon data collected from the outcrop itself, at road level. Both interpretations use the bed in Figure 5a for the purposes of restoration.

Figure 7: Interpretated and uninterpreted image of the growth fault at Armeña, location on Figure 2. The red box indicates the location of Figure 8.

Figure 8: Interpreted and uninterpreted cliff section view of pre-kinematic Upper Cenomanian limestones viewed from beneath Llosat indicating contractional features. Larger contractional faults associated with the extensional phase of DWFTB formation have been picked out in red. For location see Figure 7.

Figure 9. A 196 km long seismic section through an entire DWFTB from the Orange Basin offshore Namibia. For Location see Figure 10. The seismic profile is courtesy of Spectrum.

Figure 10: Interpreted and uninterpreted seismic sections through the extensional domain of a DWFTB in the Orange Basin, Namibia ; **a)** Uninterpreted seismic section used in this study; **b)** Zoomed in section of a) displaying potential compressional features; **c)** Interpreted section not accounting for contractional features; **d)** Interpreted section assuming features previously considered to be seismic artefacts are contractional features. The green and blue horizons are pre-kinematic horizons used for the restoration, the pink light blue and yellow horizons are syn-kinematic and indicate there have been multiple phases of activity on the faults. All sections are pre-stack depth migrated seismic reflection profiles, presented without vertical exaggeration and are courtesy of Spectrum.

Figure 11: New model for the formation and development of DWFTBs accounting for internal contraction within the extensional domain.

Table 1: Table of results for the restorations undertaken of Figure 6 a) and b).

Table 2: Table of results of restorations which were undertaken on sections presented in Figure 11 c) and d).

Figure 1

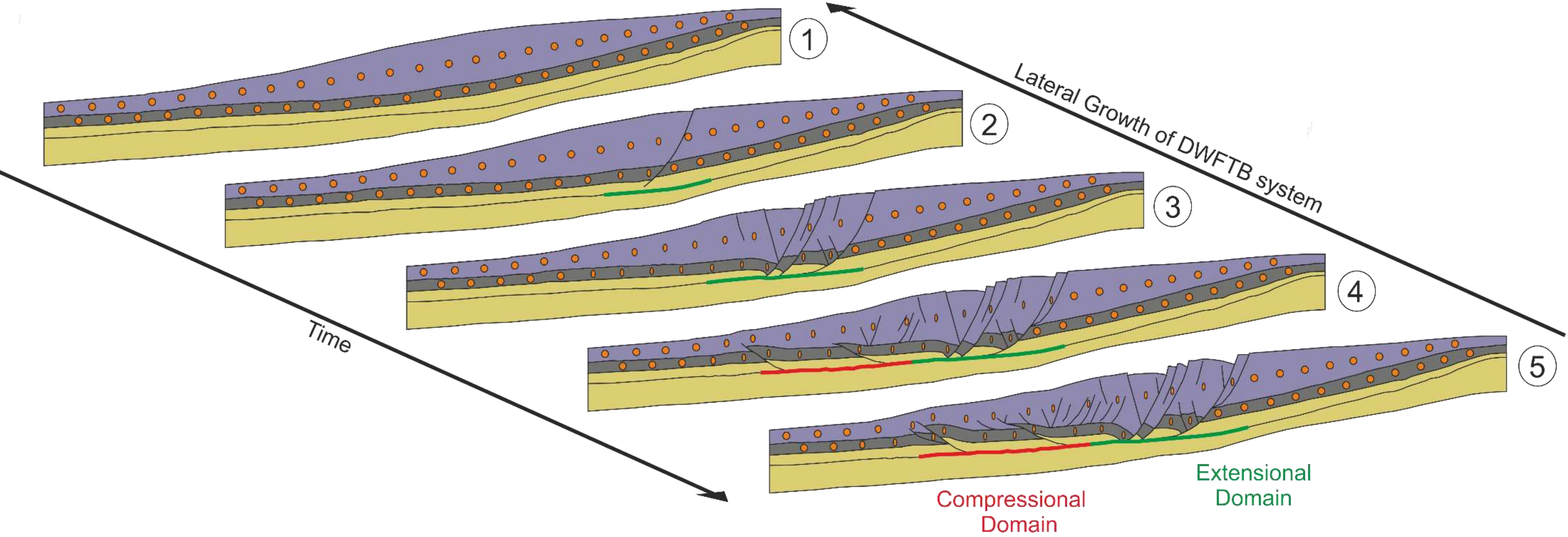

1
2
3
4
5
Lateral Growth of DWFTB system
Time
Compressional Domain
Extensional Domain

Figure 2

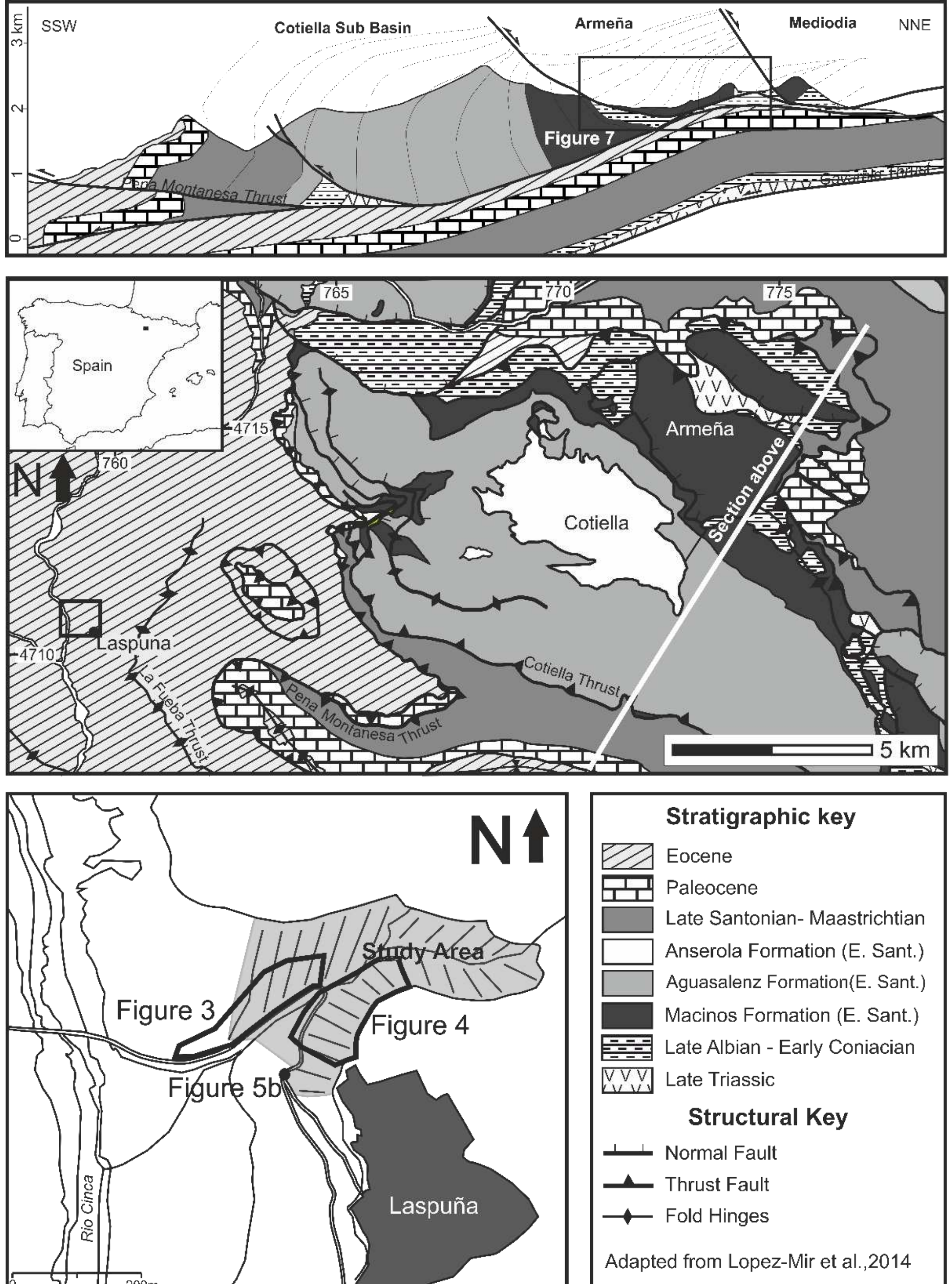

3 km
2
1
0
SSW
Cotiella Sub Basin
Armeña
Mediodia
NNE
Figure 7
Pena Montanesa Thrust
Gavarnie Thrust
Spain
765
770
775
4715
760
4710
N
Armeña
Cotiella
Section above
Laspuna
La Fueba Thrust
Cotiella Thrust
Pena Montanesa Thrust
5 km
N
Study Area
Figure 3
Figure 4
Figure 5b
Laspuña
Rio Cinca
0
200m
Stratigraphic key
Eocene
Paleocene
Late Santonian- Maastrichtian
Anserola Formation (E. Sant.)
Aguasalenz Formation(E. Sant.)
Macinos Formation (E. Sant.)
Late Albian - Early Coniacian
Late Triassic
Structural Key
Normal Fault
Thrust Fault
Fold Hinges
Adapted from Lopez-Mir et al.,2014

Figure 3

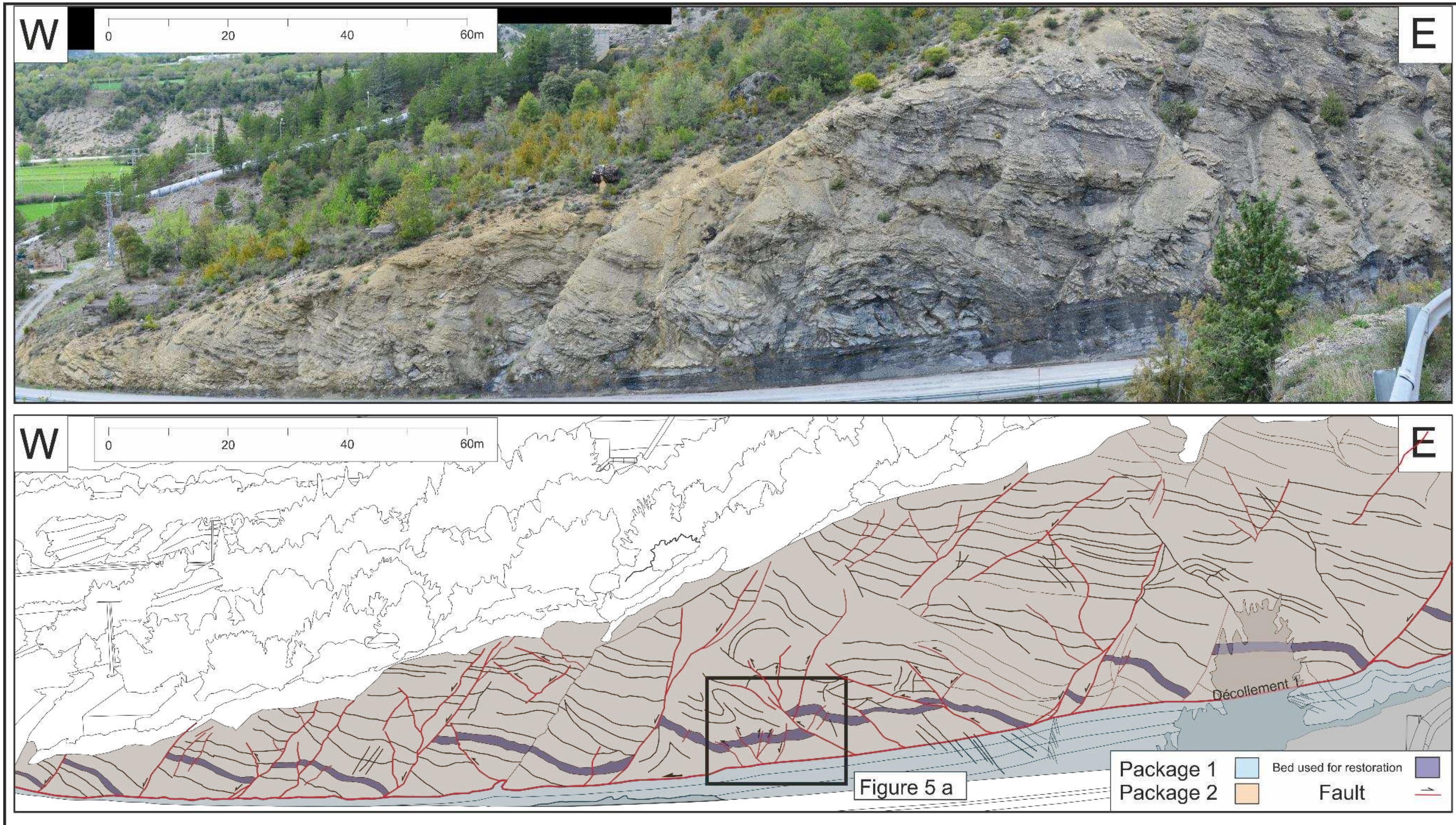

W
0
20
40
60m
E
W
0
20
40
60m
E
Décollement 1
Figure 5 a
Package 1
Package 2
Bed used for restoration
Fault

Figure 4

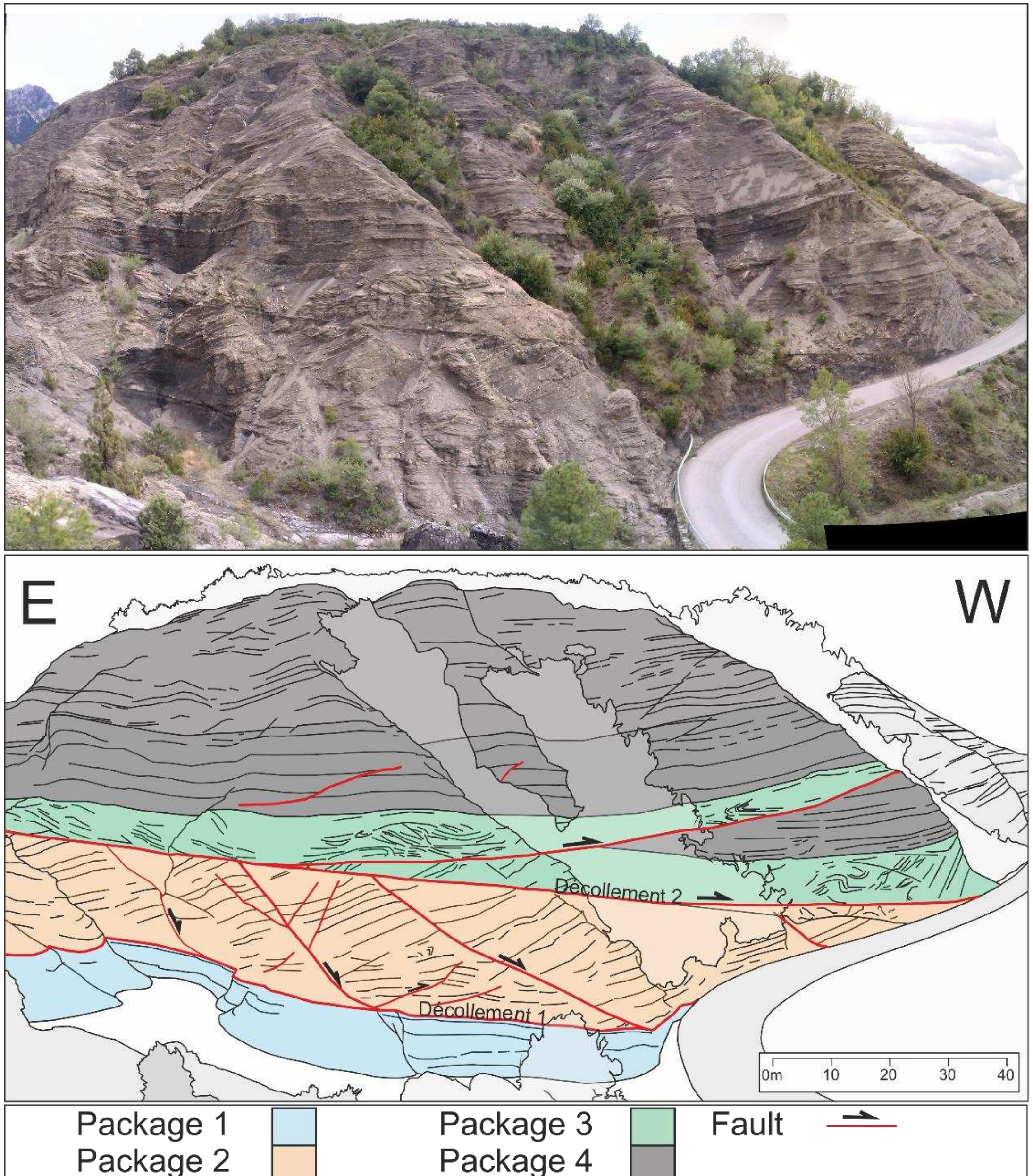
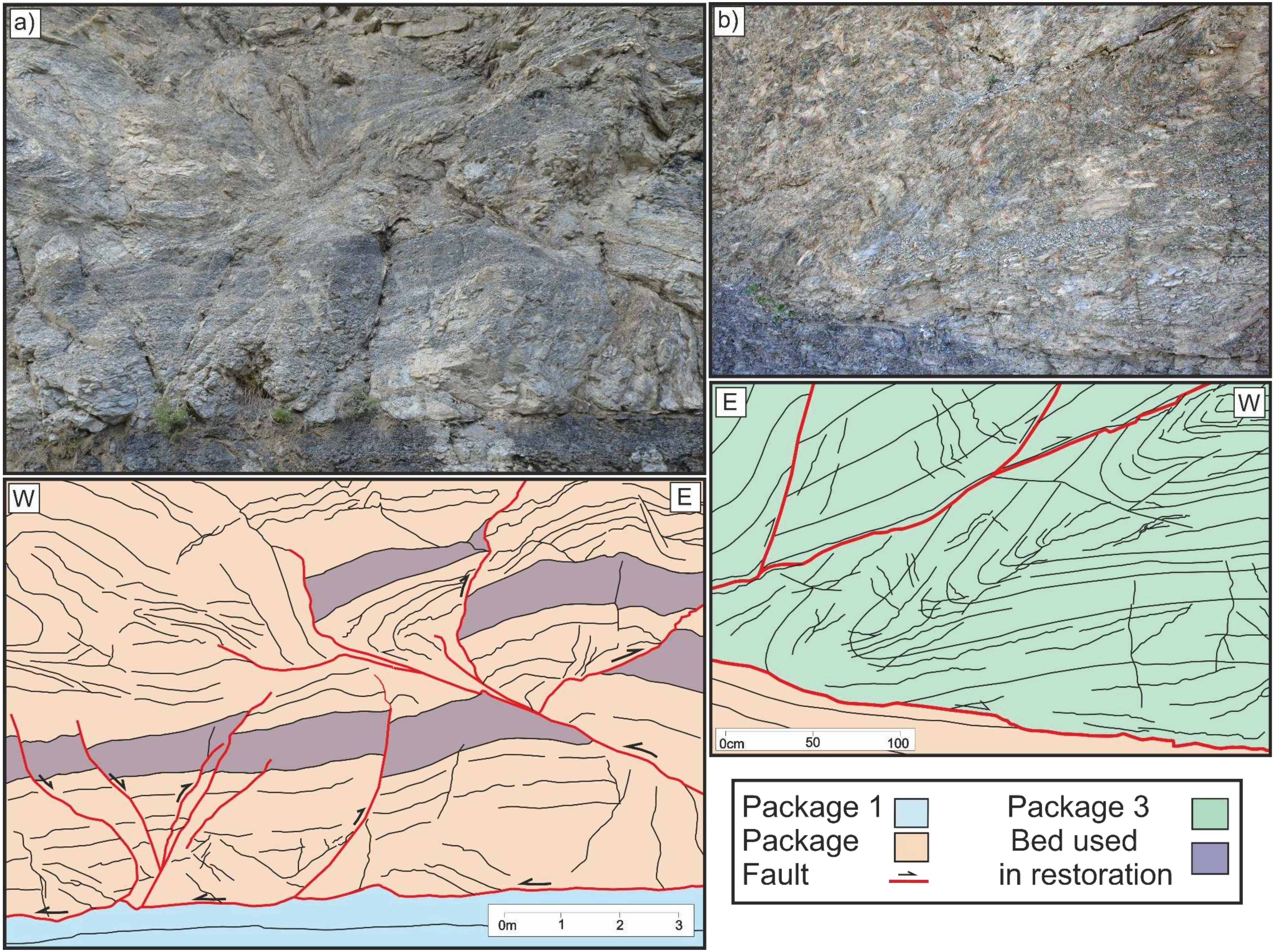
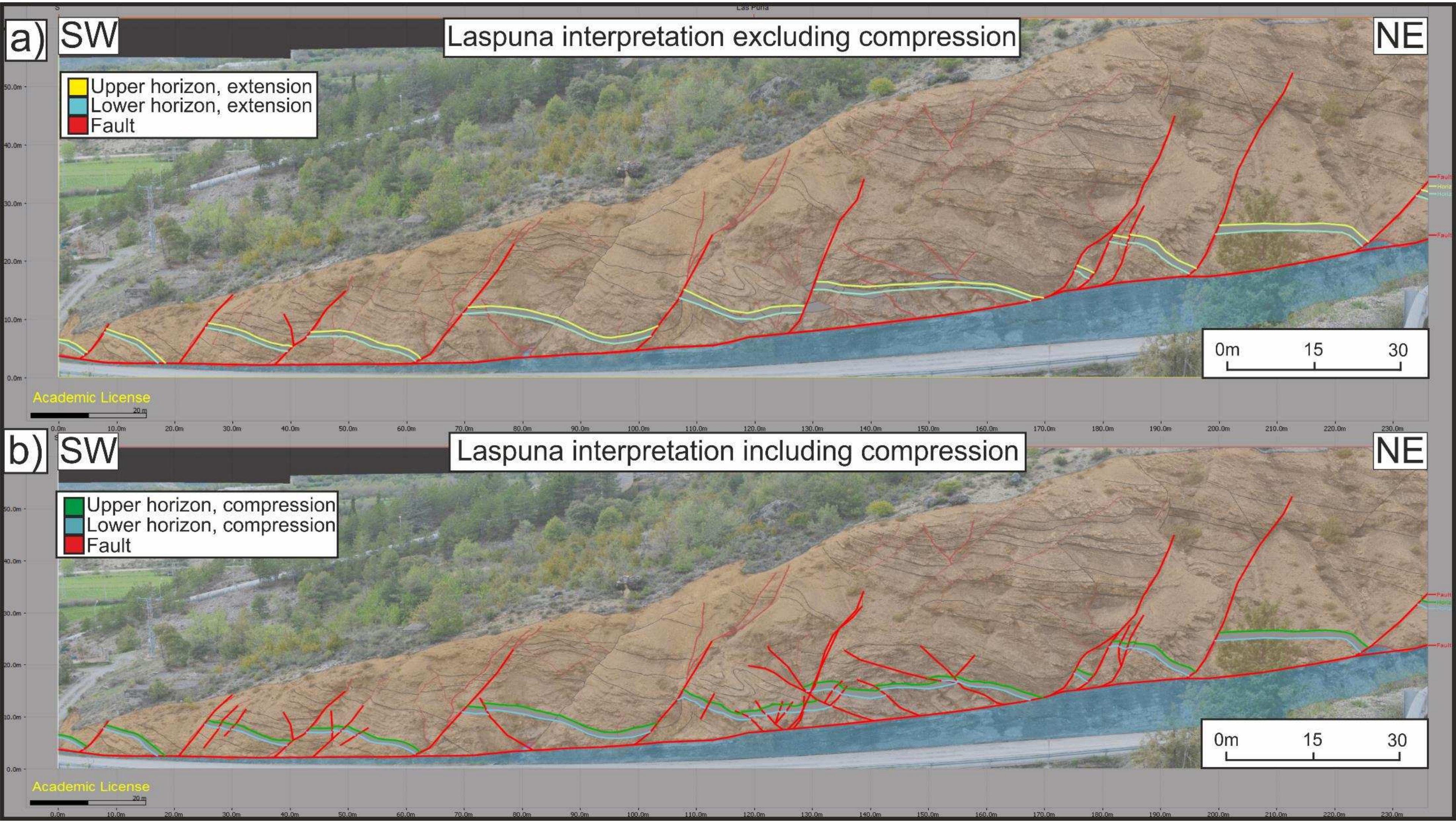

E
W
Décollement 2
Décollement 1
0m
10
20
30
40
Package 1
Package 2
Package 3
Package 4
Fault

Figure 5



a)
b)
E
W
W
E
0m
1
2
3
0cm
50
100
Package 1
Package
Fault
Package 3
Bed used
in restoration

Figure 6



a)
SW
Laspuna interpretation excluding compression
NE
Upper horizon, extension
Lower horizon, extension
Fault
0m
15
30
Academic License
b)
SW
Laspuna interpretation including compression
NE
Upper horizon, compression
Lower horizon, compression
Fault
0m
15
30
Academic License

Table 1

	Original Lengths (m)	Current Length (m)	Displacement (m)	Extension
Upper Horizon Comp.	200.5	240	39.5	**16.5%**
Upper Horizon Extension	211.5	240	28.5	**11.9%**
Lower Horizon Comp.	195.9	240	44.1	**18.4%**
Lower Horizon Extension	210	240	30	**12.5%**

	With Compression	Without Compression	Difference
Upper	16.5%	11.9%	**4.6%**
Lower	18.4%	12.5%	**5.9%**

Figure 7

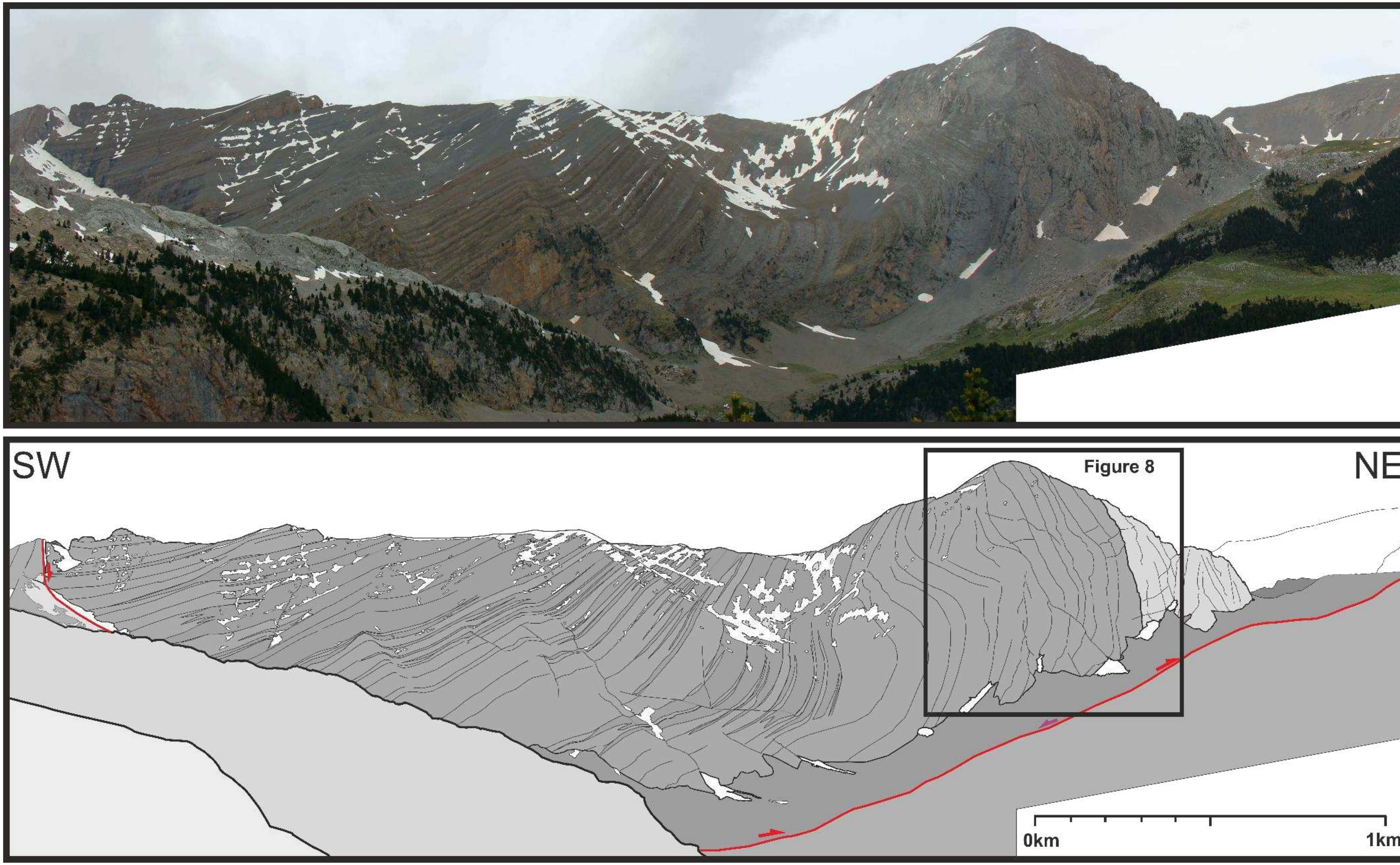


Figure 8

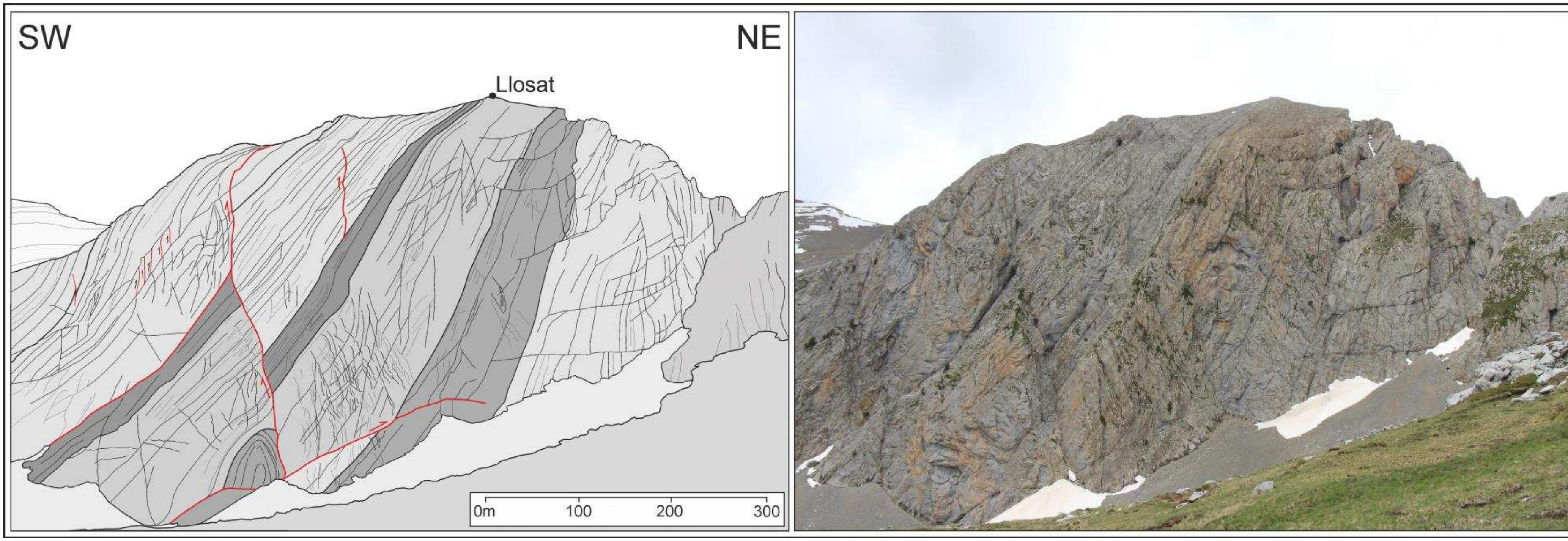


Figure 9

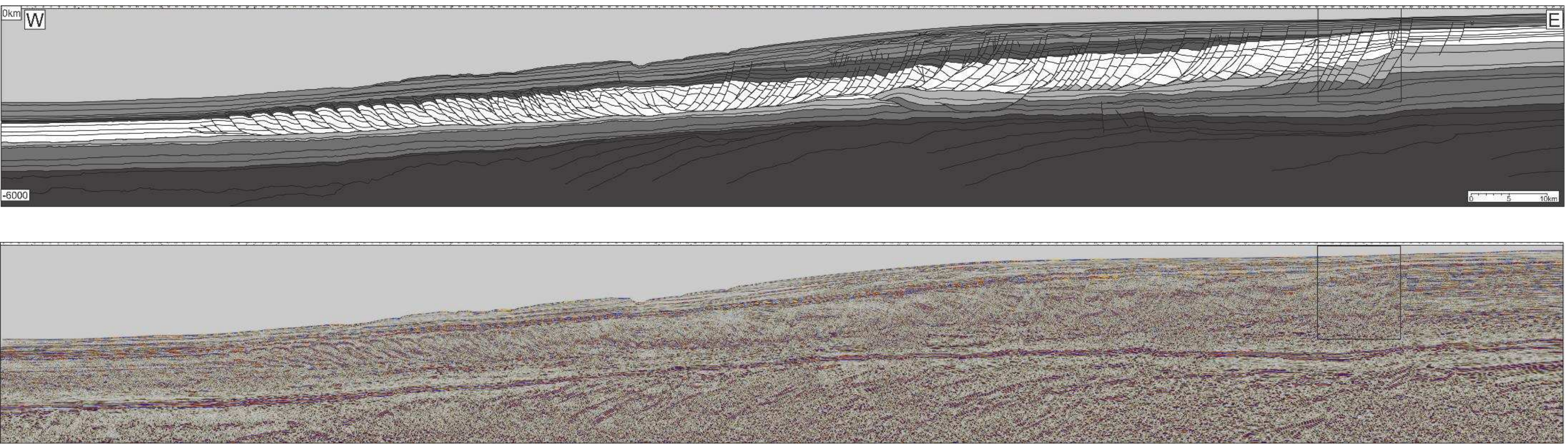
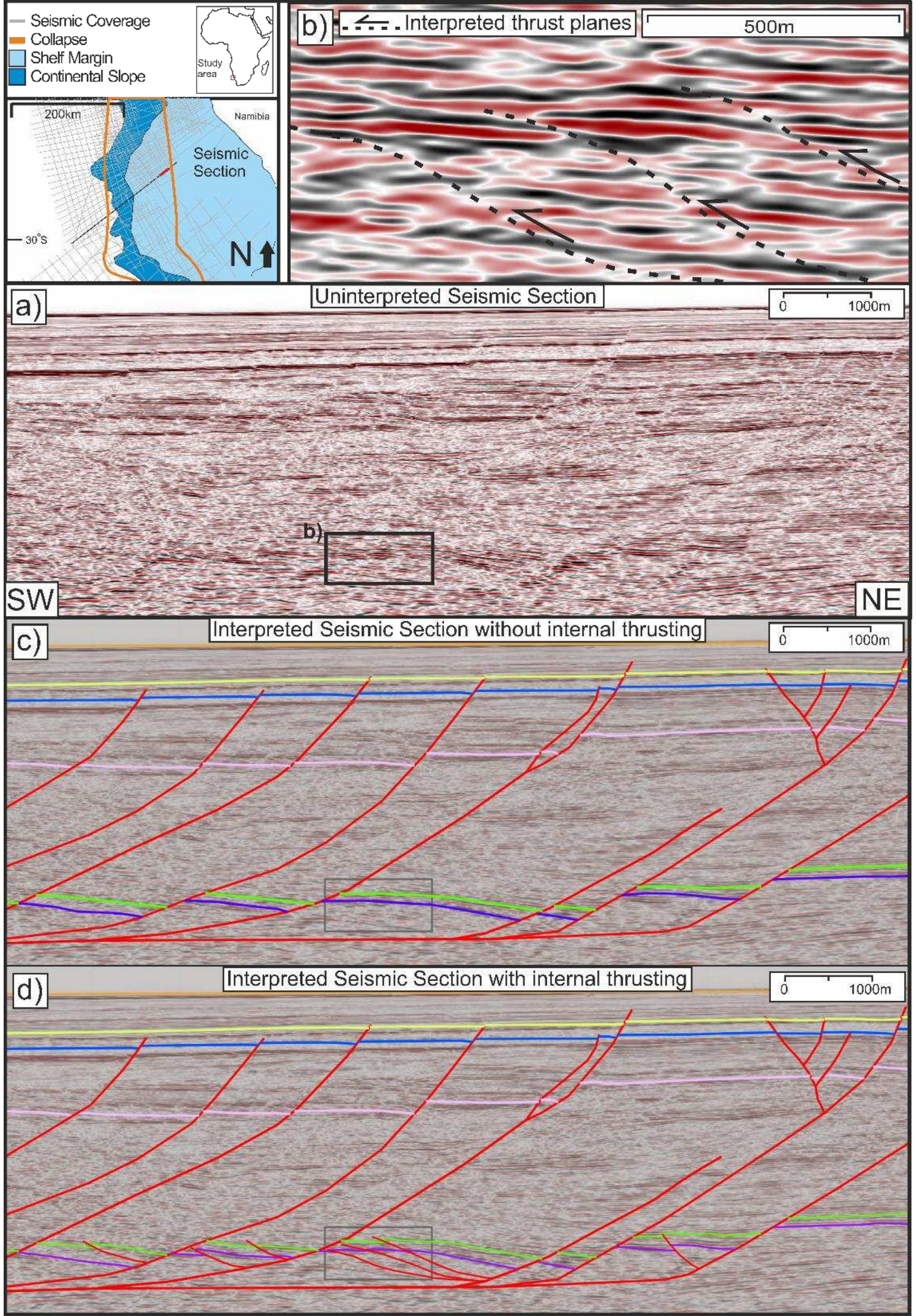


Figure 10



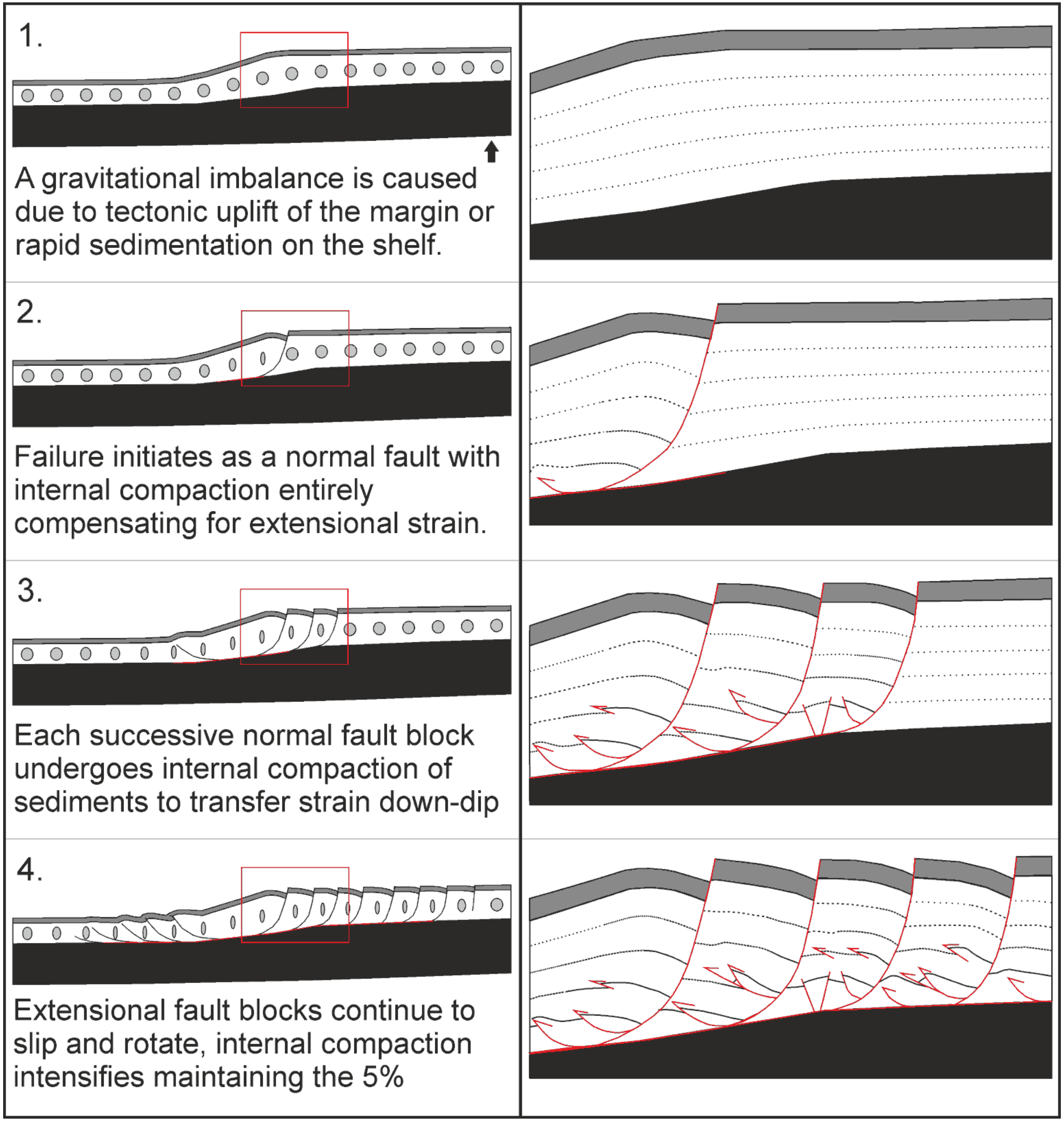
Seismic Coverage
Collapse
Shelf Margin
Continental Slope
Study area
200km
Namibia
Seismic Section
30°S
N
b)
Interpreted thrust planes
500m
a)
Uninterpreted Seismic Section
0
1000m
b)
SW
NE
c)
Interpreted Seismic Section without internal thrusting
0
1000m
d)
Interpreted Seismic Section with internal thrusting
0
1000m

Table 2

	Original Length (m)	Present Length (m)	Displacement (m)	Extension (%)
Orange	10341.8	10341.8	0	**0.0%**
Yellow	10296.3	10341.8	45.5	**0.4%**
Blue	10193.6	10341.8	148.2	**1.4%**
Pink	9667.9	10341.8	673.9	**6.5%**
Green	8534.0	10341.8	1807.8	**17.5%**
Green Comp	8939.7	10341.8	1402.1	**13.6%**
Purple	8273.7	10341.8	2068.1	**20.0%**
Purple Comp	8822.7	10341.8	1519.1	**14.7%**

	Without Compression	With Compression	Differ ence
Upper	17.5%	13.6%	3.9%
Lower	20.0%	14.7%	5.3%

Figure 11


1.
A gravitational imbalance is caused due to tectonic uplift of the margin or rapid sedimentation on the shelf.
2.
Failure initiates as a normal fault with internal compaction entirely compensating for extensional strain.
3.
Each successive normal fault block undergoes internal compaction of sediments to transfer strain down-dip
4.
Extensional fault blocks continue to slip and rotate, internal compaction intensifies maintaining the 5%

Highlights

- 5 % of strain in DWFTBs is compensated for by internal sub-seismic compression.
- Compressional features are present within the extensional portions of DWFTBs.
- DWFTBs show scalability from field to seismic scale
- A newly described field site for studying DWFTBs at Laspuña.

Abbreviations

DWFTBs– Deep water fold thrust belt