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Field-based investigation on fault architecture: a case study from the Lenghu fold-and-thrust belt, Qaidam basin, NE Tibetan Plateau

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Abstract

The fault zone architecture of a thrust fault zone is critical for understanding the strain accommodation and structural evolution in contractional systems. The fault architecture is also important for understanding fluid flow behaviour both along and/or across thrust fault zones and for evaluating potential fault related compartmentalisation. Because meso-scale (1-100 m) structural features are normally beyond the seismic resolution, high-resolution outcrop in-situ mapping (5-10 cm resolution) was employed to study the deformation features of a thrust fault zone located in the Qaidam Basin, northeastern Tibetan Plateau. The excellent exposure of outcrops enables the detailed investigation of the Lenghu thrust fault zone and its architecture. The Lenghu thrust fault, a seismically resolvable fault with up to ~800m of throw, exhibits a large variation of fault architecture and strain distribution along the fault zone. Multiple structural domains with different levels of strain were observed and are associated with the fault throw distribution across the fault. Based on previously proposed models and high-resolution outcrop mapping, an up-dated fault zone model was constructed to characterize the structural features and evo-lution of the Lenghu thrust. The possible parameters that impact fault architecture and strain distribution, including fault throw, bed thickness, lithology and mechanical heterogeneity were evaluated. Fault throw distributions and linkages control the strain distribution across a thrust fault zone, with local folding processes contributing important elements in Lenghu especially where more incompetent beds dominate the stratigraphy. Mechanical heterogeneity, induced by different layer stacking patterns, controls the details of the fault architecture in the thrust zone. The variations in bed thicknesses and mechanical property contrasts are likely to control the initial fault dips and fault/fracture density. Large fault throws are associated with wide strain accommodation and damage zones, although the relationship between the development and width of the fault zone with the throw accumulation remains to be assessed. By presenting the high resolution mapping of fault architecture this study provides an insight into the sub-seismic fault zone geometry and strain distributions possible in thrust faults and reviews their application to assessing fault zone behaviour.

Keywords

Detailed outcrop mapping, fault architecture, strain distribution, deformation mechanisms, mechanical stratigraphy

1. Introduction

The detailed meso-scale fault zone architecture controls the strain accommodation of faults and impacts on the fluid flow properties of the fault zones (e.g., Loveless et al., 2011; Seebeck et al., 2014; Childs et al., 2017a; Childs et al., 2017b; Dimmen et al., 2017; Ferrill et al., 2017a; Ferrill et al., 2017b; Homberg et al., 2017; Peacock et al., 2017a; Peacock et al., 2017b; Cawood and Bond, 2018; Cooke et al., 2018; Pei et al., 2018). In order to understand the detailed fault architecture, previous studies have investigated the deformation features of a mechanically layered sequence of beds that are subject to deformation (e.g., Ferrill and Morris, 2003; Welch et al., 2009b; Ferrill et al., 2017a; Ferrill et al., 2017b). The work shows that faults tend to form first in the brittle beds (e.g. sandstones or carbonates), while the weak/ductile beds (e.g. clay beds) can deform by distributed shearing to accommodate the overall strain (e.g., Eisenstadt and De Paor, 1987; Peacock and Sanderson, 1991; McGrath and Davison, 1995; Childs et al., 1996a; Schöpfer et al., 2006; Childs et al., 2009; Davies et al., 2012; Childs et al., 2017a; Childs et al., 2017b; Ferrill et al., 2017a; Ferrill et al., 2017b; Vasquez et al., 2018). Several quantitative dynamic models have also been presented (e.g., Egholm et al., 2008; Welch et al., 2009b; Homberg et al., 2017; Nicol et al., 2017; Peacock et al., 2017b) to analyse the mechanics of faulting and clay/shale smearing along faults in layered sand and shale/clay sequences (e.g., see also review in Grant, 2017). These models, from primarily extensional fault arrays, predict that the isolated initial faults formed within the brittle beds will grow until they eventually link up with increasing strain by propagating across the ductile intervals to create a complex fault zone architecture (Peacock and Sanderson, 1991, 1992; Childs et al., 1996a; Walsh et al., 1999; Walsh et al., 2003; Soliva and Benedicto, 2004; van der Zee and Urai, 2005; Davies et al., 2012; Ferrill et al., 2012; Ferrill et al., 2014; Ferrill et al., 2017a; Ferrill et al., 2017b). Outcrop studies supporting these models of fault zone architecture include the Moab fault, in Utah (Davatzes and Aydin, 2005); the minor normal-fault arrays exposed within Gulf of Corinth rift sediments, Central Greece (Loveless et al., 2011); and faults in the multilayer systems in the South-Eastern basin, France (Roche et al., 2012a; Roche et al., 2012b). Fault zone models defining the fault zone architecture have also been proposed in crystalline rocks (e.g., Caine et al., 1996); in poorly lithified sediments (e.g., Heynekamp et al., 1999; Rawling and Goodwin, 2003, 2006; Sosio De Rosa et al., 2018); within poorly consolidated sediments by (Loveless et al., 2011) and in transpressional faults (Choi et al., 2016).

However, most of these published studies have focused on the deformation features of extensional normal faults. There is still uncertainty on the detailed fault architecture development of thrust faults, although some studies have illustrated the impact of mechanical stacking on faulting deformation in thrust belts (Woodward and Rutherford Jr, 1989; Lloyd and Knipe, 1992; Woodward, 1992; Pfiffner, 1993; Cawood and Bond, 2018). In order to enhance the understanding of the evolution of fault architecture in thrust zones, we have studied the detailed (1m-10km scale) fault zone architectures of a thrust fault in the Lenghu fold-and-thrust belt of the Qaidam basin, northeastern Tibetan Plateau (e.g., Yin et al., 2008a; Yin et al., 2008b; Pei et al., 2014; Pei et al., 2017b). The fault architecture and strain distribution across the Lenghu thrust fault were investigated using high-resolution stratigraphic logging, satellite image interpretation and detailed outcrop mapping. The Lenghu thrust fault zone outcrops were separated into three general strain levels (high, medium and low), related to the fault throw magnitudes and the amount of layer disruption. A more detailed thrust fault model was constructed to demonstrate the fault architecture and deformation processes. The effects of parameters that may influence the fault architecture and strain distribution (e.g., fault throw, bed thickness, stratigraphy, and mechanical heterogeneity) were then evaluated.

2. Geological Setting

The Qaidam basin, an oil/gas-bearing Mesozoic-Cenozoic, fault-bound, sedimentary basin, is located in the northern edge of the Tibetan Plateau (Fig. 1). Topographically, the Qaidam basin covers an area of ~ 120,000 km^2 and has an average elevation of ~ 3 km (based on the SRTM DEM data). In map view, the Qaidam basin is a rhombic shaped basin, and its N-S width changes from ~ 150 km in the east to ~ 300 km in the west (Yin et al., 2007; Yin et al., 2008a; Yin et al., 2008b). Tectonically, the Qaidam basin is bounded by the Qilian Shan-Nan Shan thrust belt to the northeast (e.g. Molnar and Tapponnier, 1975; Burchfiel et al., 1989; Tapponnier et al., 1990; Meng et al., 2001; Yin et al., 2008a), the left-lateral strike-slip Altyn Tagh fault to the northwest (e.g. Meyer et al., 1998; Cowgill et al., 2000; Cowgill et al., 2003; Cowgill et al., 2004a; Cowgill et al., 2004b; Yue et al., 2004; Cowgill, 2007; Yin et al., 2007), and the Qimen Tagh-Eastern Kunlun thrust belt to the south and southwest (e.g. Chen et al., 1999; Meng et al., 2001; Jolivet et al., 2003; Yin et al., 2007; Craddock et al., 2012; Mao et al., 2016). The stratigraphy of the Qaidam basin is divided into three main packages, which are metamorphic basement, late Palaeozoic-Mesozoic sediments and Cenozoic sediments (e.g., Cui et al., 1995; Deng et al., 1995; Gao et al., 1995; Xia et al., 2001). Based on outcrop observations, seismic sections, boreholes, terrestrial fossils, basin-scale stratigraphic correlation, fission-track and $^{40}Ar/^{39}Ar$ dating of detrital micas (Huo, 1990; Yang et al., 1992; Song and Wang, 1993; Huang et al., 1996; Xia et al., 2001; Qiu, 2002; Sun et al., 2005; Rieser et al., 2006a; Rieser et al., 2006b), a division and time assignments of Mesozoic to Cenozoic sediments have been proposed. The Qaidam basin contains thick Cenozoic sediments (E_{1+2}-Q_1, >54.8 Ma - present) up to 16 km thick and locally-developed thin Mesozoic sediments (Jr, 206 - 65 Ma) (e.g., Huang et al., 1996; Yin et al., 2008b). The Qaidam basin contains different structural hierarchies: the first-order structure is a large-scale, regional structure composed of a series of tight anticlines and open synclines with associated faults extending for ~380kms along strike and to a maximum depth of up to ~16km. The second-order structures are regional scale folds/faults, including inverted normal faults in Mesozoic sediments and thrust faults in Jurassic-Eocene sediments that indicate a complex geological history of the Qaidam basin (Wang et al., 2006a; Yin et al., 2008b). The central thickening of Cenozoic sediments suggests the Qaidam basin was controlled by NE-SW contraction associated with the uplift of the Tibetan Plateau (e.g., Molnar and Tapponnier, 1975; Xia et al., 2001; Pang et al., 2004; Wang and Burchfiel, 2004; Wang et al., 2006b; Zhou et al., 2006; Zhu et al., 2006). The detailed Qaidam basin strain history is complex and involves some along strike extension that may have been associated with oblique slip on deep faults and/or the interference of propagating folds (Mao et al., 2016). The total shortening of the central Qaidam basin since 65 Ma is estimated as 20 ± 2 km, which leads to an estimated shortening rate of 0.30 ± 0.04 mm/yr (Zhou et al., 2006; Yin et al., 2008b; Liu et al., 2009).

The Lenghu fold-thrust belt, located in the northern portion of the Qaidam basin, is a ~ 15 km wide asymmetric anticline controlled by the underlying Lenghu thrust fault (Fig. 1), developed during the regional NE-SW oriented contraction (e.g., Chen et al., 2005; Wang et al., 2006a; Mao et al., 2016; Pei et al., 2017a; Pei et al., 2017b). The Lenghu thrust fault, with a fault throw ranging from ~300 m to ~800 m (Pei et al., 2017a), dips steeply SW at angles of 60 - 70° in the shallow subsurface, extending along strike NW to SE for ~ 80 km. An anticline belt has developed in the hanging wall of the Lenghu thrust fault.

The stratigraphy of the Lenghu fold-thrust belt is dominated by Neogene sediments, comprising primarily siltstone and sandstone (Fig. 1). The detailed stratigraphy of the Lenghu fold-thrust belt was logged on the ground along traverses that were positioned sub-perpendicular to the strike of the Lenghu fold-and-thrust belt (modified after Pei et al., 2017a; Pei et al., 2017b). The stratigraphy can be divided into four main packages (Fig. 2), (i) $\mathbf{S_a}$, the oldest package, comprises fine sandstones and red/grey/mottled siltstones, with a thickness of ~ 170 m (with individual bed thickness ranging from 1 m to ~10 m); (ii) $\mathbf{S_b}$, the lower middle sequence, includes fine-medium sandstones interbedded with very a few thin red/grey siltstones and its thickness is ~ 440 m (with individual bed thickness ranging from 0.5 m to ~5 m); (iii) $\mathbf{S_c}$, the upper middle package, is ~ 340 m thick (with individual bed thickness ranging from 0.5 m to ~20 m), shows a similar lithology to $\mathbf{S_b}$, but with thin interbedded medium-coarse sandstones; (iv) $\mathbf{S_d}$, the upper sequence, contains coarse-very coarse sandstones with a thickness exceeding 250 m (with individual bed thickness ranging from 0.5 m to ~25 m). Here the rocks finer than silty sandstone were classified as incompetent layers, whereas rocks no finer than silty sandstone were classified as competent layers. This allows us to estimate the competent : incompetent ratios and level of mechanical heterogeneity of each individual package. These four packages represent different levels of mechanical heterogeneity (see Fig. 2): the $\mathbf{S_a}$ package has a high mechanical heterogeneity (competent : incompetent = 81% : 19%), the $\mathbf{S_b}$ package has a low mechanical heterogeneity (competent : incompetent = 100% : 0%), the $\mathbf{S_c}$ package has a medium to high mechanical heterogeneity (competent : incompetent = 99% : 1%), and the $\mathbf{S_d}$ package has a medium mechanical heterogeneity (competent : incompetent = 97% : 3%). The excellent outcrops of the Lenghu thrust fault zone provide a good platform to assess the meso- and micro-scale structural features within the fault zones developed in these sequences.

3. Data and Methods

In this study, we integrated remote sensing data (e.g., Landsat images) and field observations (e.g., stratigraphy, fault system maps, and detailed maps of fault outcrops), to understand the detailed fault architecture and its controlling parameters. As meso-scale structural features are below seismic resolution, high-resolution landsat images were interpretated with validation by stratigraphic logging (Fig. 2) and outcrop structural mapping (Fig. 3). The Lenghu thrust fault zone, e.g., F1 - F3 (Fig. 4) and F4 (Figs. 5-9), were mapped in detail to investigate the meso-scale structural features. Mapping included measurement of; fault azimuth/dip, fault throw, fault populations and linkages, and an assessment of the mechanical stratigraphy. The strain distribution across the fault zones was determined based on the level of estimated fault throws and the deformation of lithologies present. Representative thrust fault outcrops with different levels of deformation, fault throw, bed thickness, stratigraphy, mechanical heterogeneity were mapped in detail to understand the meso-scale fault architecture occurring along the thrust fault zone (Fig. 10). The overall throw on the Lenghu thrust at the selected outcrops ranges from ~300 m to ~800 m. Deformation responses of interbedded competent and incompetent layers were investigated based on the outcrop observations and measurements (Figs. 11). A more detailed static model of a thrust fault zone was then built, based on previous models and the high-resolution outcrop study reported here (Figs. 12). Schematic structural evolutionary models of the different vertical stacking sequences were built to assess the control of stratigraphy and mechanical heterogeneity on fault development in the thrust fault zone (Figs. 13).

4. Strain Distribution and Fault Architecture

Landsat image interpretation and fault outcrop mapping were employed to evaluate the strain distribution (e.g., folding and faulting) along strike of the Lenghu fold-thrust belt (Fig. 2). The Lenghu thrust faults (red curves and plots in the stereonets in Fig. 3) developed from NE-SW shortening. An asymmetric anticline, with a steep or overturned NE fore-limb and relatively shallow dipping backlimb, is developed in the hanging wall of the Lenghu thrust. The topographic culmination (green triangle in Fig. 3) corresponds to the flat crest of the hanging wall anticline. The fault zone of the Lenghu fold-thrust belt is not a single fault plane in outcrop, but comprises a main thrust fault and several small splay faults. The main thrust fault, with a throw of up to 650 m, accounts for 85 – 90% of the overall fault throw of the fault zone (Pei et al., 2017a; Pei et al., 2018), although several splay faults are also observed in either the hanging wall or footwall. The splay faults, with throws of < 300 m, are not evenly distributed but concentrated along the hanging wall anticline crest and generate a number of fault bound lenses in the fault zone. Normal faults, with fault throws of up to tens of meters, form in the hanging wall (see the purple curves and plots in the stereonet in Fig. 3). The majority (~ 90%) of the minor structures develop in the fault zone and the hanging wall, suggesting that the strain is mostly concentrated in the hanging wall to the fault zone. In addition, the normal faults in the hanging wall are mostly concentrated in the silt-rich units (i.e., **Sa - Sb**, Fig. 3) present in the fold crest area and near the main Lenghu thrust. The frequency of these structures decreases away from the main fault to the SW. The normal faults often terminate at the Lenghu Thrust (Fig. 3) and appear to represent a late fault extensional strain and extensional reactivation of the Lenghu Thrust where part of the normal fault activity is taken up on the main thrust (see Fig. 7 and Section 4.2). This along strike extension may be associated with local accommodation of oblique slip (e.g., Mao et al., 2016) or a regional E-W extension.

4.1. Strain distribution and cross fault zones

A set of well-exposed outcrops (approximate section size 50 m × 30 m) in the Lenghu field enables us to link the structures present on satellite images, at the > 100 m scale, with structures at a scale of < 100 m. Three well-exposed outcrops of the main thrust fault were mapped in detail (Fig. 4) to allow the generation of sections F1, F2 and F3 (see positions in Fig. 3). These three SW-NE traverses cut through the hanging wall of the main thrust fault ~ 50 m apart and are orientated sub-parallel with each other. The three outcrops all include the main fault and the adjacent damage zones of the Lenghu thrust fault where different sedimentary stacking sequences are present.

The stereonets of measured fault strike/dip of the outcrops F1, F2 and F3 demonstrate a high-angle central fault zone and a splay thrust fault in the hanging wall, responding to the NE-SW shortening (Fig. 4). An anticline with a flat crest against the Lenghu thrust fault was developed in the hanging wall. Although the hanging wall folding clearly absorbs shortening, the overall strain is dominated by fault deformation (i.e., the Lenghu thrust fault and its splay faults). By restoring a regional seismic section, Pei et al. (2018) evaluated the contribution of faulting and folding deformation to the overall strain in the Lenghu Fold-Thrust belt, which are 80% and 20%, respectively. The steeply dipping main fault zone contains disrupted and sheared stratigraphic units composed of foliated fault rocks (primarily originally siltstones and subordinate sandstones), which accounts for the majority of the fault zone deformation in the central portion of the outcrop. The siltstones form vertical domains where they have been smeared into the fault zone from the hanging wall stratigraphy, while the sandstones are faulted and deformed by brittle deformation. The bedding within the central fault domains cannot be identified because of the intense deformation. The shearing into high strain fault zones generates silt smears and sand inclusions. The outcrops F1, F2 and F3 illustrate the lateral variation in the fault zone architecture along strike of the Lenghu fold-thrust belt. The strain distribution across the fault zone presents a similar pattern between the three outcrops (see the estimated strain curves in Fig. 4). The central portion of the fault zone mapped shows high strain deformation, while the moderate and low strain deformation are unevenly distributed around this domain.

4.2. Meso-scale fault architecture

An additional outcrop, F4 (Fig. 5a), in the southern end of the Lenghu fold-thrust belt, (see position in Fig. 3) also demonstrates the detailed meso-scale fault architecture. Based on the regional section analysis by Pei et al. (2018), the fault throw on the main thrust fault here is 640 – 847 m, large enough to be imaged in a seismic reflection section. The Lenghu thrust at F4 is not a single-plane fault, but composed of several splay faults and domains with varying amounts of strain (Fig. 5). Fig. 5b demonstrates the well-exposed outcrop of F4 and the structural interpretation. By integrating the stratigraphic sequences, Fig. 5c presents a composite of the detailed maps of five individual outcrops of splay faults; F4-1, F4-2, F4-3, F4-4 and F4-5. The outcrop F4-5 was not mapped in detail, because of the heavy weathering present. The outcrops F4-1 to F4-4 present different levels of fault throws and strain indicated by the amount of layer disruption. The uneven fault throw distribution (Fig. 5c) across the Lenghu thrust fault zone allows us to subdivide this fault zone into three structural domains with different levels of strain. These are (i). a high strain domain: splay fault zone F4-4 (Fig. 6) and F4-5; (ii). a medium strain domain: splay fault zone F4-3 (Fig. 7); and (iii). a low strain domain: splay fault zones F4-1 (Fig. 8) and F4-2 (Fig. 9). Each of these domains are reviewed separately below.

(1) High strain domain: splay fault zone F4-4

The high strain domain F4-4 (Fig. 6a), defined by intense deformation, well developed fault rocks and bed disruption, is directly in contact with the slightly deformed hanging wall (see position in Fig. 5). The stratigraphy of outcrop F4-4 fault is dominated by mottled fine-medium siltstones (see the stratigraphic column recorded in field, Fig. 6b, c). The F4-4 presents a steeply dipping fault zone (70 - 80°) , ~ 5 m wide, with sheared lithologies of foliated fault rocks composed primarily of siltstones and some sandstones. This fault zone architecture is controlled by a series of NW-SE striking high-angle thrust faults with relative large throws (up to 650 m, based on stratigraphic correlation in Pei et al. (2018)), together with several SW-directed back thrust faults with smaller offsets (<1 m), demonstrating NE-SW shortening (Fig. 6d). The siltstones form sheared domains apparently derived from both the hanging wall and the footwall. The sandstones are faulted and extended by discrete fault offsets to generate boudins in the attenuated layers. Although the fault rocks are variable in the fault zone of F4-4, the original bedding cannot be identified because of the intense shearing and faulting. In the northeast end of F4-4, the sub-horizontal footwall bedding shows only slight deformation. A distinct slip surface separates the steeply dipping and sheared fault zone from the footwall stratigraphy, suggesting this slip surface forms the northeast boundary of the main fault zone F4-4.

(2) Medium strain domain: splay fault zone F4-3

The medium strain domain F4-3 (Fig. 7a) is based on the more continuous layer continuity compared to F4-4. F4-3 is located on the northeast side of the high strain domain F4-4 (see position in Fig. 5). The stratigraphy of F4-3 is mainly composed of brown siltstones and grey sandstones (Fig. 7a, b). Thrust faults with measurable fault throws (5 cm - 5 m) are well developed in this outcrop. The cumulative throw on these thrust faults is ~ 8 m. The bedding adjacent to the fault core dips steeply (> 50°) and is folded. However, in contrast with the high strain domain F4-4, the outcrop F4-3 contains low angle thrust faults (dips of 30 - 50°) that offset beds in a tightly folded zone. Through-go ing faults are developed in the thick homogeneous units (either the thick sandstone or the siltstone beds) in the top or bottom of the section) while fault segments and lenses are developed where the stratigraphic heterogeneity increases (e.g., interbedded thin sandstones and siltstones in the central section, Fig. 7c). The stereonets of the fault planes indicate NE-SW shortening (Fig. 7d).

(3) Low strain domain: splay fault zones F4-2 and F4-1

A stack of small thrust faults representing a low strain domain, indicated by the small cumulative throw (<2m) and relatively low levels of layer folding, were also mapped in the profile of fault F4, i.e., F4-2 (Fig. 8a, b) and F4-1 (Fig. 9a, b).

The maximum throw at F4-2 reaches up to 2 m within the imbricated thrust faults (Fig. 8b). The outcrop F4-2 contains lithologies dominated by the upper siltstones and lower sandstones (Fig. 8c). More folding is observed in the silty layers (middle section) than in the sandy layers (lower section). This is likely to reflect the different mechanical properties of the stratigraphic sections with different silt/sand ratios. The strain (faulting and folding) decreases away from the largest throw thrust fault towards the edges of the outcrop and fault zone shown. The stereonets of the fault planes indicate NE-SW shortening (Fig. 8d). The thrust fault imbricates form at lower angles (20 - 40°) than in the high strain domain (e.g., F4-4 and F4-5) and the medium strain domain (e.g., F4-3). Fault splays are developed along the thrust faults, particularly where the fault propagates from sandstone layers to siltstone layers.

A second low strain thrust fault F4-1, shown in Fig. 9b, is a small pop-up structure along a minor fold axis in the Lenghu thrust footwall. The outcrop is in the domain where beds have low dips away from main thrust fault (Fig. 9b). The lower layers involved in F4-1 are primarily sandstones while the top layers are siltstone-dominated (Fig. 9c). F4-1 is a structure composed of a series of sub-parallel NW-SE trending thrust faults and SW back-thrusting faults. The stereonets of the fault planes also indicate the NE-SW contraction (Fig. 9d). The silt-rich layers (upper section) of the fore-thrust show more folding than in the sandy layers (lower section), which is similar to that observed in the outcrop F4-2. Fault lenses were also developed along the thrust faults and back-thrusts, particularly where the fault propagates from sandy layers to silt-rich layers.

Based on the outcrop mapping of the Fault F4, the deformation is primarily in the high strain fault domains F4-4/F4-5; the medium strain fault F4-3 is located in the intermediate hanging wall or footwall of the high strain splay faults; and the low strain splay fault zone domains, F4-1 and F4-2, are developed as isolated structures in the more external footwall of the high strain fault (Fig. 10). In terms of the fault zone geometry, the high strain faults form steeper fault zones than the medium and low strain faults. In addition, the fault zone width and complexity appears higher where throws are larger, although the evolution of the fault zone width with changes in throw cannot be assessed from the limited number of outcrops described here. For example, the high strain fault F4-4 has a fault zone width of ~ 7 m (Fig. 6), whereas the low strain fault F4-2 and F4-1 form fault zones widths below 0.5 m (Figs. 8 and 9).

5. Deformation Responses and Thrust Fault Model

The strain distribution across fault zones and meso-scale fault architectures of the well-exposed outcrops, together with the deformation responses associated with thrust faulting are considered in this section. A thrust fault model is then presented for the detailed fault zone architecture evolution followed by an evaluation of the role of fault throw and stratigraphy on strain accommodation.

5.1. Deformation Responses

Deformation responses to the thrust faulting are considered at the meso-scale and include an evaluation of the general strain level developed in the competent beds, the incompetent beds, and the impact of the different mechanically layered sequences present in the study area.

The competent beds, e.g., sandstones, are prone to brittle deformation, e.g., fractures or faults in the study area. The faults with minor offsets are considered to initiate early when the stress is applied. The through-going faults then develop later in the strain history. Although this is considered a continuous process, both the fractures/very low offset faults and the through-going faults with higher throws can be observed in a single outcrop. It is not possible to assign low strain features to an early time stage in the fault zone development – they may have initiated at any stage in the fault zone evolution. The deformation of competent beds is linked to a very high fault propagation/slip ratio (see Erslev, 1991). The fault lenses can also form in the developing fault zone at different stages, either from fault linkage (Peacock and Sanderson, 1991; Childs et al., 1996a; Walsh et al., 2003; Lindanger et al., 2007; Childs et al., 2009; Ferrill et al., 2012) and/or from short-cut faulting (Knipe, 1985) or asperity reduction on the fault surface (Childs et al., 1996b; Walsh et al., 1999; Ferrill et al., 2014; Ferrill et al., 2017a; Ferrill et al., 2017b).

The incompetent beds, such as siltstones in the study area experience ductile deformation, e.g., folding or smearing during faulting. The ductile folding appears to form in the incompetent beds at low strains and accommodates local shearing and more extensive smearing is then developed when increasing strain offsets the weak/ductile beds. The progress of folding and smearing can be linked to a relative low fault propagation/slip ratio. The folding and faulting process is well described by the trishear model (e.g., Erslev, 1991; Childs et al., 1996a; Childs et al., 1996b; Hardy and Ford, 1997; Childs et al., 2009; Pei et al., 2014) or the quadshear model (Welch et al., 2009a; Welch et al., 2009b), where the strain is accommodated by upward and downward propagation of folding and eventually faulting into and through the incompetent layer sandwiched between other units (see also Freitag et al., 2017; Peacock et al., 2017b). At higher offsets continuous faulting through the incompetent (siltstone) layer, may allow the smearing to become discontinuous which may leave some gouge patches along the slip surface, e.g., F4-4 (Fig. 6) (see also Welch et al., 2009a; Welch et al., 2009b).

Stacked beds define mechanically layered sequences, e.g., interbedded sandstones and siltstones (Fig. 11a_0, a_1), where strength properties have evolved differently during the burial history. Previous studies describing the structural deformation of layered sequences include (e.g.Eisenstadt and De Paor, 1987; Withjack et al., 1990; Peacock and Sanderson, 1991; McGrath and Davison, 1995; Childs et al., 1996a; Schöpfer et al., 2006; Ferrill et al., 2017a; Ferrill et al., 2017b; Homberg et al., 2017; Nicol et al., 2017; Bubeck et al., 2018; Cawood and Bond, 2018; Vasquez et al., 2018). In the examples from the Lenghu Fold-Thrust Belt, when the mechanically layered sequence of beds are initially subject to stress, the fractures or small faults appear to form in the competent beds (e.g., sandstones in the Lenghu fold-thrust belt) (Fig. 11b_0, b_1), whereas the incompetent beds (e.g., siltstones in the Lenghu fold-thrust belt) are folded or sheared to accommodate the overall strain (Fig. 11c_0, c_1). As the strain increases, the fractures or small faults confined within the competent beds are considered to grow until they eventually propagate into the incompetent beds (Peacock and Sanderson, 1991; Childs et al., 1996a; Walsh et al., 1999; Walsh et al., 2003), where siltstone folding and/or smearing can lead to gouge forming along the slip surfaces.

5.2. Thrust fault model

A basic model of fault zone development in the adjacent Junggar Basin was presented by Liu et al. (2017), where a conceptual model of reverse faults developed in igneous and sedimentary rocks was based on integrating seismic, well logs and drilled cores. However, this model did not delineate the detailed meso-scale structural features present. Here we have reviewed the key features of the fault zones mapped in the Lenghu Thrust zone in Fig. 12 and use this to evaluate the controls on fault zone architecture. The Fig. 12 shows a fault zone formed in a mechanically layered sequence of beds. The yellow and brown units represent competent layers (e.g., sandstones) and incompetent layers (e.g., silt-stones), respectively. The idealised fault zone is composed of a main slip fault, and a series of fault bound lenses, fault splays and isolated faults that make up the damage zone (see also reviews of fault damage zones in Wibberley et al., 2008; Choi et al., 2016; Peacock et al., 2017a). The amount of strain accommodated in the fault zones decreases in the damage zone away from the main slip surface.

The majority of the fault throw is located in the most central position of the faulted section (Fig. 12), and is often confined by two discrete slip surfaces that are sub-parallel to each other (e.g., F4-4 in Fig. 6b). The common occurrence of two dominant slip surfaces was also recognised by previous studies (e.g., Childs et al., 1996b; Ferrill and Morris, 2003; Loveless et al., 2011; Liu et al., 2017; Nicol et al., 2017; Nicol and Childs, 2018; Xie et al., 2018). The fault zone and fault rocks between these two discrete slip surfaces have the highest strain. The final geometry of the fault zone is dependent on the mechanical stra-tigraphy of the sequence. For example, the number of faults accommodating the strain across the central fault zone between the main slip surfaces tends to increase in domains where more layers and more mechanical contrasts are present (e.g. see F4-4 in Fig. 5). In contrast, the incompetent layers (siltstones in this case) are likely to be incorporated as smears within the high strain zones (e.g. see the smeared grey unit **H** in Fig. 6, and especially layer **B** and **D** in Fig 7). The fault damage zones in sections with, what appear to be, higher mechanical contrasts tend to form domains with increased faulting (e.g. note faults present in Layers **B** and **D** above the thick sandstone unit in Fig. 7). The detailed outcrop maps also suggest that the mechanical strength of a layered sequence is scale-dependent. For example, although sandstone is prone to brittle deformation, a thin sand-stone layer sandwiched by thick siltstone layers appears to have a limited impact on the bulk behaviour of the package and is likely to be entrained into the smear zone and follow the mechanical response of the dominant layers (e.g., the thin yellow sandstone layer sandwiched between the thick brown siltstone layers, upper section of F4-1, Fig. 9b). The degree of disruption of entrained sandstone beds therefore appears to depend on the embedded layer thickness and strength relative to the larger package. Sandstone beds may form faulted sand boudins, maintaining sand-sand continuity and defining a smear-ing-like geometry in high strain zones, whereas thin sandstone beds may break down to form isolated boudins.

The damage zones adjacent to the main slip surface (Fig. 12) are characterised by splay faults, fault bound lenses and folds, where the overall strain is lower than across the main fault surfaces. The splay faults and fault lenses appear to form within the competent beds (yellow), and then propagate into and through the incompetent beds (brown). The splay faults extend into the undeformed or slightly deformed beds, and creates more fault com-plexity. The short-cut faults that remove local asperities on the developing slip surfaces can form new fault lenses, which increase the linkage of faults within the damage zone. The edges of the damage zone, away from the main slip surfaces (Fig. 12), with low strains are characterised by isolated faults or clusters of small throw faults; although the detailed linkage to other faults in 3D (out of the plane of exposure) is unknown.

The mapped outcrops in the Lenghu fold-thrust belt expose thrust faults with different amounts of fault throw, ranging from 50 cm (e.g., F4-1) to hundreds of meters (e.g., F4-4). Accordingly, multiple fault zones, with different individual widths (ranging from tens of centimetres to 5 meters) are developed across the traverses with a high total throw (see F4 in Fig. 10b)

6. Discussion

Previous studies have highlighted that the generation and distribution of fault zone geometries and fault rocks are affected by several factors, e.g., the fault throw, lithology, deformation responses and internal fault structure (e.g., Hull, 1988; Blenkinsop, 1989; Loveless et al., 2011; Torabi and Berg, 2011; Pei et al., 2015; Childs et al., 2017a; Childs et al., 2017b; Ferrill et al., 2017b; Homberg et al., 2017). Based on the outcrop structures from the Lenghu fold-thrust belt, the effects of fault throw, bed thickness, host stratigraphy and mechanical stratigraphy on the thrust fault architecture are discussed here.

Large displacements are associated with wider fault zones (see Childs et al., 2009). In the Lenghu fold-thrust belt, thrust faults (e.g., F4-4 with displacements of > 200 m) form fault zones of high strain that are > 5 m wide (Fig. 10b), whereas the low strain thrust faults (e.g., F4-1 with a cumulative displacement of ~ 1.5 m) have ~ 50 cm wide zones of concentrated deformation (Fig. 10b). This observation concurs with previous studies (e.g., Otsuki, 1978; Robertson, 1983; Hull, 1988; Evans, 1990; Knott, 1994; Childs et al., 2009; Bastesen and Braathen, 2010; Davies et al., 2012; Childs et al., 2017a; Childs et al., 2017b; Ferrill et al., 2017a; Ferrill et al., 2017b), although the detailed relationship between the evolution of fault zone width (and fault rock width) with fault throw accumulation are still to be clearly defined. The smearing of weak/ductile beds (e.g., siltstones) are observed along the high strain fault zones in the meso-scale outcrops of thrust faults (see Fig. 6 and layers in the SW part of 4-3 in Fig. 7). However, large fault throws tend to destroy the continuity of smears, although thin silt gouges may persist along the important slip planes (Brown et al., 2003; Childs et al., 2009; Grant, 2017). A number of tools have been proposed to predict the continuity of siltstone smears in fault zones. Examples of the tools include: Clay Smear Potential (CSP) (Bouvier et al., 1989; Fulljames et al., 1997), Shale Smear Factor (SSF) (Lindsay et al., 1993), Shale Gouge Ratio (SGR) (Yielding et al., 1997), Scaled Shale Gouge Ratio (SSGR) (Ciftci et al., 2013) and more complex re-distributions of smears (e.g., Grant, 2017).

The term ‘mechanical stratigraphy’ in fracture and fault studies has been used to subdivide layered sequences into discrete mechanical units defined by properties such as tensile strength, elastic stiffness, brittleness and fracture mechanics properties (e.g., Corbett et al., 1987; Tyler and Finley, 1991; Peacock and Sanderson, 1992; Cooke, 1997; Cosgrove, 1999; Laubach et al., 2009; Ferrill et al., 2012; Delogkos et al., 2017; Ferrill et al., 2017b; Grant, 2017; Cooke et al., 2018). A mechanical stratigraphy with high heterogeneity may increase the complexity of the fault zone architecture in thrust systems (e.g., Woodward and Rutherford Jr, 1989; Woodward, 1992; Pfiffner, 1993; Welch et al., 2009b; Davies et al., 2012; Cawood and Bond, 2018; Pei et al., 2018).

For the deformation conditions experienced by the exposed Lenghu fold-thrust belt, the thrust fault architecture is influenced by the mechanical stratigraphy. We have constructed four sets of diagrams to demonstrate fault architecture and strain distribution that occur in different mechanical settings (Fig. 13a: thick competent layer; Fig. 13b: interbedded thick competent layers and thin incompetent layers; Fig. 13c: interbedded thin competent layers and thick incompetent layers; Fig. 13d: thick incompetent layer). In each case the competent : incompetent ratio varies (e.g., Ferrill and Morris, 2008; Ferrill et al., 2017b). Concurring with the previous studies (e.g., Peacock and Sanderson, 1991; Childs et al., 1996a; Ellis et al., 2004; Schöpfer et al., 2006; Bose et al., 2009; Loveless et al., 2011; Miller and Mitra, 2011; Yang et al., 2014; Homberg et al., 2017; Vasquez et al., 2018), stratigraphy dominated by competent layers normally forms a strain zone evolving from fractures, small faults to through-going faults (Fig. 13a: competent : incompetent ratio = 100% : 0%), whereas stratigraphy dominated by incompetent layers experienced folding-dominated deformation in Lenghu (Fig. 13d: competent : incompetent ratio = 0%

: 100%). In these two end-member scenarios (Fig. 13a, d), the strain distribution is determined by the different mechanical properties of the stratigraphy. When the stratigraphy contains interbedded competent and incompetent layers, the final geometry of a deformed sequence is influenced by the mixture as well as the dominant mechanical layers of the stratigraphy. As illustrated in Fig 13, where the competent layers dominate the sequence a more brittle deformation behaviour (Fig. 13b: competent/incompetent ratio = 90% : 10%) is expected. Where the incompetent layers dominate the sequence more ductile deformation features (Fig. 13c: competent : incompetent ratio = 10% : 90%) are present. In these two intermediate scenarios, the subordinate layers (e.g., incompetent layers 10% in Fig. 13b and competent layers 10% in Fig. 13c, respectively) will deform more passively to accommodate the strain distribution determined by the dominant layers (e.g., competent layers 90% in Fig. 13b and incompetent layers 90% in Fig. 13c, respectively). For example, in F4-1 (see also top-right corner in Fig. 9), as the thin sandstone layer **I** (3 cm thick) is sandwiched between two thick siltstone layers **H** (8 cm thick) and **J** (15 cm thick), the overall deformation style is determined by the dominant mechanical layers **H** and **J**, rather than the subordinate layer **I**. However, the deformation behaviour of the stacking sequence often also has a scale-independency. Although the sequence of thin incompetent layers (i.e., $\mathbf{ICL_1}$, $\mathbf{ICL_2}$) sandwiched within thick competent layers (Fig. 14a) can show an overall deformation behaviour similar to that of the sequence dominated by strong layers (Fig. 13a), thin incompetent layers (i.e., $\mathbf{ICL_1}$, $\mathbf{ICL_2}$) may still form ductile folds at the layer-scale (Fig. 14a). For example, in F4-3 (Fig. 14c), the thin siltstone layer **B**, sandwiched in between the thick sandstone layers **A** and **C**, shows continuous smearing; although through-going faults are developed within the sequence dominated by competent layers. Similarly, the thin competent beds sandwiched within thick incompetent layers may accommodate strain at the layer-scale by local faulting (i.e., $\mathbf{ICL_1}$, $\mathbf{ICL_2}$, Fig. 14b). For example, in F4-1 (Fig. 14d, see also top-right corner in Fig. 9), the thin sandstone layer **I** still illustrates faulting deformation, although the overall deformation response and strain of **H-I-J** sequence is dominated by folding deformation.

Although the competent : incompetent ratio (Ferrill and Morris, 2008; Ferrill et al., 2017b) can help understanding the control of mechanical stratigraphy on fault zone architecture, we also note that (Tyler and Finley, 1991) highlight that variation in the fault zone architecture is possible for mechanical stratigraphies with identical competent : incompetent ratios. This reflects the different stacking patterns (e.g. layer thicknesses) possible in a stratigraphy that shows the same overall ratio. The detailed outcrop studies in the Lenghu fold-thrust belt enables us to observe variations in the fault architecture that reflects this situation. For example, the stratigraphy of the outcrop F4-3 (Fig. 7c) has a similar overall competent : incompetent ratio (68%) to that of the outcrop F4-1 (Fig. 9c) with a ratio of 66%, but F4-3 appears to show a higher mechanical heterogeneity reflected by the more complex fault array. This is despite the likely impact of the higher strain and overall throw, in fault F4-3.

The field-based outcrop analyses does suggest that high mechanical contrasts produce wider and complex fault arrays, whereas low mechanical contrasts generate more planar faults with narrow or absent damage zones. Examples from Lenghu include: a) the increased folding associated with the more incompetent sequence in the upper section of fault F4-1 (Fig. 9), and b) the increased fault population and fault lenses in the incompetent layers above the thick sand in Fault F4-3 (Fig. 7). This agrees with the published field-based studies (e.g., Loveless et al., 2011; Davies et al., 2012; Ferrill et al., 2014; Ferrill et al., 2017b; Nicol et al., 2017; Cawood and Bond, 2018).

7. Conclusions

The high-resolution, detailed, field observations reported from the Lenghu Thrust Belt allow the following conclusions on fault geometry:

1) A seismically resolvable thrust fault can exhibit multiple structural domains at the meso-scale and variable complexity related to the fault throw distribution and strain accommodation processes across the fault zone.

2) Fault throw distributions and linkages control the strain distribution across the thrust fault zone, although local folding process contribute important elements in Lenghu especially where more incompetent beds dominate the stratigraphy. The variation in bed thicknesses and mechanical property contrasts are likely to control the initial fault dips and fault/fracture density. Large fault throws are associated with wide strain accommodation and damage zones, but the relationship between the development and width of the fault zone with the throw accumulation cannot be assessed from the outcrops studied.

3) Mechanical heterogeneity, induced by different sediment stacking patterns, influences the fault architecture of the thrust fault zones studied (e.g., the location and generation of fault lenses, shear smearing, splay faults or fractures).

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Figure Captions

Figure 1. (a) Structural interpretation on SRTM elevation data of Qaidam basin and (b) geological map of the northern Qaidam basin (modified after Yin et al., 2008a; Pei et al., 2017a). The Qaidam basin is an oil-bearing sedimentary basin developed associated with the uplift of the Tibetan Plateau. A series of NW-SE-trending folds and faults are developed in the basin. The study area is located in the NW-SE-trending Lenghu fold-thrust belt in the northern Qaidam basin, where a northeast-directing Lenghu thrust fault accounts for the development of the hanging wall anticline.

Figure 2. Field-based stratigraphic logging of the study area (modified after Pei et al., 2017a; Pei et al., 2017b; Pei et al., 2018). The stratigraphy is dominated by middle Neogene sediments, comprising primarily siltstones and sandstones. The lower portion of the $N_{2\text{-}1}$ unit is silt-rich fine sandstones with high heterogeneity ($\mathbf{S_a}$). The middle portion of the $N_{2\text{-}1}$ unit is fine to medium sandstones with low heterogeneity ($\mathbf{S_b}$). The top portion of the $N_{2\text{-}1}$ unit contains medium to coarse sandstones with medium to high heterogeneity ($\mathbf{S_c}$). The $N_{2\text{-}2}$ unit is made up of coarse sandstones to conglomerates with medium heterogeneity ($\mathbf{S_d}$).

Figure 3. (a) Structural interpretation based on detailed field data integrating high-resolution landsat image (see position in Fig. 1b). The hanging wall anticline, Lenghu thrust fault zone and minor faults/folds in both the hanging wall and footwall are interpreted. (b) Enlarged map showing the sites of four representative outcrops (see position in Fig. 3a), i.e., F1 - F4, used to analyse the detailed fault architecture and its controlling parameters in the Lenghu thrust-fold belt. The strain distribution of the fault outcrops was evaluated based on field mapping.

Figure 4. Detailed outcrop sections of F1 (a), F2 (b) and F3 (c) showing the lateral structural variation in the fault zone architecture along strike of the Lenghu thrust fault zone (see position in Fig. 3b) (modified after Pei et al., 2018). The strain distribution of these three sections are estimated from field observations. The strain distribution across the fault zone illustrates a similar pattern between the three outcrops (see the estimated strain curves). The siltstones form vertical domains where they have been smeared into the fault zone from the hanging wall stratigraphy, while the sandstones are faulted and deformed by brittle deformation. The bedding within the central fault domains cannot be identified because of the intense deformation. The shearing into high strain fault zones generates silt smears and sand inclusions.

Figure 5. Detailed fault architecture of the outcrop F4 in the Lenghu thrust fault zone (see position in Fig. 3b): (a) field photo of the fault outcrop F4 and (b) its structural interpretation; (c) detailed mapping of F4 illustrating the structural domains with different levels of strain. Note 1: the scale is not even across the field photo because of the perspective, although an estimated approximate scale is provided. Note 2: the beds dipping in F4-5 looks steeper in the photograph than the real dip because of perspective views.

Figure 6. (a) Field photo and (b) detailed outcrop map of the high strain domain F4-4 in the F4 (see detailed position of F4-4 in outcrop F4 in Fig. 5). (c) The F4-4 fault zone stratigraphy with a competent : incompetent percentage ratio of 58% : 42%. (d) A stereogram of structural features showing the NW-striking thrust faults.

Figure 7. (a) Field photo and (b) detailed outcrop map of the medium strain domain F4-3 in the F4 (see detailed position of F4-3 in outcrop F4 in Fig. 5). (c) The F4-3 faul zone

stratigraphy with a competent : incompetent percentage ratio of 68% : 32%. (d) A stereogram of structural features showing the NE-directing thrust faults.

Figure 8. (a) Field photo and (b) detailed outcrop map of the low strain domain F4-2 in the F4 (see detailed position of F4-2 in outcrop F4 in Fig. 5). (c) The F4-2 fault zone stratigraphy with a competent : incompetent percentage ratio of 55% : 45%. (d) A stereogram of structural features showing the NE-directing thrust faults.

Figure 9. (a) Field photo and (b) detailed outcrop map of the low strain domain F4-1 in the F4 (see detailed position of F4-1 in outcrop F4 in Fig. 5). (c) The F4-1 fault zone stratigraphy with a competent : incompetent percentage ratio of 66% : 34%. (d) A stereogram of structural features showing the NE-directing thrust faults together with SW-directing back thrust faults (d).

Figure 10. (a) Field photo of the fault outcrop F4 and its structural interpretation; (b) estimated approximate throw and strain distribution cross the fault zone. Note 1: the scale is not even across the field photo because of perspective, although an estimated approximate scale is provided. Note 2: the beds dipping in F4-5 looks steeper in the photograph than the real dip because of the perspective views.

Figure 11. Models delineating the fault kinematics for incompetent beds and competent beds within the interbedded stratigraphy. The central figures demonstrate the kinematics from the initiation of deformation to a later stage with increasing fault throw ($a_0 \rightarrow a_1$). The top figures are details capturing the faulting kinematics of a competent layer sandwiched between two incompetent layers ($b_0 \rightarrow b_1$). The bottom figures are details capturing the

faulting kinematics of an incompetent layer sandwiched between two competent layers ($c_0 \rightarrow c_1$). When the mechanically layered sequence of beds is initially deformed, the fractures or small faults (i.e., $\mathbf{f_1}$, $\mathbf{f_2}$ and $\mathbf{f_3}$) are modelled to initially form in the competent beds **A**, **C** and **E** (e.g., sandstones in the Lenghu fold-thrust belt) whereas the incompetent beds **B** and **D** (e.g., siltstones in the Lenghu fold-thrust belt) are folded or sheared to accommodate the overall strain. As the fault zone throw increases, the fractures or small faults confined within the competent beds will grow until they eventually propagate into the incompetent beds (e.g., $\mathbf{f_2}$ within layer **C** in b_0 and b_1), forming smearing along the slip surfaces. A through-going fault will be formed when the propagating faults (e.g., $\mathbf{f_1}$ and $\mathbf{f_2}$ in c_0 and c_1) are linked together. The propagation of small faults from competent beds into the incompetent beds is well described by the trishear algorithm (Erslev, 1991). However, as the incompetent beds are sandwiched by the competent beds (c_1), there may be a divergent trishear zone developed (i.e., in front of the upper tip of $\mathbf{f_1}$ and lower tip of $\mathbf{f_2}$) within the incompetent beds (i.e., **A** and **C** layers) during strain propagation from both the upper and lower competent beds (i.e., **B** layers). See also the Quadshear model of Welch et al. (2009b).

Figure 12. A review of thrust fault zone elements: central through-going faults (TGFs) and damage zone (DZ). The central through-going faults accommodate a high percentage of the fault zone strain, while in the damage zone strain decreases away from the central fault zone (see the approximate strain distribution profile below the sketch). The majority of the fault throw is located in the most central position of the faulted section, and is often defined by two discrete slip surfaces that are sub-parallel to each other. The damage zone adjacent to the main slip, through-going faults are characterised by splay faults, fault bound lenses and folds, where the overall strain is lower than across the main slip surfaces.

Figure 13. Schematic models delineating the control of stratigraphy on fault architecture and strain distribution: (a) thick competent layer (competent layers 100%), (b) competent layers dominated sequence (competent : incompetent ratio = 90% : 10%), (c) incompetent layers dominated sequence (competent : incompetent ratio = 10% : 90%), and (d) thick incompetent layer (incompetent layers 100%). Stratigraphy dominated by competent layers normally forms a strain zone evolving from fractures, small faults to through-going faults, e.g., (a), whereas stratigraphy dominated by incompetent layers often experiences folding-dominated deformation in Lenghu, e.g., (d). See text for detailed discussion.

Figure 14. Links between schematic models and field observations. (a) Sequences dominated by competent layers: larger scale faulting deformation versus local folding deformation in thin **ICLs** (incompetent layers) (see also Fig. 13b). (b) Sequences dominated by incompetent layers: larger scale folding deformation versus local faulting deformation in thin **CLs** (competent layers) (see also Fig. 13c). (c) Portion of F4-3 (see also Fig. 7), illustrating an example of a thin siltstone layer, **B**, sandwiched between thick sandstone layers, **A** and **C**, that shows continuous smearing, although through-going faults are developed. This corresponds to the situation shown in (14a). (d) Portion of F4-1 (see also Fig. 9), illustrating an example of a thin sandstone layer, **I**, sandwiched between thick siltstone layers **H** and **J** (corresponding to (14b)), that shows descrete faulting in **I**, with the faulted sandstone forming an anticline geometry.

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