Detachment fold duplexes within gravity-driven fold and thrust systems

G.I. Alsop[1], R. Weinberger[2, 3], S. Marco[4], T. Levi[2].

1) Department of Geology and Geophysics, School of Geosciences,
University of Aberdeen, Aberdeen, UK. (e-mail: ian.alsop@abdn.ac.uk)
2) Geological survey of Israel, Jerusalem, Israel.
3) Department of Geological and Environmental Sciences, Ben Gurion University of the Negev, Beer Sheva, Israel.
4) Department of Geosciences, Tel Aviv University, Israel.

Abstract

Fold duplexes transfer displacement from a lower to an upper bounding detachment system via trains of folds with broadly parallel geometries. While they have been previously recognised in orogenic systems where they are considered to be kinematically equivalent to imbricating thrust ramps, we here describe the first example from a gravity-driven fold and thrust system (FATS) developed within late-Pleistocene mass transport deposits (MTDs) that formed around the Dead Sea Basin. The recognition in this study of basal and upper detachments that bound the FATS, together with later thrust ramps that imbricate the previously folded sequence, indicates that a fold duplex model is applicable in this case. Truncation of synclinal hinges, together with trapping of duplex roof stratigraphy in synclinal fold cores indicates that initiation of buckling precedes detachments, which then propagated along the upper and lower boundaries of the FATS to create a fold duplex. Downslope-verging folds, which are bound by the detachments, are subsequently cut by thrust ramps with greatest displacement recorded where ramps branch from the basal detachment. As thrust displacement increases then ramp angles generally reduce, which allows thrusts to continue to move and accrue larger displacements. Sequential flattening of lower thrusts in overstep sequences may create apparent ‘back-steepening’ up the slope in what superficially resembles ‘pseudo-piggyback’ sequences. Flattening of thrusts is achieved through tightening, rotation and expulsion of wet sediment and fluid from the cores of footwall synclines and is a consequence of loading from overlying thrust sheets. We speculate that expelled fluids may pond directly beneath overlying detrital-rich units that act as baffles and locally increase fluid pressures thereby facilitating further movement along the upper detachment. We establish a new model, whereby the vergence of structures formed above the upper detachment depends on the relative rates of roof and FATS translation, with slower downslope translation of the roof generating upslope verging folds in a ‘sub-active’ roof, while more rapid movement of a ‘super-active’ roof creates downslope verging folds. The observation that such patterns of minor fold vergence in the roof still largely correspond with the position of folds and thrusts in the underlying FATS indicates that only limited relative translation subsequently occurred between the roof and the FATS. This suggests that displacement must have transferred upwards to new upper detachments shortly after the folds in the roof were created, thereby ‘fixing’ the spatial correlation. As older detachments are folded and ‘lock up’, displacement migrates to new upper detachments that develop along pristine ‘easy-slip’ laminations at higher stratigraphic levels, thereby thickening the deforming FATS towards the sediment free surface. The creation of these new upper detachments at higher stratigraphic levels, together with the development of local overstep imbricate sequences are the principal differences between fold duplexes observed in orogenic settings and those in surficial gravity-driven FATS.

Keywords: fold duplex; fold and thrust system; mass transport deposit; soft sediment deformation; Dead Sea Basin

1) Introduction

Detachment folds are a common form of fault-related folding that develop in both orogenic and gravity-driven settings (see recent reviews by Morley et al., 2017 and Butler et al., 2020). They are commonly defined as 'folds developed above a detachment or thrust that is bedding parallel' (McClay, 1992 p.428) where beds above the detachment shorten more than those beneath it (e.g. Fossen, 2016, p.367). Detachment folds are frequently overlooked in offshore fold and thrust systems (FATS) that form part of the downslope movement of largely unlithified sediment to create gravity-driven mass transport deposits (MTDs) (but see Moscardelli and Wood, 2008; Posamentier and Martinsen, 2011; Armandita et al., 2015; Scarselli et al., 2016; Jolly et al., 2016; Morley et al., 2017 for general reviews). Many seismic-based analyses of offshore FATS are governed by a thrust-dominated approach in which nearly all layer shortening is assumed to be accommodated by thrusts, although there is an increasingly recognition that layer-parallel compaction (e.g. Butler and Paton 2010; de Vera et al., 2010; Dalton et al., 2015, Morley and Naghadeh, 2018) and folding may also play a role in such settings (e.g. see discussion in Steventon et al., 2019). This debate is partially a consequence of seismic sections across offshore MTDs revealing much about the large-scale structure of the resulting FATS, while the seismic resolution prohibits detailed analysis of smaller scale (<10 m, see Pei et al. 2019) but potentially important structures and processes observed at outcrop (e.g. Woodcock, 1976a, b, 1979; Gibert et al., 2005; Garcia-Tortosa et al., 2011; Sharman et al., 2015; Korneva et al., 2016; Sobiesiak et al., 2017). It is timely to consider the potential that detachment folds offer in terms of largely seismically 'invisible' structures that will influence the mechanisms of emplacement of FATS. We first outline models of detachment fold trains that create 'fold duplexes' bound above and below by bedding-parallel detachments, before considering the range of kinematic scenarios that may form around FATS in well exposed MTDs developed in the Dead Sea Basin.

1.1. Fold Duplexes

Duplexes are recently described as 'closely-spaced imbricate faults sandwiched between lower and upper enveloping thrusts' (Boyer and Mitra, 2019, p.202). The usage of the term derives from previous works (e.g. Elliot and Johnson, 1980; Boyer and Elliot, 1982; see McClay 1992), which are themselves built on much earlier observations of such structures in orogenic belts (e.g. Willis, 1902; Peach et al., 1907). Gently-curving imbricate faults within duplexes transfer displacement from the lower (basal) detachment to the upper detachment, while the underlying and overlying stratigraphy remains largely undeformed (see recent review in Mitra and Boyer, 2020). Displacement along individual imbricate faults is relatively minor compared to the bounding detachments that maintain a largely bedding-parallel attitude. A fold duplex fulfils the same kinematic role as the fault/thrust ramp in the duplex described above, but in this case transfers displacement from a lower detachment to an upper detachment via a train of detachment folds with parallel geometry (Boyer and Mitra, 2019, p.203; Mitra and Boyer, 2020, p.6; see also Fossen, 2016, p.367, his fig 17.21b) (Fig. 1a). As folds absorb shortening on the underlying detachment resulting in a decrease in its displacement, the overlying upper detachment is considered to undergo a concomitant increase in displacement (Mitra and Boyer, 2020). Although 'floor' and 'roof' thrusts are used to describe such detachments in orogenic systems (e.g. Boyer and Elliot, 1982; Butler, 1987, p.620; Geiser, 1988; Butler, 2004), we prefer 'basal detachment(s)' and 'upper detachment(s)' in the case of MTDs and gravity-driven FATS, as numerous detachments develop, and such bounding fault systems are repeated for each separate MTD in a sequence (Fig. 1a).

Fold duplexes are considered to initiate as parallel folds grow and undergo tightening above, and in front of, the basal detachment (e.g. Dahlstrom, 1969, 1990; Mitra and Boyer, 2020). The fold wavelength (λ) in multi-layer sequences is controlled by the dominant thick competent layer, while fold amplitude (A) reflects the amount of shortening (Biot 1961; Fossen, 2016; Mitra and Boyer, 2020) (Fig. 1a). As beds undergo shortening that results in buckle folding, anticlines 'lift-off' the basal detachment and form vertical isoclinal folds, while material is squeezed out of synclinal hinges to accommodate the shortening (Boyer and Mitra, 2019, p.203). As shortening progresses, late stage imbricate faults cut across folds and connect the basal and upper detachments (Mitra and Boyer, 2020, their fig. 7) (Fig. 1a).

Models presented by Boyer and Mitra, (2019, p.204) assume a stratigraphically fixed basal detachment, while the geometric constraints of their kink fold model requires that the active upper detachment maintains the same 'structural elevation' above the basal detachment Boyer and Mitra, (2019, their fig. 2). As shortening and thickening of the fold duplex proceeds via increased amplitude of folding noted above, then the upper detachment must therefore progressively migrate to lower stratigraphic levels in order to maintain the same structural elevation. The consequence of this is that multiple upper detachments may be preserved in the deformed section that reflect progressive tightening of folds and switching of the upper detachment to lower stratigraphic levels (Boyer and Mitra, 2019).

1.2. Kinematic models of bounding detachment systems

Basal detachments, that form along the floor of each gravity-driven FATS and MTDs in general, have received a significant amount of attention in the literature (e.g. see Sobiesiak et al., 2018, 2020 for reviews). While the bases of some MTDs are marked by erosive contacts (e.g. Prior et al. 1984; Bull et al., 2009; Posamentier and Martinsen, 2011; Jablonska et al., 2018), we focus our attention here on those MTDs where the base comprises a distinct detachment or shear surface that forms a floor to the FATS. Basal detachments may maintain broadly the same stratigraphic level, meaning that the leading downslope toes of MTDs remain frontally confined (Frey-Martinez et al., 2006). Alternatively, they may ramp upwards to the surface meaning that the toe of the MTD becomes frontally emergent and may translate for significant distances downslope (Frey-Martinez et al., 2006). The kinematics of basal detachments within gravity-driven FATS are controlled by downslope shearing, where the hangingwall translates downslope relative to the unmoved floor beneath the detachment (Fig. 1a).

The top contact of duplexes are marked by upper detachments (or roof thrusts) which separate the deformed sequence below from the less deformed roof above (e.g. Dahlstrom, 1969; Geiser, 1988; Morley and Jitmahantakul, 2020). Roofs may be considered passive where they remain unmoved (Fig. 1b), and active where they undergo translation (Fig. 1c, d) (e.g. Boyer and Mitra, 2019 and references therein).Within gravity-driven systems, any sediments overlying the main FATS are also liable to have been carried downslope to some extent, and so truly 'passive' roofs are less likely to exist (Fig. 1b). Sediments above the upper detachment may display a relative downslope velocity compared with those in the footwall and are therefore considered 'active' (Fig. 1c, d). There are two potential relative velocity scenarios; the hangingwall (roof) to the upper detachment may move more slowly downslope (sub-active, Fig. 1c), or more rapidly downslope (super-active, Fig. 1d), compared to the underlying FATS. Such variations in relative translation of the roof are transient and will also fluctuate spatially depending on a range of influences including fluid pressure (see Butler, 2004 for a general review of orogenic roof geometries). Within MTDs, local areas of 'surging' flow may move downslope more rapidly than those above the upper detachment (e.g. Alsop and Holdsworth, 2007; Alsop and Marco, 2014). This create a shear couple marked by folds immediately above the detachment that verge back upslope (Fig. 1b, c). Alternatively, where MTD velocity has reduced to create 'slackening flow' relative to sediments above the upper detachment, then folds will verge downslope (Fig. 1d).

This research aims to apply the fold duplex models described above to gravity-driven FATS that form within MTDs around the Dead Sea Basin. Previous studies in this area by Alsop and Marco (2012) have suggested that some structures in MTDs are created by the effects of shear against the overlying water column and this hypothesis will be critically assessed. We will also consider the following more general research questions.

1) What deformation sequences develop within gravity-driven FATS?
2) How do FATS evolve during downslope shearing?
3) What factors influence detachments in FATS?
4) Is deformation created by shear along an upper detachment or by moving water?
5) Are fold duplex models applicable to gravity-driven FATS?
6) How do gravity-driven fold duplexes compare to those in orogenic settings?

2. Regional setting

2.1. Regional geology

The Dead Sea Fault system (DSF) is defined by two major, left-stepping, sinistral fault strands, that generate numerous earthquakes and bound the pull-apart Dead Sea Basin (Fig. 2a, b) (e.g. Marco et al. 1996, 2003; Ken-Tor et al. 2001; Migowski et al. 2004; Begin et al. 2005; Levi et al., 2006a, b). The DSF is considered to have been active from the early Miocene to recent, (Bartov et al., 1980; Garfunkel, 1981; Nuriel et al., 2017), including during 70-14 ka when the late Pleistocene Lisan Formation was deposited in Lake Lisan, which was a pre-cursor to the present Dead Sea (e.g. Haase-Schramm et al. 2004). Within Lake Lisan, increased evaporation of hypersaline waters in the summer months resulted in precipitation of mm-scale aragonite laminae, while detrital-rich layers were washed into the lake during flood events more frequent in the wet winter period (Begin et al. 1974; Ben-Dor et al. 2019). The Lisan Formation was deposited at an average rate of ~1 mm per year, based on counting of annual aragonite-detrital varves noted above, and supported by isotopic dating (Prasad et al., 2009). The detrital input comprises quartz and calcite grains with minor feldspar, and clays (illite-smectite) (Haliva-Cohen et al., 2012). Detrital laminae developed on a mm-scale comprise grain sizes of ~8-10 µm (silt), whereas thicker (> 10 cm) detrital-rich beds are typically very fine (60 – 70 µm) sands (Haliva-Cohen et al., 2012). The Lisan Formation presently exposed around the Dead Sea was deposited in water depths of <100 m, apart from a short period from 26-24 ka when water reached a maximum depth of 200 m (Bartov et al. 2002; 2003).

2.2. Regional patterns of MTD movement

The Lisan Formation is exposed for ~100 km along the western margin of the Dead Sea Basin and contains numerous MTDs thought to be triggered by earthquakes along the bounding Western and Eastern Border fault zones (Fig. 2b) (e.g. Marco et al., 1996; Agnon et al., 2006; Alsop et al., 2016a, 2018a; Lu et al., 2017; Levi et al., 2018). The MTDs, which may be up to 3 m thick, are bound above and below by very gently dipping (<1°) beds that remain apparently undeformed (e.g. Marco et al., 1996; Agnon et al., 2006). FATS are locally eroded by overlying beds, resulting in the deposition of a sedimentary cap, which demonstrates that MTDs formed at the sediment surface (e.g. Alsop and Marco, 2012; Alsop et al., 2016a; 2019). The MTDs and intervening undeformed sedimentary packages are subsequently cut across by clastic dykes generated during later earthquakes (e.g. Levi et al., 2006a, 2006b; Weinberger et al., 2016).

The FATS within MTDs define a regional pattern of radial slumping directed towards the depo-centre of the basin (Alsop et al. 2016a; 2020a) (Fig. 2b). In the northern parts of the basin MTDs move towards the east, in the central area around Masada movement is towards the ENE, whereas MTDs are NE-directed at Peratzim in the southern portion of the basin (Alsop et al. 2016a) (Fig. 2b, c). The overall radial pattern of MTD movement is completed by westerly-directed slumping reported from Jordan along the eastern shore of the Dead Sea (El-Isa and Mustafa, 1986). Analysis of drill cores from the centre of the basin reveal numerous MTDs with the stratigraphic thickness of the Lisan Formation being three times greater than its equivalent currently exposed onshore (Lu et al., 2017; Kagan et al., 2018). This is considered a consequence of the radial input of MTDs from around the basin margins, which collectively combine to create increased sediment accumulation in the depo-centre (Lu et al., 2017; Kagan et al., 2018). In the extreme southern part of the basin, MTDs are directed towards the south and are thought to be influenced by the transverse Amazyahu Fault (Weinberger et al. 2017; Alsop et al., 2018a; 2020a) (Fig. 2b). Directions of MTD movement established from structural analysis have been subsequently supported by analysis of Anisotropy of Magnetic Susceptibility (AMS) fabrics (Weinberger et al., 2017; Alsop et al., 2020b).

2.3. Rationale of the case study area

The Lisan Formation outcropping around the Dead Sea Basin is ideally suited to the detailed study of FATS developed in MTDs as the general palaeo-geographic setting that controls the gravity-driven deformation is well understood. Moreover, the intricate varve stratigraphy developed on a mm scale captures a host of structural detail that may otherwise be lost in more crudely stratified systems (Fig. 2b, c) (see Alsop et al., 2020a). The present study focusses on FATS developed in MTD horizons that are exposed in outcrops around Peratzim [N31°:0449.6 E35°:2104.2] located on the Amia'z Plain in the southern Dead Sea area (Fig. 2b, c, d). The study area is bound ~2 km to the east by the actively rising Sedom salt wall that penetrates and locally deforms the Lisan Formation (e.g. Alsop et al., 2016b, 2018b; Zucker et al., 2019) (Fig. 2c, d). To the west of the study area, the Lisan Formation is juxtaposed with Cenomanian-Senonian carbonates outcropping in the footwall of the Dead Sea Western Border Fault Zone (Fig. 2c, d).

Exposures of Lisan Formation in the study area are formed on the steep walls of deeply incised wadis that cut down into the Ami'az Plain (Fig. 2e, f). The drainage network is a consequence of Holocene and recent flash floods that periodically erode intricate channels that reveal a stacked system of MTDs within the underlying Lisan Formation. Although six individual MTDs have been recognised in the Peratzim area, we here focus our attention on one single event (slump 4 in the scheme of Alsop et al., 2016a). The rationale for examining the FATS that form in this particular slump or MTD 'event' is based on the observation that erosive surfaces and overlying sedimentary cap that was deposited following slope failure do not cut down into the underlying FATS (Fig. 3a-d, see section 3 below and Alsop et al., 2019 for a review). Any prospective upper detachment that potentially forms above the FATS is still therefore largely preserved, whereas in other MTDs, the erosive surface may have removed details of detachments that previously existed (e.g. see Mitra and Boyer, 2020, p.5). Focussing on one particular MTD also has the advantage that the stratigraphy in the lacustrine setting is broadly 'layer-cake' and can be correlated at each site. The position of detachments can then also be matched and examined allowing broader implications about various controls to be drawn. In addition, the case study MTD has affected a heterogeneous sequence of distinct aragonite-rich and detrital-rich laminae. These bi-laminates allow the relative strengths of individual layers to be readily assessed and to some extent simplify the controls on the resulting structures (see Alsop et al., 2020c). The exceptionally coherent and well-preserved nature of structures within the MTDs may reflect relatively modest transport distances (the studied MTDs are only 1km east of the basin bounding faults), combined with negligible (<1°) slopes and the simplified bi-laminate stratigraphy that was water-saturated during deformation (for further discussion of influences on MTD development see Alsop and Marco, 2011, p.438-440).

3. General analysis of folding and thrusting

We have undertaken structural analysis in cuttings along wadi walls that are developed at high angles to fold hinges, thereby providing transport-parallel (or hinge-normal profile) sections (e.g. Alsop et al., 2017a). Structures within the FATS may be broadly correlated across opposite walls of the wadis, indicating that transport-normal expulsion and along strike 3-D variability is not a significant factor in this case (see Alsop and Weinberger, 2020 for a review). Although some differences exist, fold hinges typically trend NW-SE and verge towards the NE and the depocentre of the basin (Alsop and Marco, 2012; Alsop et al., 2016a; 2019) (Figs 2b, 3a-k, 4a-d). Within the analysed FATS, fold axial planes dip variably towards the SW, while downslope-verging forethrusts also dip variably towards the SW at shallower angles (Figs 3a-k, 4a-d) (Alsop et al., 2017a). We have also separately analysed a prominent thin detrital marker bed that is developed towards the upper part of the FATS and is highlighted in dark blue in Figs 3a-h. This marker bed displays distinctly different patterns of fold vergence, together with shorter fold wavelengths (typically <30 cm) that are largely unrelated to the underlying structures (Figs 3a-h, 4a, b). The orientation of the folds in this abnormal marker layer are shown in Fig. 4d with NW-SE trending fold hinges and mean NE-dipping axial planes marginally (~10°) clockwise of the underlying NE-verging folds. Details of this particular marker bed were also the focus of attention by Alsop and Marco (2012). The deformed FATS and blue marker bed are overlain by a thin (<15 cm) sedimentary cap with an erosive base (highlighted in orange in Fig. 3a-d) that was deposited out of suspension following slope failure (see Alsop and Marco, 2012; Alsop et al., 2016a).

3.1. Analysis of fold geometries

Previous work in the study area has shown that it is the heterogeneity of aragonite- and detrital- rich layered sediments that controls structural style (Alsop et al., 2016a). Thus, heterogeneous sediments develop buckle folding, while adjacent homogenous (aragonite-rich) sequences that are weaker are dominated by thrusting and fault-propagation folding (Alsop et al., 2017a). In order to ascertain the relative competency of aragonite-rich and detrital marker beds during deformation, Alsop et al. (2020c) undertook investigation of folds using dip-isogon analysis (Ramsay, 1967). The dip-isogon method is a well-established technique of fold classification where dip isogons join points of equal dip on adjacent folded surfaces within the fold profile (e.g. Ramsay, 1967, p.363) (Fig. 4e). Class 1 folds are marked by convergent dip isogons, Class 2 folds by parallel dip isogons, and Class 3 folds by diverging dip isogons (e.g. Ramsay, 1967, p.365; see Fossen, 2016, p.263).

In the present study, we use the dip-isogon method to analyse and compare fold geometries formed in the detrital-rich (brown) marker bed (Fig. 3,4e). Our analysis includes data from both the SW (backlimb) and NE (forelimb) of folds and shows that the brown marker bed displays a strongly convergent isogon pattern representing Class 1C or 1B parallel folds consistent with buckling (Fig. 4e, h). This is in accord with previous studies (e.g. Alsop et al., 2020c) that also note the aragonite-rich units display a sub-parallel or parallel isogon pattern most consistent with Class 1C or Class 2 similar folding (Ramsay, 1967; Fossen, 2016, p.263). Analysis of fold classes on each limb of anticlines A and B reveals that the steep common limbs on each side of the intervening syncline maintain thickness (Class 1B) or may even become slightly thicker (Class 1A) (Fig. 4e, h). Upright antiformal hinges that are locally thinned compared to limbs has been attributed to particulate flow away from antiformal crests into synformal troughs, combined with a component of later vertical flattening created by subsequent loading from overlying MTDs (Alsop et al., 2020c).

In summary, these relationships indicate that detrital-rich layers were locally more competent and deformed by buckle folding, whereas aragonite-rich units appear weaker and accommodate deformation by greater internal flow resulting in more pronounced thickening and thinning of beds around folds.

3.2. Estimates of % shortening

Having established that detrital layers are more competent, and at least initially deform by buckle folding to create Class 1B parallel folds, we now estimate the amount of shortening along prominent detrital marker beds in the FATS. The % shortening accommodated by folds and thrusts was calculated by measuring line lengths for each colour-coded marker up through the FATS (e.g. Figs 3a-h, 4a, b). We emphasise that this estimate of shortening is a crude approximation as it does not take into account any potential lateral compaction, out of plane movement and later modification of buckle fold geometries (see Butler and Paton, 2010 and Alsop et al., 2017a). For instance, previous studies have shown that lateral compaction may increase by 10% towards the sediment surface where greater original porosity existed (Alsop et al., 2017a). However, these estimates of shortening do show distinct and repeated patterns with shortening reducing up through the FATS from ~50% above the basal detachment, to ~35% along the upper (light blue) marker, to a pronounced reduction (12%) in the uppermost blue marker bed (Fig. 3a-h) (Table 1). In addition, when the relative components of % shortening by folding and thrusting are investigated for the section shown in Fig. 3, it is found that the proportion of shortening taken up by folding increases up through the sequence (Table 2). Although estimates of shortening are admittedly crude and sections are of different lengths, there is a broad reduction in shortening for each marker layer as they are traced from each adjacent section towards the SW i.e. greatest shortening tends to develop towards the NE (i.e. slump toe) when comparing Figs 3 and 11 (Table 1).

4. Relative timing of fold and thrust sequences

As is frequently observed in lithified rocks from orogenic belts, thrusts and folds may display a range of relative timing relationships, with thrusts either pre-dating (and being folded) or post-dating (and cutting) adjacent folds. In addition, thrusting and folding may be synchronous, with propagation of thrusts leading to fault-propagation folds (e.g. see Fossen, 2016, p.365 or Butler et al., 2020 for reviews). Overall systems of thrusts may in general display either piggyback, overstep or synchronous timing patterns that are discussed below (see Fossen, 2016 or Alsop et al., 2018a for a review).

4.1. Timing of folds and thrusts

Within the case study, there are numerous observations that support thrusts post-dating folds that are preserved in their footwalls. Firstly, thrusts are not folded by underlying anticlines or synclines and maintain a planar geometry where they cut across such folds (e.g. Fig. 4a, b, c). Secondly, thrusts cut directly across steepened aragonite-rich bedding on the limbs of underlying upright folds and are not affected by such folds (e.g. Fig. 5c). Models of fault-propagation folds, where folds form as a consequence of variable displacement along thrusts (e.g. Fossen, 2016, p.365), may also be discounted as many folds in the case study are not associated with thrust ramps (e.g. Fig. 3a-h). Where thrust ramps are present, then they rotate upright folds in their hangingwalls rather than 'tipping-out' directly into these folds (Fig. 4a, b). Thus, although thrusts may locally modify and rotate the forelimbs of folds, we suggest that buckle folds typically pre-dated the thrusts. Having established the relative order of folds and thrusts, we now examine the sequencing of late thrusts themselves.

4.2. Piggyback thrusting

In piggyback thrusting, new thrusts develop in the footwall of existing thrusts, potentially resulting in a back-steepening and rotation of the older thrust, and an overall forward propagating system of thrusts (e.g. Dahlstrom, 1970, p.349; Butler, 1982, p.240). Examples of piggyback sequences are locally observed in heterogeneous sediments with sequentially back-rotated thrusts in the upslope direction (e.g. Figs 3c, d, 4a, b, g). Some thrusts are ultimately back-rotated through the vertical so that hangingwall sequences become inverted (e.g. Fig. 3d, 5a).

4.3. Overstep thrusting

In overstep sequence thrusts, new thrusts form in the hangingwall of existing thrusts, resulting in a backward propagating system of thrusts. (i.e. in the opposite direction to thrust transport) (e.g. Elliot and Johnson, 1980, p.90; Boyer and Elliot, 1982, p.1209). In addition, new thrusts may cut through existing thrusts in their footwall, resulting in re-imbrication of the sequence. Systems of overstep thrusting have been suggested to form elsewhere in the Lisan Formation (Alsop et al., 2018a). Evidence for overstep thrusting includes younger overlying thrusts cutting hangingwall anticlines created by underlying (older) thrusts (e.g. Figs 4a, b, c, 5e). Some thrusts cut across axial planes of the adjacent upright anticline (e.g. Fig. 5c), while others cut across the axial plane of the underlying steeper footwall syncline (e.g. Fig. 5d, e), suggesting overstep thrusting.

4.4. Synchronous thrusting

During synchronous thrusting, thrusts which initiate first continue to move as new thrusts move, and therefore accrue the greatest displacements (e.g. Morley, 1988; Boyer, 1992; Butler, 2004). Using sandbox models, Koyi et al. (2000) have shown that such patterns may relate to the nature of the underlying detachment, with several thrusts being simultaneously active above low-friction detachments, whereas above high-friction detachments only one structure is active at a time. Continued movement after thrusts have been over-steepened in piggyback sequences may result in new gently dipping downslope verging 'short-cut' thrusts developing which cut through the already steepened thrust sequence (Figs 4a, b, c, 5d). Where synchronous thrusting operates in tandem with thrust sequences, then this may lead to displacement systematically increasing towards either the foreland or hinterland in orogenic settings (e.g. Boyer, 1992), or in an upslope or downslope direction the case of MTDs. Although this has been recorded from MTDs elsewhere in the Lisan Formation (Alsop et al., 2018a), estimates of % contraction along sections (Fig. 3) remain similar, suggesting that it may not be significant in the present study (Fig. 3). We now analyse cumulative displacement-distance plots from along the section that enable overall displacement gradients to be evaluated and may therefore allow synchronous thrusting to be identified.

5. Analysis of displacement-distance in FATS

5.1. Cumulative displacement-distance plot

Chapman and Williams (1984) originally developed cumulative displacement-distance (C D-D) plots to measure thrust displacement in orogenic settings. Shortening is accommodated in a linked fault system formed above a floor thrust (basal detachment) with a fixed reference point (R) established where the leading imbricate branches and ramps up from the basal detachment (Chapman and Williams, 1984, p.124). The distance from R is then measured to where each individual ramp branches from the basal detachment, and these distances successively combined to create the cumulative distance on the horizontal axis of the plot (Fig. 3h, 3l). Displacement of a chosen marker bed is then measured across each thrust ramp, starting with the first, and then progressively combined with each successive ramp to form a measurement of cumulative displacement on the vertical axis of the plot (Fig. 3l).

In the case study, we measured displacement of the lowermost green detrital marker bed starting from the NE end of the section (Fig. 3h, 3l). We specifically chose this horizon as offset of marker beds close to the basal detachment should approximate to the maximum displacement on each imbricate fault (Chapman and Williams, 1984, p.124). The C D-D plot displays a remarkably linear profile (R^2=0.995) and constant gradient, suggesting that displacement and distance are proportional and representative of constant rates of slip along the exposed 25 m section of basal detachment (Fig. 3l). This result indicates that no significant variation in thrust displacement occurs along the section and therefore does not support models of synchronous thrusting, where C D-D plots display steepened displacement profiles across the older thrusts where movement has continued to accumulate (e.g. Alsop et al., 2018, p.103). However, given the 25m section length, we are unable to ascertain whether this linear C D-D profile is representative of the entire MTD, or if variations may occur elsewhere as recorded in other adjacent thrust sequences (e.g. Alsop, 2017a). We note that unlike the original Chapman and Williams (1984) analysis, that the thrust ramps in the case study form relatively late-stage structures that cut across pre-existing buckle folds. Hence, the spacing and potential timing of ramps is to some extent controlled by these earlier folds. A further difference with the original Chapman and Williams (1984) model is that the section displays evidence for both localised piggyback and overstep thrust sequences (see section 4 above). Following analysis of FATS elsewhere in the Lisan Formation and many MTDs in general (Alsop et al., 2018a), we have simplified this to a bulk overstep sequence, meaning that the distance measured from 'R' to the branching point of each new thrust ramp remains unaltered by later thrusts as these develop upslope and above existing thrusts. Despite these issues and simplifications, the C D-D plot displays a constant gradient suggesting constant rates of slip along the basal detachment exposed along the 25 m section, although it is possible that displacement variations may develop elsewhere along the basal detachment.

5.2. Displacement-distance plots

Displacement-distance plots record the distance along the hangingwall of a thrust from a fixed reference point ('R' near the fault tip) to a marker horizon, and compare this distance with the displacement of that marker across the thrust (e.g. Muraoka and Kamata, 1983; Williams and Chapman, 1983; Chapman and Williams, 1984; see review by Hughes and Shaw, 2014) (Figs 1a, 5a). The measurements are then repeated for different marker beds along the length of the fault to create a displacement-distance (D-D) plot for that individual fault. D-D plots with steeper gradients are generally thought to represent slower propagation of the thrust tip relative to slip in weaker units, whereas gentle slopes on D-D plots signify more rapid propagation of the thrust tip relative to slip in more competent units (e.g. Williams and Chapman, 1983; Ferrill et al., 2016). Because displacement on faults is generally considered to be time-dependent, then older portions of faults are thought to accumulate the greatest displacement (e.g. Ellis and Dunlap, 1988; Hedlund, 1997; Kim and Sanderson, 2005). The nucleation site of a fault is therefore considered to coincide with the point of maximum displacement on a D-D plot (e.g. Ellis and Dunlap, 1988; Peacock and Sanderson, 1996; Hedlund, 1997; Ferrill et al., 2016).

A number of general patterns emerge when examining D-D plots of thrusts cutting buckle folds in the case study. D-D plots may display relatively straight (Fig. 5a) or irregular curves (Fig. 5b-e). Thrusts with greater overall displacement generally have smoother more linear D-D plots, compared to neighbouring thrusts with smaller displacement that cut the same stratigraphy (compare neighbouring thrusts shown in Fig. 5a, e). Where significant steps in D-D plots exist, they typically coincide with where thrusts cut thicker detrital marker beds (brown marker bed in Fig. 5a, c, e). The gentle gradients around thick detrital beds suggest more rapid propagation of the thrust tip relative to slip in these more competent units (e.g. Williams and Chapman, 1983).

All D-D curves show the greatest displacement towards the basal detachment, with displacement progressively diminishing upwards along each thrust ramp (Fig. 5a-e). Displacement reducing upwards suggest thrusts propagated from the underlying basal detachment that must have already existed as detachment folds were 'riding' on it and later thrusts then cut these detachment folds. We also note that greater displacement along thrust ramps generally correlates with greater angular differences in mean hinge trends of associated footwall synclines and hangingwall anticlines as shown in stereonets (Fig. 5a-e). We now examine these fold patterns in more detail.

6. Geometric analysis of folds

In this study, we specifically analyse relationships between folds that form downslope verging fold pairs to ascertain how progressive deformation affects fold geometries. Fold pairs may form hangingwall anticlines and footwall synclines to NE-verging fore-thrusts that cut the common (short) limbs between folds (Alsop et al., 2017a). We have undertaken this detailed and systematic analysis of fold orientations and geometries exposed along the section shown in Fig. 3a, b. Fold hinges are sub-horizontal, trend NW-SE and typically verge towards the NE (Fig. 3i-k). Associated axial planes strike NW-SE and dip gently to moderately towards the SW (Fig. 3i-k). In some cases, folds are cut by NW-SE striking thrust ramps that dip gently towards the SW and imbricate the sequence (Fig. 3a-k,). We now analyse geometric relationships of hangingwall anticlines and footwall synclines formed in the 25 m long transport-parallel section.

6.1. Orientation of footwall synclines and hangingwall anticlines

We use the same (brown) stratigraphic horizon to analyse the orientation of footwall synclines and hangingwall anticlines on either side of the late imbricating thrust ramps that cut folds in the section (Fig. 3). When examining fold pairs, we find that:

a) the mean trend of footwall syncline fold hinges (323°) is 11° clockwise of the adjacent hangingwall anticline trend (312°) (Figs 3k, 5a-e, 6a, b);

b) the mean trend (strike) of footwall syncline axial planes (315°) is 14° anticlockwise of the associated hangingwall anticline axial plane (329°) (Figs 3k, 6a, b);

c) the mean trend (strike) of footwall syncline axial plane (315°) is closer to the trend of the thrust (311°) when compared to the axial planes of hangingwall anticlines (329°) (Figs 3k, 6c) and;

d) the trend of footwall syncline fold hinges displays a progressively greater clockwise obliquity to the trend of adjacent hangingwall anticlines towards the NE end of the section (Fig. 5a-e located on Fig. 3a-h).

It is notable that these same geometric relationships are measured across individual fold pairs cut by thrusts (e.g. Fig. 5a-e), shorter segments of the section (e.g. Fig. 4d), and the complete section (Figs 3k, 6a-c). This indicates that the observed patterns are a consistent and reliable consequence of deformation during gravity-driven downslope shear.

6.2. Interlimb angles of footwall synclines and hangingwall anticlines

Interlimb angles of folds were measured around the thick brown detrital marker horizon (see Figs 1a, 3a-h). The interlimb angles of folds were compared with the dip of associated axial planes for all folds (Fig. 6d) and for folds specifically associated with thrusts (Fig. 6e). Folds cut by thrusts generally display smaller interlimb angles and more gently-dipping axial planes (Fig. 6e). For a given value of axial planar dip, anticlines generally have more open interlimb angles compared to synclines (Fig 6d, e). As the dip of the axial plane reduces then interlimb angles also decrease.

Hangingwall anticlines positioned above thrusts may display interlimb angles of up to 96°, while the associated axial plane dips at 23° (Fig 6d, e). As the fold tightens and the interlimb angle reduces to 30°, then the axial plane becomes very gently dipping at 10°. (Fig 6d, e). Footwall synclines positioned below thrusts display interlimb angles of up to 30°, with axial planes dipping at 26° (Fig 6d, e). Synclines interlimb angles may reduce to 8°, with associated axial planes dipping at angles of between 14° and 33° Fig 6d, e). Thus, hangingwall anticlines with steeper axial planes have more open interlimb angles (Fig. 6d, e). Despite having upright axial planes, some synclines have very low interlimb angles (e.g. Figs 4e, f, 6d). Where synclines and anticlines have similar trends to one another, then the synclines consistently display tighter interlimb angles (Fig. 6f).

Interlimb angles of the brown marker bed that defines hangingwall anticlines positioned directly above thrusts are up to 78°, while the associated footwall syncline has an interlimb angle of just 8° (Fig. 6g). Where the interlimb angle of the footwall syncline has increased to 30°, then the interlimb angle of the associated hangingwall anticline has reduced to 30 - 40° (Fig. 6g). Thus, interlimb angles of footwall synclines are always less than that of adjacent hangingwall anticlines affecting the same stratigraphic level, with more open anticlines linked to tighter synclines (Fig. 6g).

6.3. Angles of thrust ramps separating footwall synclines and hangingwall anticlines

Fore thrust ramps display variable angles of dip relative to the basal detachment (Fig. 1a) which range between 5° and 45° and are generally between 20° and 35° (Figs 5a-e, 6h, i). There is no specific correlation between the dip of thrust ramps and the interlimb angles of associated hangingwall anticlines and footwall synclines (Fig. 6h). However, steeper ramp angles are associated with less displacement of the lowermost green marker bed (Figs 3, 6i). This relationship between displacement and dip of ramps is similar to that reported by Alsop et al. (2017a, b) for forethrusts and backthrusts in other thrust-dominated MTDs and attributed to thrusts accruing displacement as they are rotated.

6.4. Thinning and thickening of fold limbs cut by thrusts

The geometry of folds may be analysed by examining the relative thinning (-ve%) or thickening (+ve%) of the shorter fold forelimb compared to the longer backlimb (e.g. Jamison, 1987) (Fig. 1a). Within folds cut by thrust ramps, the interlimb angles of hangingwall anticlines reduces as forelimbs display a progressive reduction in thickness, until a marked % thinning is developed where interlimb angles have reduced to <50° (Fig. 6j). Furthermore, increasing thinning of forelimbs is also weakly correlated with greater displacement on thrust ramps linked to lower thrust ramp angles (Fig. 6k, l). In models of fault-propagation folds (e.g. Jamison, 1987), the interlimb angle of hangingwall anticlines is classically considered to be a function of thrust ramp angle (as defined on Fig. 1a) and amount of fold forelimb thinning (-ve %) or thickening (+ve %) (Fig. 6m). While the buckle folds in the case study are not considered to be fault-propagation folds, as many folds are not associated with ramps, and some thrust ramps cut directly across both fold limbs (e.g. Fig. 7a-h), there is a general correlation of folds with thinned and thickened forelimbs into the correct 'fields' on the plot (Fig. 6m). We also examined folds in terms of the detachment fold models of Jamison (1987), where the interlimb angle of hangingwall anticlines is considered to be a function of the dip of backlimbs and amount of fold forelimb thinning (-ve %) or thickening (+ve %) (Fig. 6n). Combining plots reveals that detachment folds cut by thrusts typically have more gently dipping fold backlimbs and slightly reduced interlimb angles compared to detachment folds that are not subsequently cut by late thrusts (Fig. 6o). This suggests that the geometry of buckle folds may be modified by the later propagating thrust ramps.

7. Details of refolding and deformation along detachments

7.1. Fanning crown of folds above detachments

Thinner detrital-rich beds overlying synclines are marked by smaller wavelength buckle folds with axial planes that progressively steepen and then switch vergence as they cross the axial surface of the underlying syncline to define a fanning 'crown of folds' arrangement (Figs 4c, 7a-h, 8a-f, 9a-g). These overlying beds typically display less shortening than the underlying folds (Table 1) and appear to have become detached from the underlying structures along aragonite-rich horizons (Figs 7c, d, g, h, 8a-f, 9d-g). In addition, aragonite units may actually thicken beneath these fanning folds, resulting in an overall 'upward-arching' despite the synformal setting (Figs 4c, 7c, d, 8d-f, 9f, g). Folds are created where the blue marker bed has rotated out of the bedding-parallel shear plane, in particular where underlying synclines appear to have perturbed the general flow. Tightening of synclines marked by thick detrital beds is associated with overlying, thinner detrital beds displaying shorter-wavelength buckle folds and 'out-of-syncline' thrusts (Figs 7a-h, 8a-f). The sense of buckle fold vergence and 'out-of-syncline' thrust direction may reverse across the overall underlying syncline (Figs 8d-f, 9f, g).

7.2. Creation of new upper detachments

Detailed examination of the upper portions of the FATS reveals that adjacent detrital-rich marker beds fold at different wavelengths and amplitudes (Figs 4a-f, 8a-f, 10a-f). This disharmonic folding is achieved through multiple bedding-parallel detachments that operate within the intervening aragonite-rich horizons and effectively separate the folded beds (Figs 8a-c, 10c-f). In some cases, underlying folds verge in the same direction as the overlying structures in the roof, suggesting that deformation has been only partially decoupled across the upper detachment (e.g. Fig. 8a). Some upper detachments are folded by underlying synclines, while detachments at higher structural levels maintain more planar geometries suggesting they are unaffected by the folding (Figs 8a-c, 10a-f). These timing relationships between detachments and underlying folds allow us to distinguish older (1) and younger (2) upper detachments (Figs 8a-c, 10a-f). Folds with opposite senses of vergence to underlying structures may effectively form above the new and uppermost detachment (2) (Fig. 10a-f). The general sequence appears to be that upper detachments get progressively younger up through the structural pile. The uppermost shear event is developed directly beneath the sedimentary cap that may locally erode underlying folds (Figs 4c, 8a-e, 9g). This appears to be the youngest event as folds and fabrics developed above underlying detachments are themselves reworked and refolded with apparently increasing shear upwards towards the cap (Fig. 8a-e).

7.3. Refolding adjacent to detachments

Refolds are created where smaller scale folds are 'wrapped around' larger recumbent antiforms and synforms (Fig. 10a-f). Smaller-scale folds may be associated with earlier detachments, that are themselves also folded by the larger folds (see previous section) (Fig. 10a-f). The resulting structures resemble those produced in classical poly-deformed metamorphic terranes, where there have been long-standing debates regarding the significance of fold 'phases' and 'D-numbers' (see Fossen, 2019 for a review). Clearly, the structures within the present case study formed geologically instantaneously, thereby confirming an origin linked to progressive deformation rather than separate events (see Alsop et al., 2020c). We interpret folding of earlier detachments to mean that they must have become 'locked', with displacement transferring to newer higher-level structures that maintain a more planar geometry.

8. Backthrust sequences

Backthrusts have been defined by Van der Pluijm and Marshak (2004, p.446) as "a thrust on which the transport direction is opposite to the regional transport direction" and may develop in gravity-driven systems where downslope-moving sediment is 'wedged' and underthrust beneath the downslope-dipping thrust fault (Alsop et al., 2017b, 2018a). Although such backthrusts verge upslope, there is no actual upslope-directed movement of sediment and the backthrust may be considered a consequence of the sediment positioned upslope translating more rapidly than that further downslope (Alsop et al., 2017b). Backthrusts are therefore a product of changes in relative downslope velocity. Within the case study, the thinner blue detrital bed undergoes less percentage shortening than the major backthrusts and synclines that it overlies, and is therefore considered to be separated by a detachment (Fig. 11a, b). While backthrusts verge upslope, the overlying buckle folds verge downslope, and may even be cut by small downslope-verging thrusts where they are positioned above 'pinched' synclines (Fig. 11c). Some minor folds are reworked and refolded by the downslope-directed folding (Fig. 11c). Minor buckle folding was completed prior to deposition of the overlying sedimentary cap that erosively truncates the underlying structures (Fig. 11c). Minor buckle folds verge downslope above backthrusts, while they verge upslope above downslope verging thrusts strongly suggesting that the kinematics of minor buckle folds are linked to the underlying FATS (Fig. 11d).

9. Discussion

9.1. What deformation sequences develop within gravity-driven FATS?

Improved resolution of seismic sections across offshore continental margins has revealed much about the large scale gravity-driven FATS that create MTDs (e.g. Corredor et al., 2005; Zalan, 2005; Bull et al., 2009; Butler and Paton, 2010, de Vera et al., 2010; Morley et al., 2011; Jackson, 2011; Peel, 2014; Scarselli et al., 2016; Reis et al., 2016; Steventon et al., 2019). Despite the increasing recognition of such systems, the limits of seismic imaging still typically inhibit detailed analysis of the local structural evolution, which we now discuss in relation to the case study.

9.1.1. Fold sequences

Sedimentary successions that comprise heterogeneous beds will typically encourage buckle folding to develop during layer-parallel contraction (see Price and Cosgrove, 1990 for a review). It is commonly suggested that earlier upright buckle folds may be modified by distributed simple shear, or cut across by later thrusts, resulting in overturning of fold limbs (e.g. see summary in Fossen, 2016, p.368). Noble and Dixon (2011, p.66) note that buckle folds in experimental models form first and are then cut across by thrusts, while Butler and McCaffrey (2004, p.920) also suggest that early buckle folding may subsequently be cut by thrusts that initiate as shorter segments in more competent horizons. Thrusts are also considered a late stage feature developed at the toes of MTDs where the ‘rapid arrest’ of downslope movement leads to a late phase of contraction (Strachan, 2002, p.18). This pattern of folds forming prior to thrusts is generally also the sequence in the case study, with thrusts cutting and potentially modifying folds, and no evidence of thrust planes being later folded.

9.1.2. Thrust sequences

As is frequently observed in thrusts cutting lithified rocks in orogenic belts, thrusts cutting unlithified sediments may display both piggyback (Fig. 12a) and overstep sequencing (Fig. 12b) (see Alsop et al., 2018a). Piggyback sequences, marked by back-steepening of earlier thrusts, are seen in parts of the described section (Figs 3a, 5a) and are summarised in cartoon form in Fig. 12a. Thrusts may be so back steepened that they become unstable and start to collapse back up the regional slope (Fig. 5a, b). Overstep thrust sequences, where thrusts get younger up the regional slope, may be marked by older rotated and flattened thrusts accommodating larger displacements (Fig. 12b). However, back steepened piggyback thrust sequences do not display such displacement ramp angle relationships as back steepening only occurs after younger underlying thrusts have formed (Fig. 12a). If thrusts develop during downslope translation of the gravity-driven FATS then a variety of sequences, including piggyback and overstep sequences, may form. Conversely, thrusting which forms during cessation of fold and thrust movement generates contractional strain that propagates back up the slope from the toe (e.g. Farrell, 1984), and will therefore create overstep thrusts i.e. new downslope verging thrusts develop in the hangingwall (upslope) of older thrusts (Fig, 12b). Over-steepened back thrusts indicate that basin-ward-directed movement continued upslope of the backthrusts (Fig. 11d). This suggests a degree of synchronous thrust movement, which is supported by modelling performed by Liu and Dixon (1995, p.885) who note that early thrusts were still moving while later ones were nucleating i.e. strict thrust sequences are not supported by the modelling. In addition, modelling studies performed by Koyi et al. (2000) suggest that if underlying detachments are relatively low-friction then this would also encourage simultaneously active thrusts to form.

9.1.3. Displacement-distance distributions along thrusts

D-D plots in this study (Fig. 5a-e) are marked by steeper curves than D-D plots for thrusts with equivalent displacements that cut more homogeneous aragonite in downslope areas of the same MTD event (see figs 10, 11 in Alsop et al., 2017a). It is generally assumed that D-D plots with steeper gradients represent slower propagation of the thrust tip relative to slip in weaker units, whereas gentle slopes on D-D plots signify more rapid propagation of the thrust tip relative to slip (e.g. Williams and Chapman, 1983; Ferrill et al., 2016). As our analysis of folding demonstrates that detrital-rich units are more competent than aragonite-rich beds, then the difference in D-D gradients may reflect slower propagation of thrust tips across already folded and buckled heterogeneous sediment layers i.e. our D-D plots do not relate to fault-propagation folds as per the original model of Williams and Chapman (1983). Downslope areas within the same MTD that lack significant earlier folding do develop thrusts that create synchronous fault-propagation folds and may propagate more rapidly across pristine layers (Alsop et al., 2017a).

A further difference between thrusts associated with fault-propagation folds and thrusts cutting earlier buckle folds is that D-D plots from the former may show local displacement maximums close to the basal detachment (e.g. figs 9g-9j of Alsop et al., 2017a) or alternatively, next to competent layers suggesting that ramps initiated at these levels in the stratigraphic package above the basal detachment (e.g. fig. 10g, 11a-g of Alsop et al., 2017a). In the present study, the D-D plots along thrust ramps that post-date and cut buckle folds consistently display the largest displacements where the ramp branches from the underlying basal detachment (Fig. 5a-e). The D-D patterns of thrusts cutting buckle folds are therefore potentially quite different from D-D plots along thrusts that initiated in competent layers and are associated with fault-propagation folds from the same slump event (e.g. Alsop et al., 2017a). Greatest displacement being recorded towards the base of individual thrust ramps is in agreement with the fold duplex model by Mitra and Boyer (2020), where displacement is transferred upwards from the basal detachment to join the overlying upper (roof) detachment.

9.2. How do FATS evolve during progressive downslope shearing?

9.2.1. Rotation of buckle folds during downslope shearing

When pairs of hangingwall anticline and adjacent footwall syncline fold hinges are measured from the section in Fig. 3, the syncline hinges are found to trend more clockwise (while their axial planes are more anticlockwise) of the adjacent anticlinal fold pair (Figs 3j, k, 6a). Interlimb angles of footwall synclines are consistently tighter than adjacent hangingwall anticlines (Fig. 6d-f), with more open anticlines being paired with even tighter synclines (Fig. 6g). The geometric relationships noted above are summarised on Fig. 13 and are interpreted to reflect anticline hinges (mean 312°) having maintained almost orthogonal relationships with the 040° slope direction while their axial planes (mean 329°) also preserve original trends. Conversely, tighter synclines are marked by more intense deformation, with fold hinges (mean 323°) that have rotated slightly (~11°) towards the downslope direction (040°). The observation that the synclinal (or return hinge) has undergone greater deformation is similar to relationships observed during shearing in metamorphic conditions where synclinal return hinges are rotated more (e.g. Alsop and Holdsworth, 2007, 2012).

We also record a progressive increase in obliquity between footwall synclines and hangingwall anticlines towards the NE end of the section (Fig. 5a-e located on Fig. 3a-h). While anticlinal hinges maintain a relatively constant trend along the section (i.e. mean hinge trends only vary from 304° to 311°), the associated synclinal hinges rotate from 317° to 346° towards the NE end of the section (Fig. 5a-e). These spatial differences may suggest greater shearing and rotation of synclinal folds towards the NE end of the section, perhaps implying that deformation initiated here and was potentially more protracted.

9.2.2. Squeezing of buckle folds and sediment expulsion during downslope shearing

Squeezing of overturned footwall synclines - Hangingwall anticlines with steeper axial planes are generally associated with more open folds, whereas synclines are typically tighter with smaller interlimb angles for any given value of axial-planar dip (Fig. 6d, e). Tightening of footwall synclines may result in expulsion of sediment from the core of the syncline as it tightens (Fig. 9g). The expelled sediment forms ‘out of syncline’ thrusts, the vergence of which is typically opposite to the axial planar dip direction of the syncline from which they were expelled (Fig. 10a-f). Thus, downslope verging synclines will generate upslope verging out of syncline thrusts. These geometries are created by loading and downslope shearing of the hangingwall block as it moves up the thrust ramp. Expelled sediment may be ‘wrapped around the nose’ of the advancing hangingwall anticline, resulting in attenuation and smearing of the sediment (Fig. 10c-f). Backthrusts follow similar patterns, resulting in expelled sediment creating downslope verging secondary thrusts (Fig. 11c). Thus, tighter interlimb angles of synclines compared to adjacent anticlines may reflect ‘loading’ and flattening of the footwall syncline as the anticline is thrust over the top. Reduced interlimb angles of synclines is achieved by the expulsion of material up and out of the core of the syncline as it tightens, as summarised in Figures 10g and 12b. Tighter synclines may also reflect the pre-thrust geometry of the buckles, with detachment folds typically displaying tighter synclines (Fig. 9c, d).

Pinching shut of upright synclines - The relatively thick (~10 cm) brown detrital marker layer displays isoclinal synclines while adjacent anticlines are only tight. (Fig. 8d, e). Upright to vertical synclines defined by thicker detrital beds contain thin seams or 'wisps' of aragonite within the core of the fold (Figs 4e, 8d, 10e, 11c). In some instances, small upright antiformal 'billows' of aragonite and detrital layers extend upwards from the synclinal core (Figs 4f, 8e, f). Such 'billows' and the upright, tight-isoclinal synclines are created by 'pinching shut' of the fold hinge, with expulsion of weaker sediment from the core of the syncline sometimes resulting in 'collapse folds' of Ramsay (1974). Such 'pinched synclines' form a subset of synclines marked by tight to sub-isoclinal geometries with steeper axial planes (Fig. 6d). This contradicts typical models of progressive deformation where folds systematically tighten as they rotate and flatten towards the (horizontal) shear plane with increasing deformation (e.g. Escher and Watterson, 1974; Alsop and Holdsworth, 2007 and references therein). Pinched upright synclines reflect the control exerted by the heterogenous layering coupled with weak (aragonite-rich) beds that are readily expelled from the cores of synclines to allow continued tightening.

9.2.3. Buckle folds cut by thrusts during downslope shearing

Larger thrusts have ramps with lower values of dip (Fig. 6i). As thrusts develop, loading caused by the movement of the hangingwall anticline results in underlying footwall synclines being tightened. Expulsion of sediment from the core of the syncline allows the overlying thrust to rotate and become more gently dipping (Fig. 10g). Thrusts may thus initiate with steeper (~35°) ramp angles which are then progressively reduced as each footwall syncline is pinched shut (Fig. 12b). These thrusts may then be back-steepened once again if underlying thrusts develop in a piggyback sequence. In such cases, a check should be made on the amount of displacement and tightness of the footwall syncline, as increased loading of basin-ward (foreland) thrusts could result in an apparent back-steepening. Indeed, greater loading and expulsion of sediment from the cores of footwall synclines will naturally increase towards the lowermost thrusts, resulting in an apparent reduction in angles of thrust ramps in this direction. Flattening of thrusts may partially counteract back-steepening associated with piggyback thrusting. Overstep thrust sequences will form apparently back-steepened thrusts which are actually a consequence of older, structurally lower thrust ramps being flattened (see Figures 12a and 12b to compare back-steepening and fore-flattening). Therefore using variable thrust dip to determine thrust sequences on seismic sections, that may themselves have been vertically exaggerated, should be applied with extreme caution.

When models of interlimb angles and thrust ramp angles are compared with % shortening, as in the models of Jamison (1987), it is found that forelimb thickening and thinning broadly sit in the 'correct' fields with regard to interlimb angles and backlimb dips (Fig. 6m, n, o). However, the estimates of % forelimb thickening or thinning are inaccurate whether models of fault-propagation folds cut by thrusts (Fig. 6m) or detachment folds are used (Fig. 6n, o). These discrepancies reflect the fact that buckle folds and their forelimbs are cut across and modified by later thrust ramps, rather than being created by synchronous ramps as in the fault-propagation model. Heterogeneous and detrital-rich sediments in the case study appear even more sensitive to changes in the interlimb angle influencing thickening or thinning of the forelimbs when compared to folds and thrusts in homogeneous aragonite-rich units (i.e. compare Fig. 6j with fig, 5c of Alsop et al., 2017). Observations by Alsop et al. (2016a) from the case study MTD that fold-dominated deformation may pass laterally downslope into thrust controlled deformation, where aragonite-dominated sediments are more homogeneous, suggests that sediment heterogeneity is crucial in determining structural style.

9.2.4. Summary of fold and thrust evolution

Data from section shown in Fig. 3 shows that thrusts with steeper ramps generally have less displacement (Fig. 6i). As thrusts become larger with increased displacement, their ramp angles generally reduce. This is achieved through tightening of the footwall synclines and may result in ‘pseudo-piggyback’ sequences where the angle of thrust ramps systematically reduces in the direction of transport. Reduction in ramp angles allows thrusts to continue to move and accrue larger displacements. Thrusts are considered to initiate with steeper angles and become shallower as displacement and loading from overlying thrust sheets increases (Fig. 12b). Thus, ‘back-steepening’ of overlying thrusts is only apparent in this case, as it is actually the systematic reduction in the angle of dip of underlying thrusts that creates the geometry. The expulsion of sediment from the cores of synclines that allows thrusts to flatten occurs during the thrust process (rather than a consequence of later loading from overburden) as the overlying sedimentary cap is unaffected by thrusts and associated expulsion of sediment.

9.3. What factors influence detachments in FATS?

Within the case study, the basal detachment is typically developed below detrital rich units, as observed elsewhere in the Lisan Formation by Alsop et al., (2018a), while the upper detachment is also formed below a distinctive 3-4cm thick detrital (blue) marker bed (Fig. 3). The depth of sediment that originally buried the detachment is not known, due to an undetermined thickness of sediment being removed along the erosive base of the sedimentary cap that covers the deformed sequence. However, the remaining 20 cm of sediment that still locally overlies the detachment provides a minimum estimate. The detrital bed above the upper detachment is laterally continuous, and forms buckle folds, indicating it is more competent than the aragonite-rich facies above and below it. We have previously suggested that detrital marker beds act as barriers or baffles to fluid flow, thereby forming seals to overpressured sediment that fails directly beneath it and locally fluidizes to create injected gouge (Alsop et al., 2018a). Mechanical heterogeneity linked to alternating detrital and aragonite layers, combined with variations in fluid pressure are thought to be the likely controls on positioning of both the basal and upper detachments, and bed-parallel slip planes in general (Alsop et al., 2020d). Thus, we interpret the aragonite-rich sediment above the uppermost (blue) detrital as fluid rich and weak due to being non-compacted and close to the sediment surface, while the aragonite-rich layers below the marker were overpressured and failed.

If detachment buckle folds grow by simple 'pin-joint' rotation of relatively rigid limbs towards steeper dips (see Butler et al., 2020 p.24), then the maximum 'height' a fold can reach is determined by the wavelength of the original buckle (fold height will be half original wavelength). Although buckles are likely to lock before this is achieved, this relationship may help explain why the top of the buckle fold train maintains the same 'level' as the original buckle wavelength is a consequence of dominant layer thickness and viscosity contrasts between layers (e.g. Price and Cosgrove, 1990). Buckle anticlines grow upwards towards the free surface, sometimes resulting in the anticline achieving 'lift-off' and folding existing basal detachments. Estimates of the amount of weak mobile sediment forming the core of growing detachment anticlines are broadly equivalent to the amount of weak material available to flow into the fold core from above the basal detachment and from between the two flanking synclines (see Stewart, 1996). There is therefore no necessity for this weak material that fills anticlinal cores of detachment folds (e.g. Fig. 9c, d) to be sourced from greater distances, or to have significantly moved in or out of the plane of section along fold hinges.

However, as the troughs of synclines remain at the same level and generally cannot grow downwards (e.g. Butler et al., 2020 p.30), then they must expel excess core material upwards and outwards as they tighten (although some sediment may transfer laterally along the hinge to create out of plane movement). Ultimately, folding leads to expulsion of fluids (Price and Cosgrove, 1990, p.398) thereby strengthening sediments and leading to thrusts cutting folded sequences. Based on analysis of detachment folds in the Lisan Formation, Alsop et al. (2020c) have recently argued that increased shortening leads to expulsion of fluids from weaker (saturated?) layers thereby increasing the viscosity of these layers while reducing the overall viscosity contrast between the detrital and aragonite-rich beds. Recent numerical modelling of porosity variation in buckle folds by Liu et al. (2020) has shown that porosity decrease occurs in the hinges of competent layers, while porosity increase is created in the thickened limbs of folds in incompetent beds. The net effect may be for fluids to be expelled and migrate away from pinched synclinal hinges in competent detrital layers, and flow along fold limbs towards overlying beds thereby reducing their strength and encouraging new detachments to form at higher levels. The expelled fluid may 'pond' below overlying detritals thereby facilitating further movement on the upper detachment. We suggest that this ponding of fluids below the upper detrital that acts as a baffle to fluid flow encourages failure and detachments to develop at this level rather than ramps propagating directly to the surface.

9.4. Is deformation created by shear along an upper detachment or by moving water?

In the FATS that forms the present case study, it was originally assumed that displacement along folds and thrusts transferred upwards to the sediment-water interface where it simply dissipated (Alsop and Marco, 2012). While this may be true in some slumps where erosive down-cutting has now removed details of the original top surface, the recognition in this study that: a) there is no stratigraphic break or hiatus (such as a breccia horizon) identified between the uppermost blue marker and the underlying stratigraphy that forms the FATS, and b) there is no structural break or significant thrusts that cut the uppermost blue marker, means that displacement is unable to transfer across the blue marker to the free surface. We therefore now consider the various lines of evidence that relate to either: a) the seiche model where deformation in the topmost sediment pile is created by relative shear associated with the movement of the overlying water column in a seiche or tsunami wave (Alsop and Marco, 2012), or: b) the fold duplex model where deformation in the topmost sediment pile is created by relative shear across the upper detachment that bounds the underlying FATS (this paper).

It is worth highlighting that in both the seiche and fold duplex model, it is the topmost sedimentary pile that impacts on, and modifies the structures in the underlying MTD. We therefore now concentrate on this upper part of the deformed sequence, and present a number of critical observations that support a model involving an upper detachment rather than the seiche model as originally proposed by Alsop and Marco (2012).

a) Folds in the blue marker layer are coaxial with those in the underlying slump (Fig. 4d). This could be caused by a coincidence of movement directions between sediment slumping downslope towards the NE, and seiche waves moving obliquely towards the N-S trending margin of the basin (Alsop and Marco, 2012). Alternatively, parallelism of fold hinges is simply a consequence of both sets of folds being created by the same downslope shear couple across an upper detachment.

b) Folds are not universally developed in the upper blue marker layer and are preferentially formed above synclines and thrusts in the underlying FATS, while the marker layer is attenuated and stretched over underlying antiformal crests (e.g. Figs 4a, b, 10a, f). Folding of the upper detachment would encourage folds to form in these specific locations where bedding and the detachment are locally rotated out of the sub-horizontal shear plane, whereas shear against a water column would operate along the entire slump and could generate ubiquitous folds in the marker layer.

c) Vergence of folds switches across pinched synclines to create fanning ‘crowns of folds’ (e.g. Figs 4f, 9f, g). Such distinct geometries are consistent with reversals in relative shear across a folded upper detachment that has become locked (Fig. 10a-f) but are inconsistent with uniform shear caused by a moving water column in a seiche or tsunami wave (Alsop and Marco, 2012).

d) The vergence of the folded blue marker layer above backthrusts switches to become downslope (e.g. Fig. 11a-c), thereby suggesting a linkage to the kinematics of the underlying structure rather than shearing by the overlying water column.

e) Examples of refolding (e.g. Fig. 8a-f) were originally described by Alsop and Marco (2012) and attributed to repeated swash and backswash of water during seiche waves. However, such reversals in apparent shear sense may also be sequentially created as upper detachments are folded, locked and abandoned with displacement transferring upwards to new detachments at higher stratigraphic levels towards the sediment surface.

f) Shearing of the blue marker creates folds of varying wavelength and vergence that do not affect underlying beds, thereby suggesting that a detachment must exist directly beneath it (Figs 7c, d, g, h, 10a-f). Conversely, shearing against an overlying water column would perhaps be expected to affect even lower beds at some point and not abruptly terminate at a given level.

g) The sediment above the blue marker layer shows increasing deformation and attenuation upwards towards the sedimentary cap (Fig. 8a-c). As the erosive surface marking the base of the sedimentary cap truncates structures and folds formed in the roof of the upper detachment, then the FATS must have formed immediately below the sediment surface. Following Alsop and Marco (2012), we still interpret this increase in deformation in the topmost sediment pile directly below the erosive cap as reflecting the effects of shear against the water column during seiche. Alternatively, if translation of the roof to the FATS is relatively fast (i.e. super-active, Fig. 1c), then it may lead to erosion of the uppermost sediment along the interface with the water, although the water column itself may not necessarily have moved (see Butler et al., 2016). Such erosive surfaces would not be limited by water depth (or wave base etc) and may actually be enhanced in the dense hyper-saline brines of the Dead Sea.

9.5. Are fold duplex models applicable to gravity-driven FATS?

Within orogenic thrust systems, duplexes are considered to be bound by basal and upper detachments that are sub-parallel to one another and the stratigraphic layering, and are connected by some form, or combination, of fault and fold imbricates in which displacement along individual structures is relatively minor compared to the bounding detachments (Boyer and Mitra, 2019, p.202). The relative amounts of shortening associated with faulting and folding in a duplex have been discussed by Mitra and Boyer (2020), with the current analysis suggesting that the FATS shown in Fig. 3 could be referred to as a hybrid fold-fault duplex reflecting the relative shortening of each fold or fault component in all layers (Table 2). However, the role of lateral compaction, which may increase by 10% towards the sediment surface remains unknown (Alsop et al., 2017a), and so these estimates of line length shortening, and the relative contribution of folding and faulting, are crude approximations of overall shortening. Estimates of lateral compaction from both sandbox experiments (e.g. Koyi, 1995) and orogenic belts such as the Pyrenees (e.g. Koyi et al., 2004) indicate that it may form a significant component of overall shortening. Experimental sandbox models generally display a reduction in layer-parallel compaction upwards through the model (e.g. Koyi et al., 2004), which is the reverse to that estimated in MTD's of the Lisan Formation (e.g. Alsop et al., 2017a). Within MTDs, the increase in lateral compaction towards the sediment surface may reflect less compaction and overburden loading during deposition, which then results in the uppermost sediment being more prone to lateral compaction, expulsion of fluids and horizontal shortening during subsequent MTD movement (see Alsop et al., 2017a, p.112 for further discussion). We suggest that discrepancies in the amounts of measured fold and fault shortening up through the sequence may be accommodated by increasing lateral compaction and/or internal detachments formed within the sequence.

A key component of any duplex model, including fold duplexes, is the presence of an upper detachment or detachments that accommodate displacement that is transferred upwards from a basal detachment via a series of faults or folds (see section 1.1, Fig. 1) (Boyer and Mitra, 2019). There are a number of critical observations in the present study that relate to the development and kinematics of this upper detachment.

9.5.1. Stratigraphic correlation across the upper detachment

In some cases, detached remnants of the dark blue upper marker bed are tightly folded into the cores of synclines, while the same blue marker is continuous in the overlying roof of the upper detachment (Figs 7e-h, 14a). We suggest that buckle folds of marker layers are initiated in front of the downslope propagating basal and upper detachments that bound the FATS (Fig. 14a, stage i) (see Alsop et al., 2016a, 2017a; Mitra and Boyer, 2020). As downslope translation of the FATS continues, buckle folds rotate and grow in amplitude via lifting of anticlines and expulsion of sediment from synclinal cores (Fig. 14a, stage ii). Downslope propagation of basal detachments (e.g. Fig. 9c-e) and upper detachments cut across and truncate the buckle folds, with late stage thrust ramps preserving marker beds 'trapped' in footwall synclines (Fig. 14a, stage iii). The implication is that the trapped blue marker in the synclinal core was translated downslope as part of the FATS to lie beneath the same continuous blue marker in the overlying roof. The relative displacement across the upper detachment created the upslope-verging folds of the blue marker preserved in the roof of the upper detachment (Fig. 7e-h, Fig. 14a, stage iii). This demonstrates that there must have been significant differential movement between the FATS and blue marker preserved in the roof of the upper detachment (Fig. 14a, stage iii; Fig. 7e-h). It also proves that the uppermost (blue) marker bed forms a continuous and integral part of the FATS stratigraphy and requires a further analysis of the kinematics and structural relationships exposed along the top of the MTD.

9.5.2. Folding of upper detachments in pinched synclines

Downslope translation of the FATS causes buckle folds to progressively rotate and grow in amplitude (Fig. 10g, 14b, stage i). The upper detachment that bounds the system may locally become involved in the folding process causing it to become inefficient as a slip surface (Fig. 14b, stage ii). As translation continues, folding of the upper detachment tightens resulting in it becoming entirely locked, and potentially cut by thrusts that are ramping towards the upper detachment (Fig. 14b, stage iii). Fanning crowns of folds displaying reversals in vergence across underlying synclines and thrusts indicates that there has been no significant translation across the upper detachment since the folds were formed (Fig. 14b, stage iv; Fig. 9c-f)

9.5.3. 'Locking' of upper detachments and upwards transfer of displacement

As noted above, downslope translation of the FATS generates a shear couple across the upper detachment that potentially creates upslope-verging folds in the roof of the detachment (Fig.

14c, stage i). Deformation associated with the upper detachment diminishes and dissipates upwards towards the free surface so that overlying marker beds are passively carried without significant disturbance (Fig. 14c, stage i). If the upper detachment is intensely folded and 'locked' during tightening and amplification of buckle folds, then continued downslope translation of the FATS may cause displacement to be transferred to a new upper detachment (2) that starts to propagate at a higher stratigraphic level (Fig. 14c, stage ii). This effectively thickens the FATS meaning that folds that were above the original upper detachment (1) will now be in the footwall of the new active detachment (2) and form part of the downslope translating system (Fig. 14c, stages ii, iii). Hence, they will be reworked with the opposite sense of shear, potentially leading to reversals in fold vergence and refolding (Fig. 14c, stage iii). Marker beds that were originally passively carried downslope above the early upper detachment are now deformed by the shear couple across the new upper detachment (2) (Fig. 14c, stage iii).

9.5.4. Kinematics of upper bounding detachments

The range of structures created within the FATS, together with kinematics generated across the upper detachment noted above may be interpreted in terms of variations in relative velocity both within the FATS, and also between the FATS and its roof. Note that all structures are considered to form by variable downslope-directed velocity, rather than any actual flow back up the regional slope (see also Alsop et al., 2017b). In addition, the shortening recorded by folds above detachments does not necessarily reflect total movement along the detachment, as this is dependent on when marker layers were rotated out of the bedding-parallel shear plane and folding initiated. A schematic cartoon summarising structures formed in the FATS, as well as those in the roof above the upper detachment is shown in Fig. 14d.

Within FATS, greater downslope velocity on the upslope side of forethrusts causes overlying thrusts to progressively load and flatten underlying thrust ramps (Fig. 14d). This is accommodated by expulsion of weak and saturated sediment out of the cores of the pinched footwall synclines (Figs 10g, 12b). Conversely, greater downslope velocity on the upslope side of backthrusts causes a relative back-steepening of thrust ramps that act as a buttress and impede downslope flow (Figs 11d, 14d). This again results in the expulsion of weak and saturated sediment out of the cores of footwall synclines. Pinching shut of upright synclines is also generated by differences in downslope velocity on each limb of the fold, with greater velocity on the upslope side resulting in expulsion of saturated sediment that may facilitate further movement across the overlying upper detachment (Fig. 14d). Late-stage thrust ramps that cut across earlier buckle folds may display overstep sequences, where ramps simply link the basal and upper detachments that had formed previously during detachment folding. Minor buckle folds that verge downslope above backthrusts, while they verge upslope above forethrusts strongly suggests that buckle folding is linked to the underlying FATS (Fig. 11d).

The kinematics of the shear couple generated across the upper detachment is dependent on the relative downslope velocities of the FATS and its overlying roof that will vary in both space and time (Fig. 14d). Lesser (sub-active, Fig. 1c) or greater (super-active, Fig. 1d) velocity of the roof compared to underlying FATS may create folds in the roof that verge either up or down the regional slope respectively (Fig. 14d). The roof and the FATS may also theoretically move at broadly the same rates resulting in no relative translation across the upper detachment, although this is considered to be a localised and temporary scenario (inactive roof in Fig. 14d). Differences in relative velocity across the upper detachment leads to fanning crowns of folds with vergence reversing around the underlying synclinal closure (Fig. 10a-f). The juxtaposition of fanning crowns of folds with the underlying syncline or thrust ramp in the FATS indicates that there has been little or no relative translation across the upper detachment since they formed i.e. pinching shut of synclines is a ‘locking-up’ process created during cessation of movement.

It is also possible that displacement along the upper detachment transferred to a higher level closer to the sediment-water interface locking the original upper detachment. In this regard it is notable that the detachment below the cyan marker is itself folded around some folds in the FATS, and is also cut by thrust ramps indicating that upper detachments get reworked once incorporated within the FATS (e.g. Figs 10a-g, 11a-d). Thus, there may be multiple re-worked detachments that are sequentially abandoned as displacement is progressively transferred to higher levels in what was the original roof to the FATS (Fig. 14c).

9.6. How do gravity-driven fold duplexes compare to those in orogenic settings?

There are two principal differences in the fold duplexes we describe from surficial gravity-driven FATS compared to those from orogenic systems recently identified by Boyer and Mitra (2019) and Mitra and Boyer (2020).

Firstly, while multiple upper detachments are identified in both orogenic and surficial settings, displacement in orogenic settings is considered to migrate to new detachments at lower levels in order to maintain ‘structural elevation’ required in the ‘kink fold’ models of Boyer and Mitra (2019). The recognition in this study that new detachments may form above older detachments in surficial gravity-driven FATS is therefore the opposite to that generally recorded in orogenic settings (Boyer and Mitra, 2019). In this respect, it is noteworthy that Morley and Jitmahantakul (2020) have recently suggested that multiple detachments may form within folded and thrust carbonates in orogenic settings, and that such detachments may not follow a simple sequence of progressively younger detachments with increasing depth. We suggest that in the case study, displacement was transferred to higher-level detachments because: a) the small-scale gravity-driven systems operated very close (metres) below the lake bed, and as such lacked overburden to constrain deformation and surficial uplift; b) new detachments avoided complexly folded heterogeneous stratigraphy and migrated to overlying layer-cake, varved couplets that offer pristine bed-parallel slip planes and; c) as stratigraphic seals were potentially broken by folding and thrusting, trapped fluids may have migrated upwards and thereby facilitated slip along new detachments that formed at these higher levels.

Secondly, Boyer and Mitra (2019) and Mitra and Boyer (2020) describe fold duplexes from foreland-propagating orogenic systems in which thrust ramps follow a broadly 'piggyback', although potentially synchronous, sequence. In the gravity-driven FATS we describe, the detachment buckle folds form first and may be truncated by the bounding detachments. The imbricate faults develop subsequently and cut through the folded sequence, thereby creating 'link thrusts' (McClay 1992, p.426) between the already established basal and upper detachments. The locally variable piggyback and overstep sequence of imbricate fault propagation is therefore separate to the propagation of bounding detachments and may relate to late-stage strain that propagates back up the slope when translation ceases first at the toe. Such cessational strain has long been recognised from outcrops of the exhumed toes of MTDs where Martinsen and Bakken, (1990, p.163) note that the "development of thrusts in an overstep manner rather than in a piggyback fashion may be the expected". This has been subsequently supported by seismic sections across offshore gravity-driven FATS (e.g. de Vera et al., 2010; Ireland et al., 2011), and indeed by studies of thrust systems from elsewhere in the Lisan Formation (Alsop et al., 2018).

10. Conclusions

We have for the first time applied the fold duplex model to gravity-driven FATS that develop in MTDs. We establish a new model whereby the vergence of structures formed above the upper detachment to the duplex depends on if the roof translates downslope more slowly (sub-active and creating upslope verging folds; Fig. 1c), or more rapidly than the underlying FATS (super-active and generating downslope verging folds; Fig. 1d). Our structural analysis of a FATS within a single MTD event in the Peratzim case study area of the Dead Sea Basin is summarised on Fig. 15 and allows us to draw the following general conclusions.

1. Deformation sequences within gravity-driven FATS

Downslope-verging folds that are bound by basal and upper detachments are subsequently cut by thrust ramps with the greatest displacement recorded where ramps branch from the basal detachment. Subordinate piggyback, overstep and potentially synchronous sequences are locally developed that may reflect spatial and temporal variation in downslope shear associated with second-order flow cells. Greater rotation of folds suggests more protracted deformation towards the downslope toe of the FATS.

2. Evolving FATS during downslope shear

As thrust displacement increases then ramp angles generally reduce which allows thrusts to continue to move and accrue larger displacements. This is achieved through tightening and expulsion of wet sediment from the cores of footwall synclines as a consequence of loading from overlying thrust sheets. The observed ramp angle may not represent the true angle of ramp initiation, with sequential flattening of overstep thrust creating apparent 'back steepening' in what superficially may resemble 'pseudo-piggyback' sequences.

3. Factors influencing detachments in FATS

Geometries within the FATS are controlled by the nature of heterogeneous sediments and thickness of competent detrital marker beds. During continued downslope movement of the FATS, sequential tightening of folds that are subsequently cut by thrusts leads to expulsion of fluids from fold cores. Fluids may pond directly beneath overlying detrital-rich units that act as baffles and locally increase fluid pressures thereby facilitating further movement along the upper detachment. New upper detachments may develop at higher levels as older detachments are folded into synclines and 'lock up'. New detachments at higher levels reflects increased fluids, with these detachments avoiding previously folded beds and simply transferring towards the pristine 'easy-slip' laminations closer to the free surface.

4. Deformation created by shear along an upper detachment

The recognition in this study of continuous stratigraphic markers in the roof above the FATS demonstrates that deformation cannot have propagated directly to the sediment surface. The correlation of fold orientation and reversals in vergence in the roof with structures in the underlying FATS establishes that FATS was the controlling influence rather than a universal shear caused by the overlying water column. Intense deformation directly (<10 cm) below the erosive base of the undeformed sedimentary cap is however considered a consequence of shearing against water.

5. Applicability of fold duplex models to gravity-driven FATS

The recognition in this case study of basal and upper detachments that bound the FATS, together with thrust ramps that imbricate the folded sequence indicates that a fold duplex model is applicable. The truncation of folds by detachments, and trapping of roof stratigraphy in synclinal folds, indicates folding initiated prior to detachments, which then propagated along the upper and lower boundaries of the FATS to create a fold duplex. The spatial correlation of folds in the roof with structures in the underlying FATS indicates that only limited relative translation subsequently occurred across the upper detachment, with displacement potentially transferring to higher stratigraphic levels thereby 'fixing' the spatial coincidence across the original boundary.

6) Comparing gravity-driven fold duplexes with those in orogenic settings

There are two principal differences when comparing fold duplexes from gravity-driven FATS (this study) from those in orogenic settings. a) The recognition in this study that new upper detachments form above older detachments is the opposite to that generally recorded in orogenic settings and reflects the shallow nature of deformation with pristine easy-slip planes preserved at higher stratigraphic levels. b) Within orogenic settings, fold duplexes tend to broadly follow piggyback and synchronous sequences. However, the thrust ramps in the case study are late structures that cross-cut pre-existing folds to link basal and upper detachments. They may display locally variable piggyback and overstep sequences reflecting the role of cessational strain that propagates back up the slope during 'lock-up' at the toe of gravity driven FATS.

Acknowledgements

RW was supported by the Israel Science Foundation (ISF grant No. 868/17). SM acknowledges the Israel Science Foundation (ISF grant No. 1645/19). TL was supported by a grant from the Israeli Government under Geological Survey of Israel DS project 40706. We would like to thank Chis Morley and an anonymous reviewer for detailed and constructive reviews, together with Cees Passchier for efficient editorial handling.

References

Agnon, A., Migowski, C., Marco, S., 2006. Intraclast breccia layers in laminated sequences: recorders of paleo-earthquakes, in Enzel, Y., Agnon, A., and Stein, M., eds., New Frontiers in Dead Sea Paleoenvironmental Research, Geological Society of America Special Publication, p. 195-214.

Agnon. A., Weinberger, R., Zak, I., Sneh, A. 2006. Geological Map of Israel. Sheet 20-I, II Sedom, scale 1:50,000. Israel Geological Survey, Jerusalem.

Alsop, G.I., Holdsworth, R.E. 2007. Flow perturbation folding in shear zones. In: Ries, A.C., Butler, R.W.H. & Graham, R.D. (Eds) Deformation of the Continental Crust: The legacy of Mike Coward. Geological Society, London, Special Publications, 272, 77-103

Alsop, G.I., Holdsworth, R.E. 2012. The three dimensional shape and localisation of deformation within multilayer sheath folds. Journal of Structural Geology. 44, 110-128.

Alsop, G.I.**,** Marco, S 2011. Soft-sediment deformation within seismogenic slumps of the Dead Sea Basin. Journal of Structural Geology 33, 433-457.

Alsop, G.I., Marco, S. 2012. Tsunami and seiche-triggered deformation within offshore sediments. Sedimentary Geology 261, 90-107.

Alsop, G.I.**,** Marco, S. 2014. Fold and fabric relationships in temporally and spatially evolving slump systems: A multi-cell flow model. Journal of Structural Geology, 63, 27-49.

Alsop, G.I., Marco, S., Weinberger, R., Levi, T. 2016a. Sedimentary and structural controls on seismogenic slumping within Mass Transport Deposits from the Dead Sea Basin. Sedimentary Geology 344, 71-90.

Alsop, G.I., Weinberger, R., Levi, T., Marco, S. 2016b. Cycles of passive versus active diapirism recorded along an exposed salt wall. Journal of Structural Geology, 84, 47-67.

Alsop, G.I., Marco, S., Levi, T., Weinberger, R. 2017a. Fold and thrust systems in Mass Transport Deposits. Journal of Structural Geology 94, 98-115.

Alsop, G.I., Marco, S., Weinberger, R., Levi, T. 2017b. Upslope-verging back thrusts developed during downslope-directed slumping of mass transport deposits. Journal of Structural Geology 100, 45-61.

Alsop, G.I., Weinberger, R., Marco, S. 2018a. Distinguishing thrust sequences in gravity-driven fold and thrust belts. Journal of Structural Geology 109, 99-119.

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2018b. Fault and fracture patterns around a strike-slip influenced salt wall. *Journal of Structural Geology 106, 103-124.*

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2019. Identifying soft-sediment deformation in rocks. Journal of Structural Geology, 125, 248-255.

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2020a. Fold and thrust systems in mass transport deposits around the Dead Sea Basin. In: Ogata, K., Festa, A., Pini, G.A. (Editors). Submarine landslides: subaqueous mass transport deposits from outcrops to seismic profiles. American Geophysical Union Monograph Series. 246, p.139-154. John Wiley & Sons Inc. 384pp. ISBN: 978-1-119-50058-2.

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2020b. Distinguishing coeval patterns of contraction and collapse around flow lobes in mass transport deposits. Journal of Structural Geology 134, 104013

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2020c. Folding during soft-sediment deformation. Geological Society Special Publication, Bond, C.E. and Lebit, H.D. (Editors) Folding and fracturing of rocks: 50 years since the seminal text book of J.G. Ramsay. 487, 81-104. doi.org/10.1144/SP487.1

Alsop, G.I., Weinberger, R., Marco, S., Levi, T. 2020d. Bed-parallel slip: Identifying missing displacement in mass transport deposits. Journal of Structural Geology 131, 103952.

Alsop, G.I., Weinberger, R., 2020. Are slump folds reliable indicators of downslope flow in recent mass transport deposits? Journal of Structural Geology 135, 104037

Armandita, C., Morley, C.K., Rowell, P. 2015. Origin, structural geometry, and the development of a giant slide: The South Makassar Strait mass transport complex. Geosphere, 11, 376-403.

Bartov, Y., Steinitz, G., Eyal, M., Eyal, Y., 1980. Sinistral movement along the Gulf of Aqaba - its age and relation to the opening of the Red Sea: Nature 285, 220-221.

Bartov, Y., Stein, M., Enzel, Y., Agnon, A., Reches, Z., 2002. Lake levels and sequence stratigraphy of Lake Lisan, the late Pleistocene precursor of the Dead Sea. Quaternary Research 57, 9-21.

Bartov, Y., Goldstein, S.L., Stein, M., Enzel, Y. 2003. Catastrophic arid episodes in the Eastern Mediterranean linked with the North Atlantic Heinrich events. Geology 31, 439-442.

Begin, Z.B., Ehrlich, A., Nathan, Y., 1974, Lake Lisan, the Pleistocene precursor of the Dead Sea: Geological Survey of Israel Bulletin, 63, p. 30.

Begin, B.Z., Steinberg, D.M., Ichinose, G.A., and Marco, S., 2005. A 40,000 years unchanging of the seismic regime in the Dead Sea rift: Geology, v. 33, p. 257-260.

Ben Dor, Y., Neugebauer, I., Enzel, Y., Schwab, M.J., Tjallingii, R., Erel, Y., Brauer, A. 2019. Varves of the Dead Sea sedimentary record. Quaternary Science Reviews 215, 173-184.

Biot, M.A. 1961. Theory of folding of stratified visco-elastic media and its implications in tectonics and orogenesis. Geological Society of America Bulletin 72, 1595-1620.

Boyer, S.E. 1992. Geometric evidence for synchronous thrusting in the southern Alberta and northwest Montana thrust belts. In: McClay, K. (Editor), Thrust Tectonics. Chapman and Hall. London. p. 377-390.

Boyer, S.E., Elliot, D. 1982. Thrust systems. American Association of Petroleum Geologists Bulletin 66, 1196-1230.

Boyer, S.E.,Mitra, G. 2019. Fold duplexes. Journal of Structural Geology 125, 202-212.

Bull, S., Cartwright, J., Huuse, M. 2009. A review of kinematic indicators from mass-transport complexes using 3D seismic data. Marine and Petroleum Geology 26, 1132-1151.

Butler, R.W.H., 1982. The terminology of structures in thrust belts. Journal of Structural Geology 4, 239-245.

Butler, R.W.H., 1987. Thrust sequences. Journal of the Geological Society, London, 144, 619-634.

Butler, R.W.H. 2004. The nature of ‘roof thrusts’ in the Moine Thrust Belt, NW Scotland: implications for the structural evolution of thrust belts. Journal of the Geological Society, London 161, 1-11.

Butler, R.W.H., McCaffrey, W.D. 2004. Nature of thrust zones in deep water sand-shale sequences: outcrop examples from the Champsaur sandstones of SE France. Marine and Petroleum Geology 21, 911-921.

Butler, R.W.H., Paton, D.A. 2010. Evaluating lateral compaction in deepwater fold and thrust belts: How much are we missing from “nature’s sandbox”? GSA Today 20, 4-10.

Butler, R.W.H., Eggenhuisen, J.T., Haughten, P., McCaffrey, W.D., 2016. Interpreting syndepositional sediment remobilization and deformation beneath submarine gravity flows; a kinematic boundary layer approach. Journal of the Geological Society, 173, 46-58.

Butler, R.W.H., Bond, C.E., Cooper, M.A., Watkins, H. 2020. Fold-thrust structures – where have all the buckles gone? Geological Society Special Publication, Bond, C.E. and Lebit, H.D. (Editors) Folding and fracturing of rocks: 50 years since the seminal text book of J.G. Ramsay. 487, 21-44.

Chapman, T.J., Williams, G.D. 1984. Displacement-distance methods in the analysis of fold-thrust structures and linked-fault systems. Journal of the Geological Society 141, 121-128.

Corredor, F., Shaw, J.H., Bilotti, F., 2005. Structural styles in the deep-water fold and thrust belts of the Niger Delta. American Association of Petroleum Geologists Bulletin 89, 753-780.Dahlstrom, C.D.A., 1969. The upper detachment in concentric folding. Bulletin of Canadian Petroleum Geology 17, 326-347.

Dahlstrom, C.D.A. 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. Bulletin of Canadian Petroleum Geology 18, 332-406.

Dahlstrom, C.D.A. 1990. Geometric constraints derived from the Law of Conservation of Volume and applied to evolutionary models of detachment folding. American Association of Petroleum Geologists Bulletin 74, 336-344.

Dalton, T.J.S., Paton, D.A., Needham, D.T., Hodgson, N. 2015. Temporal and spatial evolution of deepwater fold thrust belts: Implications for quantifying strain imbalance. Interpretation, 3, SAA59–SAA70.

de Vera, J., Granado, P., McClay, K. 2010. Structural evolution of the Orange Basin gravity-driven system, offshore Namibia. Marine and Petroleum Geology 27, 223-237

El-Isa, Z.H., Mustafa, H. 1986. Earthquake deformations in the Lisan deposits and seismotectonic implications. Geophysical Journal of the Royal Astronomical Society 86, 413-424.

Elliot, D., Johnson, M.R.W. 1980. Structural evolution in the northern part of the Moine thrust belt of NW Scotland. Transactions of the Royal Society of Edinburgh, Earth Science, 71B, 69-96.

Ellis, M.A., Dunlap, W.J. 1988. Displacement variation along thrust faults: implications for the development of large faults. Journal of Structural Geology 10, 183-192.

Escher, A., Watterson, J. 1974. Stretching fabrics, folds and crustal shortening. Tectonophysics 22, 223-231.

Farrell, S.G. 1984. A dislocation model applied to slump structures, Ainsa Basin, South Central Pyrenees, Journal of Structural Geology 6, 727-736.

Ferrill, D.A., Morris, A.P., Wigginton, S.S., Smart, K.J., McGinnis, R.N., Lehrmann, D. 2016. Deciphering thrust fault nucleation and propagation and the importance of footwall synclines. Journal of Structural Geology, 85, 1-11.

Fossen, H. 2016. Structural Geology. 2nd Edition. Cambridge University Press, Cambridge, UK, p.510.

Fossen, H., Cavalcante, G.C.G., Pinheiro, R.V.I., Archanjo, C.J. 2019. Deformation – Progressive or multiphase? Journal of Structural Geology doi: 10.1016/j.jsg.2018.05.006

Frey-Martinez, J., Cartwright, J., James, D. 2006. Frontally confined versus frontally emergent submarine landslides: A 3D seismic characterisation. Marine and Petroleum Geology23, 585-604.

Garcia-Tortosa, F.J., Alfaro, P., Gibert, L., Scott, G. 2011. Seismically induced slump on an extremely gentle slope (<1°) of the Pleistocene Tecopa paleolake (California). Geology 39, 1055-1058.

Garfunkel, Z., 1981. Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics: Tectonophysics 80, p. 81-108.

Geiser, P.A., 1988. The role of kinematics in the construction and analysis of geological cross sections in deformed terranes. In: Mitra, G. and Wotal, S. (eds.), Geometries and Mechanisms of Thrusting with special reference to the Appalachians. Geological Society of America, Special Paper, 222, 47-76.

Gibert, L., Sanz de Galdeano, C., Alfaro, P., Scott, G., Lopez Garrido, A.C. 2005. Seismic-induced slump in Early Pleistocene deltaic deposits of the Baza Basin (SE Spain). Sedimentary Geology 179, 279-294.

Haase-Schramm, A., Goldstein, S.L., Stein, M. 2004. U-Th dating of Lake Lisan aragonite (late Pleistocene Dead Sea) and implications for glacial East Mediterranean climate change. Geochimica et Cosmochimica Acta 68, 985-1005.

Haliva-Cohen, A., Stein, M., Goldstein, S.L., Sandler, A., Starinsky, A. 2012. Sources and transport routes of fine detritus material to the Late Quaternary Dead Sea Basin. Quaternary Science Reviews 50, 55-70.

Hedlund, C.A. 1997. Fault-propagation, ductile strain, and displacement-distance relationships. Journal of Structural Geology 19, 249-256.

Hughes, A.N., Shaw, J.H. 2014. Fault displacement-distance relationships as indicators of contractional fault-related folding style. American Association of Petroleum Geologists Bulletin 98, 227-251.

Ireland, M.T., Davies, R.J., Goulty, N.R., Moy, D.J. 2011. Thick slides dominated by regular-wavelength folds and thrusts in biosiliceous sediments on the Vema Dome offshore of Norway. Marine Geology, 289, 34-45.

Jablonska, D., Di Celma, C., Tondi, E., Alsop, G.I. 2018. Internal architecture of mass-transport deposits in basinal carbonates: A case study from southern Italy. *Sedimentology 65 (4), 1246-1276. doi:* 10.1111/sed.12420

Jackson, C. A-L. 2011. Three-dimensional seismic analysis of megaclast deformation within a mass transport deposit: implications for debris flow kinematics. Geology 39, 203-206.

Jamison, W.R. 1987. Geometric analysis of fold development in overthrust terranes. Journal of Structural Geology 9, 207-219.

Jolly, B.A., Lonergan, L., Whittaker, A.C., 2016. Growth history of fault-related folds and interaction with seabed channels in the toe-thrust region of the deep-water Niger delta. Marine and Petroleum Geology 70, 58-76.

Kagan, E.J., Stein, M., Marco, S. 2018. Integrated palaeoseismic chronology of the last glacial Lake Lisan: From lake margin seismites to deep-lake mass transport deposits. Journal of Geophysical Research: Solid Earth 123 (4) 2806-2824.

Ken-Tor, R., Agnon, A., Enzel, Y., Marco, S., Negendank, J.F.W., and Stein, M., 2001. High-resolution geological record of historic earthquakes in the Dead Sea basin: J. Geophys. Res., v. 106, p. 2221-2234.

Kim, Y.S., Sanderson, D.J. 2005. The relationship between displacement and length of faults. Earth Science Reviews 68, 317-334.

Korneva, I., Tondi, E., Jablonska, D., Di Celma, C., Alsop, I., Agosta, F. 2016. Distinguishing tectonically- and gravity-driven synsedimentary deformation structures along the Apulian platform margin (Gargano Promontory, southern Italy). Marine and Petroleum Geology 73, 479-491.

Koyi, H. 1995. Mode of internal deformation in sand wedges. Journal of Structural Geology 17, 293-300.

Koyi, H.A., Hessami, K., Teixell, A. 2000. Epicenter distribution and magnitude of earthquakes in fold-thrust belts: Insights from Sandbox Models. Geophysical Research Letters, 27, 273-276.

Koyi, H.A., Sans, M., Teixell, A., Cotton, J., Zeyen, H. 2004. The significance of penetrative strain in the restoration of shortened layers – insights from sand models and the Spanish Pyrenees. In: McClay, K.R. (Editor) Thrust Tectonics and hydrocarbon systems. American Association of Petroleum Geology Memoir 82, 207-222.

Levi, T., Weinberger, R., Aïfa, T., Eyal, Y., S. Marco, S. 2006a. Injection mechanism of clay-rich sediments into dikes during earthquakes, Geochemistry, Geophysics, and Geosystems 7, no. 12, Q12009.

Levi, T., Weinberger, R., Aïfa, T., Eyal, Y., S. Marco, S. 2006b. Earthquake-induced clastic dikes detected by anisotropy of magnetic susceptibility, Geology, 34(2), 69–72.

Levi, T., Weinberger, R., Alsop, G.I., Marco, S. 2018. Characterizing seismites with anisotropy of magnetic susceptibility. *Geology* 46 (9), 827-830.

Liu, S., Dixon, J.M. 1995. Localization of duplex thrust-ramps by buckling: analog and numerical modelling. Journal of Structural Geology 17, 875-886.

Liu, X., Eckert, A., Connolly, P., Thornton, D. 2020. Visco-elastic Parasitic Folding: Influences on the Resulting Porosity Distribution. Journal of Structural Geology 130, 103892.

Lu, Y., Waldmann, N., Alsop, G.I., Marco, S. 2017. Interpreting soft sediment deformation and mass transport deposits as seismites in the Dead Sea depocentre. Journal of Geophysical Research: Solid Earth, 122. 10, 8305-8325.

Marco, S., Stein, M., Agnon, A., and Ron, H., 1996. Long term earthquake clustering: a 50,000 year paleoseismic record in the Dead Sea Graben: J. Geophys. Res., 101, 6179-6192.

Martinsen, O.J., Bakken, B. 1990. Extensional and compressional zones in slumps and slides in the Namurian of County Claire, Eire. *Journal of the Geological Society, London* 147, 153-164.

McClay, K.R., 1992. Glossary of thrust tectonic terms. In: McClay, K.R. (Editor) Thrust Tectonics. Chapman and Hall, London. P. 419-433.

Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., and Stein, M., 2004, Recurrence pattern of Holocene earthquakes along the Dead Sea transform revealed by varve-counting and radiocarbon dating of lacustrine sediments: Earth and Planetary Science Letters, v. 222, p. 301-314.

Mitra, G., Boyer, S.E. 2020. Duplexes as slip transfer zones: Application to the Himalayan fold-thrust belt. Journal of Asian Earth Sciences 190, 104214.

Morley, C.K. 1988. Out-of-sequence thrusts. Tectonics 7, 539-561.

Morley, C.K., King, R., Hillis, R., Tingay, M., Backe, G. 2011. Deepwater fold and thrust belt classification, tectonics, structure and hydrocarbon prospectivity: A review. Earth Science Reviews, 104, 41-91.

Morley, C.K., von Hagke, C., Hansberry, R.L., Collins, A.S., Kanitpanyacharoen, W., King, R. 2017. Review of major shale-dominated detachment and thrust characteristics in the diagenetic zone: Part 1, meso- and macro-scopic scale. Earth Science Reviews173, 168-228.

Morley, C.K., Naghadeh, D.H. 2018. Tectonic compaction shortening in toe region of isolated listric normal fault, North Taranaki Basin, New Zealand. Basin Research 30, 424-436.

Morley, C.K., Jitmahantakul, S. 2020. Secondary detachments within carbonates of the Saraburi Group, Triassic Khao Khwang Fold and Thrust Belt, Thailand. Journal of Structural Geology, https://doi.org/10.1016/j.jsg.2020.104162

Moscardelli L., Wood L. 2008. New classification system for mass transport complexes in offshore Trinidad. Basin Res 20:73–98.

Muraoka, H., Kamata, H., 1983. Displacement distribution along minor fault traces. Journal of Structural Geology 5, 483-495.

Noble, T.E., Dixon, J.M., 2011. Structural evolution of fold-thrust structures in analog models deformed in a large geotechnical centrifuge. Journal of Structural Geology 33, 62-77.

Nuriel,P., Weinberger, R., Kylander-Clark, A.R.C., Hacker, B.R., Cradock, J.P. 2017. The onset of the Dead Sea transform based on calcite age-strain analyses. Geology 45, 587-590.

Peach, B.N., Horne, J., Gunn, W., Clough, M.A., Hinxman, L.W. 1907. The geological structure of the North-west Highlands of Scotland. Geological Survey of Great Britain.

Peacock, D.C.P., Sanderson, D.J. 1996. Effects of propagation rate on displacement variations along faults. Journal of Structural Geology 18, 311-320.

Peel, F.J., 2014. The engines of gravity-driven movement on passive margins: Quantifying the relative contribution of spreading vs. gravity sliding mechanisms. Tectonophysics 633, 126-142.

Pei, Y., Paton, D.A., Knipe, R.J., Lickorish, W.H., Li, A., Wu, K., 2019. Field-based investigation of fault architecture: A case study from the Lenghu fold-and-thrust belt, Qaidam Basin, NE Tibetan Plateau. Geological Society of America Bulletin. doi: https://doi.org/10.1130/B35140.1

Posamentier, H.W., Martinsen, O.J. 2011. The character and genesis of submarine mass-transport deposits: Insights from outcrop and 3D seismic data. Mass transport deposits in Deepwater settings: Society for Sedimentary Geology (SEPM) Special Publication 96, 7-38.

Prasad, S., Negendank, J.F.W., Stein, M. 2009. Varve counting reveals high resolution radiocarbon reservoir age variations in palaeolake Lisan. Journal of Quaternary Science 24, 690-696.

Price, N.J., Cosgrove, J.W. 1990. Analysis of Geological Structures. Cambridge University Press. 502pp.

Prior, D.B., Bornhold, D., Johns, M.W. 1984. Depositional characteristics of a submarine debris flow. Journal of Geology 92, 707-727.

Ramsay, J.G. 1967. Folding and fracturing of rocks. McGraw-Hill. New York. pp.568.

Ramsay, J.G. 1974. Development of chevron folds. Geological Society of America Bulletin 85, 1741-1754.

Reis, A.T., Araújo, E., Silva, C.G., Cruz, A.M., Gorini, C., Droz, L., Migeon, S., Perovano, R., King, I., Bache, F. 2016. Effects of a regional décollement level for gravity tectonics on late Neogene to recent large-scale slope instabilities in the Foz do Amazonas Basin, Brazil. Marine and Petroleum Geology 75, 29-52.

Scarselli, N., McClay, K., Elders, C. 2016. Seismic geomorphology of Cretaceous megaslides offshore Namibia (Orange Basin): Insights into segmentation and degradation of gravity-driven linked systems. Marine and Petroleum Geology 75, 151-180.

Sharman, G.R., Graham, S.A., Masalimova, L.U., Shumaker, L.E., King, P.R. 2015. Spatial patterns of deformation and palaeoslope estimation within the marginal and central portions of a basin-floor mass-transport deposit, Taranaki Basin, New Zealand. Geosphere, 11, 266-306.

Sneh, A., Bartov, Y., Weissbrod, T., Rosenaft, M. 1998. Geological map of Israel, Scale 1: 200,000, Geological Survey of Israel, Jerusalem.

Sneh, A., Weinberger, R. 2014. Major structures of Israel and Environs, Scale 1:500,000. Israel Geological Survey, Jerusalem.

Sobiesiak, M., Kneller, B.C., Alsop, G.I., Milana, J.P. 2017. Sub-seismic scale folding and thrusting within an exposed mass transport deposit: A case study from NW Argentina. *Journal of Structural Geology* 96, 176-191.

Sobiesiak, M., Kneller, B.C., Alsop, G.I., Milana, J.P. 2018. Styles of basal interaction beneath mass transport deposits. Marine and Petroleum Geology 98, 629-639.

Sobiesiak, M., Kneller, B.C., Alsop, G.I., Milana, J.P. 2020. Block generation, deformation and interaction of mass-transport deposits with the seafloor: An outcrop-based study of the Carboniferous Paganzo Basin (Cerro Bola, NW Argentina). In: Ogata, Kei; Festa, Andrea; Pini, Gian Andrea (Editors) *Submarine landslides: subaqueous mass transport deposits from outcrops to seismic profiles*. American Geophysical Union Monograph Series, 246, p.91-104. John Wiley & Sons Inc. 384pp. ISBN: 978-1-119-50058-2.

Steventon, M.J., Jackson, C,A-L, Hodgson, D.M., Johnson, H.D. 2019. Strain analysis of a seismically imaged mass-transport complex, offshore Uruguay. Basin Research 31, 600-620.

Stewart, S.A. 1996. Influence of detachment layer thickness on style of thin-skinned shortening. Journal of Structural Geology 18, 1271-1274.

Strachan, L.J. 2002. Slump-initiated and controlled syndepositional sandstone remobilization; an example from the Namurian of County Clare, Ireland. *Sedimentology*, 49, 25-41.

Van der Pluijm, B.A., Marshak, S. 2004. Earth Structure. An introduction to structural geology and tectonics. 2nd Edition. W.W. Norton and Company. New York. 656pp.

Weinberger, R., Levi, T., Alsop, G.I., Eyal, Y. 2016. Coseismic horizontal slip revealed by sheared clastic dikes in the Dead Sea basin. Geological Society of America Bulletin 128, 1193-1206.

Weinberger, R., Levi, T., Alsop, G.I., Marco, S. 2017. Kinematics of Mass Transport Deposits revealed by magnetic fabrics. Geophysical Research Letters 44, 7743-7749.

Williams, G., Chapman, T. 1983. Strains developed in the hangingwall of thrusts due to their slip/propagation rate: a dislocation model. Journal of Structural Geology 5, 563-571.

Willis, B., 1902. Stratigraphy and structure, Lewis and Livingston Ranges, Montana. Geological Society of American Bulletin, 13, 305-352.

Woodcock, N. H 1976a. Ludlow Series slumps and turbidites and the form of the Montgomery Trough, Powys, Wales. Proceedings of the Geologists Association 87, 169-182.

Woodcock, N. H 1976b. Structural style in slump sheets: Ludlow Series, Powys, Wales. Journal of the Geological Society, London 132, 399-415.

Woodcock, N.H. 1979. The use of slump structures as palaeoslope orientation estimators. *Sedimentology*, 26, 83-99.

Zalan, P.V., 2005. End members of gravitational fold and thrust belts (GFTBs) in the deep waters of Brazil. In: Shaw, J.H., Connors, C., and Suppe, J., (Editors) An AAPG Seismic Atlas: AAPG studies in Geology 53, 147-156

Zucker, A., Frumkin, A., Agnon, R., Weinberger, R. 2019. Internal deformation and uplift-rate of Salt walls detected by a displaced dissolution surface, Dead Sea basin Journal of Structural Geology 127, 103870

Figure Captions

Fig. 1. a) Schematic cartoon of a fold duplex that illustrates geometric parameters such as bed thicknesses, ramp angles, fold wavelengths (λ) and amplitude (*A*) that are measured around early buckle folds and late thrusts within the fold and thrust system (FATS). b) Schematic cartoon illustrating how the roof above the upper detachment may be passive and remains fixed and unmoved (pinned) relative to the sequence beneath the basal detachment. Differences in relative downslope velocity between the roof and underlying FATS generate a shear couple that creates upslope-verging folds in the hangingwall of the upper detachment. c) Schematic cartoon illustrating how the roof above the upper detachment may be active and moves downslope more slowly than the underlying FATS. The roof is sub-active with the hangingwall velocity (Hw V) above the upper detachment being less than the footwall velocity (Fw V) beneath it (Hw V < Fw V). This difference in relative downslope velocity generates a shear couple that creates upslope-verging folds in the hangingwall of the upper detachment. d) Schematic cartoon illustrating how the roof above the upper detachment may be active and moves downslope more rapidly than the underlying FATS. The roof is super-active with the hangingwall velocity above the upper detachment being greater than the footwall velocity beneath it (Hw V > Fw V). This difference in relative downslope velocity generates a shear couple that creates downslope verging folds in the hangingwall of the upper detachment. In all cases, the folds and late thrusts are considered to transfer displacement from the basal to upper detachments to create a fold duplex.

Fig 2. a) General map showing tectonic plates in the Middle East and the location of the Dead Sea Fault (DSF). b) Map of the Dead Sea showing the position of the study area (red box) (based on Sneh and Weinberger, 2014). c) Perspective view (looking NNE) of a geological map draped on a Google Earth image of the southern Dead Sea Basin. Upper Cretaceous (greens and browns) outcrops to the west of the Dead Sea Western Border Fault Zone, while Lisan Formation (buff colour) outcrops to the east. Geology is after Sneh et al. (1998) and

Agnon et al. (2006). d) Image of the light-coloured Lisan Formation at Wadi Peratzim, with the brownish Cretaceous rocks to the west and the Sedom salt wall to the east. e) Aerial photograph showing the case study outcrops and gullies within the Lisan Formation. Extent of the studied MTD is highlighted in yellow (see Alsop et al., 2016). Coordinates of the Israel national grid are shown. f) Drone photograph giving a perspective view looking NE down Wadi Peratzim towards the Sedom salt wall in the distance. The position of some studied sections on the walls of gullies are highlighted in yellow.

Fig 3. a) Panoramic view, and b) interpreted line drawing of a transport-parallel section across a gravity-driven fold and thrust system (FATS) at Peratzim (see Fig. 2 for location). The position of detailed overlapping photographs (c, e, g) and the annotated line drawings (d, f, h) are located on b). Thrusts and the lower detachment are shown in red, while the upper detachment is a red dotted line. Arrows (red) indicate interpreted local kinematics across thrust ramps and detachments. The position of the sedimentary cap with erosive base that overlies the deformed sequence is highlighted in orange. Particular marker horizons are shown in different colours and an estimate of the % line-length contraction for that marker shown at the ends of each section. The dark blue detrital marker bed positioned above the upper detachment is highlighted and displays significantly less shortening and reversals in fold vergence compared to the underlying FATS. Stereonets of slump folds from i) entire MTD horizon (N=150 folds), and j) panoramic section shown in Fig. 3a (N=106 folds). In each stereonet, fold hinges (solid red circles) and mean fold axial plane shown by blue great circle and poles to individual fold axial planes (solid blue squares). Mean thrust plane shown by dashed red great circle and poles to individual thrust planes (solid red triangles). k) Stereonet of slump folds from panoramic section (Fig. 3a) that are cut by late thrusts. Fold hinge data with anticlines (solid red circles) and synclines (solid blue circles). Poles to anticline axial planes (solid red squares) and syncline axial planes (solid blue squares). Mean anticline and syncline axial planes are shown by red and blue great circles respectively. Mean fold hinges and poles to axial planes are shown by open red (anticline) and blue (syncline) symbols. Mean thrust plane shown by red great circle and poles to individual thrust planes (solid red triangles). L) Cumulative displacement-distance (C-DD) graph from the section shown in Fig. 3a, b. Distance is measured from the reference point (R) marking the start of the section (shown by yellow circle in h) to the point where each imbricate ramps from the basal detachment. Displacement is measured across the lowermost green marker bed. See section 5.1. for details.

Fig. 4. Panorama and interpreted line drawing (b) of the NE end of the transport-parallel section shown in Fig. 3g, h). The position of detailed photographs (c, e, f, g) are located on b). Thrusts and the lower detachment are shown in red, while the upper detachment is a red dotted line. Arrows (red) indicate interpreted local kinematics across thrust ramps and detachments. Particular marker horizons are highlighted in different colours and an estimate of the % contraction for that marker shown at the ends of each section. The dark blue marker bed positioned above the upper detachment displays significantly less shortening and reversal

in fold vergence compared to the underlying FATS. Details of imbricates are shown in g), with an example of a ramp along an 'internal' detachment. d) Stereonet of anticline fold hinges (red circles) and associated poles to axial planes (red squares), syncline fold hinges (blue squares) and associated poles to axial planes (blue circles). Data collected from the blue marker layer above the upper detachment is shown as fold hinges (blue diamonds), poles to axial planes (blue triangles). In each case, the mean data point is shown by an equivalent open symbol, whereas mean axial planes are shown as red (for FATS) and blue (folds above detachment) dashed great circles. The orientation of mean thrust plane is shown by solid red great circle. The overall transport direction (TD) of the FATS is towards 040°. 10 cm chequered rule and 15 mm diameter coin act as scales. h) t'_α graph (where $t'_\alpha = t_\alpha / t_0$) where t_0 is layer thickness measured along the axial surface, while t_α is orthogonal layer thickness measured at various angles (α) to the reference plane oriented at 90° to the axial surface (Ramsay 1967, p. 366). Graphs normalise thicknesses by using t'_α and plot this value against dip angle (α) to create a series of fold classes with data from detrital-rich marker bed around buckle folds A and B shown in e). Data is divided into SW fold limbs (squares) and NE fold limbs (circles).

Fig 5. a-e) Sets of detailed photographs, associated stereonets and displacement-distance (D-D) plots from individual structures within the transport-parallel section shown in Fig. 3. Individual marker beds are partially highlighted and colour-coded with data on associated D-D plots. In a) and e), the data from two thrusts (labelled 1, 2 and 3, 4 respectively) are shown on the same D-D plots. The position of the reference datum (R) for measuring distances along thrust planes is located on each photograph (yellow circle). In each case, displacement is greatest near the basal detachment and decreases up the thrust ramp. Stereonets show anticline fold hinges (red circles) and associated poles to axial planes (red squares), syncline fold hinges (solid blue squares) and associated poles to axial planes (open blue squares). In each case, the mean fold hinge data point is shown by an equivalent open symbol, whereas thrust planes are shown as solid great circle and poles as solid triangles. Syncline fold hinges are consistently clockwise of adjacent anticline hinges, and oblique to the calculated transport direction (TD).

Fig 6. Analysis of structural data measured along the 25 m section shown in Fig. 3a, b. a) Plot comparing trends of hangingwall anticline hinges and axial planes with adjacent footwall syncline hinges and axial planes measured directly across associated thrust (N=13). b) Plot comparing trends of hangingwall anticline hinges and footwall syncline hinges with trends of associated thrusts (N=13). c) Plot comparing trends of hangingwall anticline axial planes and adjacent footwall syncline axial planes with trend of associated thrust (N=12). d) Plot comparing interlimb angles with dip of axial planes of anticlines (N=48), hangingwall anticlines (N=12), synclines (N=52) and footwall synclines (N=12). e) Plot comparing interlimb angles with dip of axial planes of hangingwall anticlines and footwall synclines (N=12). f) Plot comparing interlimb angles with the trends of hangingwall anticlines and footwall synclines (N=13). g) Plot comparing interlimb angles of hangingwall anticlines with adjacent footwall synclines (N=13). h) Plot comparing interlimb angles of hangingwall anticlines and footwall synclines with dip of thrust ramps. (N=11). i) Plot comparing dip of thrust ramp with maximum displacement along thrust. (N=25). Plots comparing % thinning (-ve) or thickening of anticline forelimbs with j) interlimb angle of hangingwall anticlines (N=15), k) maximum displacement along thrust ramps (N=15), l) angle of dip of thrust ramps (N=15). Plots showing % thinning (-ve) or thickening of anticline forelimbs compared to backlimbs plotted against, m) interlimb angles and thrust ramp angles (N=14); n) interlimb angles and dip of backlimbs where not cut by thrusts (N=17), o) interlimb angles and dip of backlimbs where both cut and not cut by thrusts (N=31) (based on Jamison, 1987). Red symbols represent thickened fold limbs, whereas blue symbols represent thinned limbs with the % thinning (-ve) and thickening given in each case.

Fig 7. a, e) Photographs and b, f) associated line drawings of the FATS (see Fig. 3b, g for locations, and Fig. 5a, e for further data). The amount of % shortening across different marker layers is shown in the boxes. Photographs c, d) and g, h) show details of the upper detachment (red dotted line) in each case. Large displacements along thrust ramps are transferred onto the upper detachment leaving the overlying blue marker horizon unaffected by thrusts and with SW-verging folds. The blue marker layer is also locally trapped in synclinal cores (g) beneath the upper detachment. Scale is provided by the 10 cm chequered rule and 15 mm diameter coin.

Fig 8 Detailed photographs of pinched synclines and upper detachment in the studied section (see Fig. 3e for locations) Photograph a) shows that in some instances folds verge in the same direction above and below the upper detachment (red dotted line), thereby suggesting only partial decoupling across this structure. Photographs b, c) and e, f) show further details of the upper detachment in each case. b) Pinching shut of synclines causes local folding and imbrication of the blue marker layer above the upper detachment, together with the development of new higher-level detachments (2). e) Refolding of folds in the blue marker layer with increasing shear upwards towards the sediment surface. Scale is provided by the 10 cm chequered rule and 15 mm diameter coin.

Fig 9 a, c) Photographs and b, d) associated line drawings of the FATS (see Fig. 2e for location). The amount of % shortening across different marker layers is shown in the boxes in b) and d). Photograph e) shows details (from c) of stratigraphic cut-offs along the basal detachment, while f) shows fanning folds above the upper detachment (red dotted line). f) Fanning crowns of folds formed above the upper detachment and underlying thrusts and synclines. Note that fanning folds are truncated by the overlying sedimentary cap. Scale is provided by the 10 cm chequered rule.

Fig. 10 a) Photograph and b) associated line drawing of the FATS (see Fig. 2e for location). The amount of % shortening across different marker layers is shown in the boxes in b).

Photographs c, d) and e, f) show details of folding above multiple upper detachments (red and pink dotted lines), together with refolding of earlier axial planes. Scale is provided by the 10 cm chequered rule. g) Schematic summary cartoons illustrating the role of fold tightening in generating a range of potential fold and thrust geometries. Structures are shown evolving from an early stage (i) to a later stage (iii) during downslope translation of FATS. Thrust ramps are progressively flattened resulting in earlier buckle folds being systematically tightened and 'pinched' during expulsion of sediments from fold cores. Reversals in fold vergence in the blue marker bed reflect variations in relative downslope velocity across the upper detachment (see Fig. 1b-d).

Fig 11 a) Photograph and b) associated line drawing of backthrust system (see Fig. 2e for location). The amount of % shortening across different marker layers is shown in the boxes in b). Photograph c) show details of backthrusting, together with folding of the blue marker layer above multiple upper detachments (red and pink dotted lines). Scale is provided by the 10 cm chequered rule. d) Schematic summary cartoons illustrating the role of fold tightening in generating a range of potential fold and thrust geometries. Structures are shown evolving from an early stage (i) to a later stage (iii) during downslope translation of FATS. Backthrust ramps are progressively steepened resulting in earlier buckle folds being systematically tightened and synclines 'pinched' during expulsion of sediments from fold cores. Reversals in fold vergence in the blue marker bed reflect variations in relative downslope velocity across the upper detachment, with fanning crowns of folds formed above tightened synclines.

Fig. 12. Summary cartoon showing a) downslope-propagating piggyback thrust sequences, and; b) upslope-propagating overstep thrust sequences. In piggyback thrusting (a), new gently-dipping thrusts (4) develop in the footwalls of existing thrusts thereby causing a rotation and progressive back-steepening of the older, overlying thrusts. In overstep thrusting (b), new moderately-dipping thrusts (4) form in the hangingwalls of existing thrusts and progressively load and flatten the underlying pinched synclines resulting in reduced dips of underlying thrusts. Continued movement on thrusts during loading results in greater displacement on gently-dipping thrusts.

Fig. 13. Summary cartoon based on orientation data in Fig. 6, highlighting geometric obliquities between hangingwall anticlines and adjacent footwall synclines developed across late thrust ramps. Synclines are generally tighter, and trend clockwise of anticlines, due to loading from overlying thrust ramps and progressive shear during continued downslope translation. See text for further discussion.

Fig 14. Schematic summary cartoons highlighting the role of variations in relative velocity across upper detachments in generating a range of potential fold and thrust geometries. In each case, structures are shown evolving from an early stage (i) to a later stage (iii) during progressive downslope translation of FATS. a) A relatively late-stage upper detachment propagates across and truncates earlier buckle folds that are systematically tightened and 'pinched' during expulsion of sediments from fold cores. b) Upper detachment is folded by continued shortening in FATS resulting in a fanning 'crown' of folds above the 'locked' detachment. c) Upper detachment is folded and 'locked' by continued shortening in FATS, resulting in displacement transferring to a higher level to create a new upper detachment (2). d) Synthesis cartoon illustrating how variations in relative hangingwall velocity (Hw) and footwall velocity (Fw) across the upper detachment create sub-active roofs, inactive roofs and super-active roofs. Displacement is transferred from the basal detachment to the upper detachment via folds and late-stage thrusts.

Fig 15 Summary cartoon of reversals in relative shear sense across upper detachments that bound fold duplexes in gravity-driven FATS. Folds formed in the hangingwall of the upper detachment are typically coaxial to, but verge in the opposite sense to folds in the underlying downslope-translating FATS. The overlying sedimentary cap is deposited out of suspension following cessation of movement that creates the MTD and may in some cases erode the upper detachment.

Marker Bed	Fig. 3 (26.4m)	Fig. 10 (16.2m)	Fig. 11 (5.0m)	Fig. 12 (7.6m)	Section X (8.8m)	Section Y (6.1m)	Weighted % shortening
Blue	12.2% (3.7m)	4.6% (0.8m)	10.2% (0.6m)	6.9% (0.6m)	8.4% (0.8m)	15.5% (1.1m)	9.5% (7.4m)
Cyan	35.9% (14.8m)	7.9% (1.4m)	27.8% (1.9m)	11.5% (1.0m)	24.4% (2.8m)	26% (2.1m)	23.9% (22.0m)
Brown	50.8% (27.3m)	33.3% (8.1m)	45.9% (4.2m)	27.0% (2.8m)	40.0% (5.9m)	48.7% (5.8m)	42.3% (51.4m)
Magenta	49.9% (26.3m)	43.8% (12.6m)	41.1% (3.5m)	32.5% (3.7m)	40.0% (5.9m)	51.4% (6.4m)	44.9% (57.1m)
Green	49.9% (26.3m)	Excised	46.5% (4.3m)	29.3% (3.1m)	40.0% (5.9m)	44.8% (4.9m)	42.3% (39.5m)

Table 1. Amounts of line length shortening of the different marker beds measured in different transport-parallel sections totalling 70.1 m across the studied FATS. Refer to Fig. 2e for locations of each figure and section. Data shows that most shortening occurs in the central brown and magenta beds (~45% or ~55m) and this decreases slightly towards the base (green) and top (cyan). The uppermost blue layer always displays significantly less shortening. Note that part of the lowermost green marker in the Fig. 10 section was partially excised by the basal detachment, meaning that the original length of the green marker in this section cannot be estimated and has been discounted.

Marker Bed	Fig. 3 Total %	Fig. 3 % Folding	Fig. 3 % Thrusting	Fig. 3 Folding	Fig 3 Thrusting
Blue	12.2%	11.1%	1.1%	90.1%	9.9%
Cyan	35.9%)	24.2%	11.6%	67.4%	32,6%
Brown	50.8%	40.6%	10.2%	79.9%	20.1%
Magenta	49.9%	27.8%	22.1%	55.7%	44.3%
Green	49.9%	12.2%	37.7%	24.5%	75.5%

Table 2. Amounts of line length shortening of the different marker beds measured in the studied FATS shown in Fig. 3 (refer to Fig. 2e for location). Data for each coloured marker layer is divided into columns for total % shortening, % shortening by folding, % shortening by thrusting, proportion of total shortening by folding, proportion of total shortening by thrusting. The total % shortening decreases up through the stratigraphy, with a marked reduction in the uppermost blue marker layer. In detail, the proportion of shortening represented by thrusting increases up through the sequence, while there is a concomitant reduction in the proportion of thrusting.