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Combined control of décollement layer thickness and cover rock cohesion on structural styles and evolution of fold belts: a discrete element modelling study

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Abstract

A series of numerical experiments based on the discrete element method were performed to simulate the formation of fold belts, with varied décollement layer thickness and cover rock cohesion, to investigate their controls on structural styles of fold belts. Each model consists of a weak, unbonded basal décollement layer with a relatively low to high thickness, and a bonded cover with a relatively low to high cohesive strength. Horizontal shortening of the particle assemblage was achieved by horizontal motion of a vertical boundary wall, resulting in deformations in the system. The results show that shortening was mainly accommodated by detachment folds (sinusoidal and box folds), fault-related folds and opening-mode fractures in the models. The combination of a lower cohesion and a thinner décollement resulted in more distributed strain and a larger number of folds, whilst the combination of a higher cohesion and a thicker décollement led to more pronounced strain localisations in fewer folds. Surface uplift and fold amplitude (diapir height) are mainly positively affected by the décollement thickness, i.e. the thicker the décollement is, the greater the surface uplift and fold amplitude are. The propagation rate of deformation is predominately controlled by the cover rock cohesion. A lower cohesion led to a higher propagation rate of deformation. The model with a relatively low

cohesion and décollement thickness produced regularly-spaced box folds, which are comparable to those in the southern Zagros Fold-and-Thrust Belt. The models presented demonstrate that the combined effect of décollement layer thickness and cover rock cohesion can play a critical role in the structural styles and kinematic evolution of fold belts.

Key words: discrete element method, fold-and-thrust belt, cohesion, décollement thickness

1. Introduction

Fold-and-thrust (FAT) belts occur worldwide and are widely recognised as the most common mode in which the crust accommodates shortening (Davis et al., 1983; Poblet and Lisle, 2011). FAT belts, as the result of contractional tectonics, commonly exhibit a variety of structural styles (Cooper, 2007), which have long been the focus of research of structural geologists. Multiple factors have been suggested to play an important role in controlling structural styles in FAT belts, mainly including the distribution, thickness, dip and shear resistance of décollement levels, and mechanical contrasts between décollement levels and the rocks above and below these levels (e.g. Dahlen et al., 1984; Davis and Engelder, 1985; Costa and Vendeville, 2002; Bahroudi and Koyi, 2003; Massoli et al., 2006; Vidal-Royo et al., 2009; Ruh et al., 2012), the thickness, facies distribution and mechanical stratigraphy of the overburden (e.g. Marshak and Wilkerson, 1992; Erickson, 1996; Alavi, 2004; Farzipour-Saein et al., 2009; Morley et al., 2011), and temporal and spatial variations of these factors (Letouzey et al., 1995; Dooley et al., 2007).

Laboratory sandbox (e.g. Cobbold et al., 2001; Costa and Vendeville, 2002; Bahroudi and Koyi, 2003; McClay et al., 2004; Massoli et al., 2006; Sherkati et al., 2006; Leever et al., 2011), finite

element (e.g. Vanbrabant et al., 1999; Simpson, 2006; Stockmal et al., 2007; Nilfouroushan et al., 2012; Ruh et al., 2012, 2013) and finite difference (Weiss et al., 2018) modelling have been extensively used to simulate the development of FAT belts, and to investigate the geological controls on the structural styles and kinematics of the FAT belt studied. With rapid progress in computing power, the numerical modelling approach based on the discrete element method has become more frequently applied to study tectonic deformations across a wide range of scales, including the development of normal and thrust faults (Saltzer and Pollard, 1992; Donzé et al., 1994; Abe et al., 2011; Schöpfer et al., 2006, 2016, 2017; Hardy, 2011, 2013; Smart et al., 2011; Deng et al., 2017; Finch and Gawthorpe, 2017), relay structures (Imber et al., 2004), detachment and fault-related folds (Finch et al., 2003; Cardozo et al., 2005; Hardy and Finch, 2005, 2006, 2007; Benesh et al., 2007; Hughes et al., 2014), accretionary wedges and FAT belts (Burbidge and Braun, 2002; Naylor et al., 2005; Yamada et al., 2006; Hardy et al., 2009; Dean et al., 2013; Morgan, 2015; Morgan and Bangs, 2017).

This paper presents a series of two-dimensional discrete element models with varied basal décollement thickness and cover rock cohesion, which were subjected to horizontal shortening. Pioneering work by Stewart and Coward (1995) has addressed the question of the role of décollement thickness in structural styles of FAT belt. Nilfouroushan et al. (2012) and Morgan (2015) have made insightful investigations into the effect of cover rock cohesion on geometry and kinematics of FAT belts. However, the impact of a combination of the two factors received less attention, especially their relative significance. The aim of this study is: 1) to conduct discrete element experiments with the produced folds generally comparable to those observed in nature; and 2) to evaluate the combined control of décollement thicknesses and cohesion on

kinematics and structural styles of fold belts. The results presented here exhibit first-order structural similarities to the detachment folds in the southern Zagros FAT Belt, and are believed to be of great implications for structural analysis of many other FAT belts with one major décollement level, especially the effect of décollement thickness and rock mechanical properties on structural styles of the fold belt studied.

2. Discrete element modelling

2.1. Basic principles

The discrete element modelling (DEM), based on elastic interactions between frictional particles, was firstly proposed by Cundall and Strack (1979) to study the mechanical behavior of granular media composed of discrete particles. A single particle is represented by a rigid body that occupies a finite amount of space, and contacts with the neighbouring particles using a soft contact approach. The contact is defined as a linear spring in compression that resists particle overlap (Fig. 1a). The magnitude of particle overlap is related to the contact force via the force-displacement law. Particles can be bonded together by applying interparticle bonding at their contact points so as to resist both shear and extensional displacement. The bonds cannot resist a bending moment or oppose rolling. The bonds are assumed to deform in a linear elastic manner, and can be broken when the interparticle forces acting at any bond exceed the bond strength. This allows the development of fractures within the simulation domain, and permits tensile forces being supported between particle pairs. Slip between particles that is resisted by a frictional strength (defined by the coefficient of friction) can occur between particles with unbonded contacts. Deformation of a particle assembly is driven by the movement of user defined, elastic walls and/or by gravity.

The DEM employs an explicit timestepping algorithm with a central-difference scheme to repeatedly apply Newton's second law of motion to each particle that determines the motion, and a linear force-displacement law to each particle contact to update the contact forces (Cundall and Strack, 1979). Time integration is performed through a Verlet scheme. At each time step, the contact forces are integrated to produce a finite displacement for that time step. This is followed by calculating new particle contacts and forces using the updated particle positions for the next time step.

Due to the particle-based nature, numerical models based on the DEM method can produce realistic faults and fractures with a finite displacement (Schöpfer et al., 2006; Yamada et al., 2006). Additionally, the model size, time and gravity are fixed to typical Earth values for discrete element models (Strayer and Suppe, 2002). No scaling is required to achieve reasonable computation times. The advantages of the DEM method and its extensive applications to geological studies make it an ideal method for addressing problems in FAT belt.

2.2. Model design and setup

We used Particle Flow Code (PFC) software in this study for the simulations. Our two-dimensional models consist of a 20 km long, rectangular-shaped box filled with numerous densely-packed circular particles (Fig. 1b). The particle assemblage includes a basal décollement layer, and a homogeneous cover that is composed of 12,903 particles with a thickness of 1.2 km (Table 1). The model geometries and their aspect ratios are similar to previous models developed by Dean et al. (2013) and Sun et al. (2016), and have been proved to be reasonable. The

thickness of the décollement layer varies from 50, 100 to 150 m to simulate sedimentary systems with a thin, intermediate-thickness to thick basal décollement, which contains 4697, 9031 and 13728 particles respectively. The thick décollement represents 11.1% of the stratigraphic package, and is believed to be capable of significantly changing the structural style of the entire package as revealed by scaled sandbox models (Spratt et al., 2004). Colours in the cover rock do not represent mechanical contrasts, and are simply used for bedding correlations.

The particle radii range from 5.0 to 10.0 m for the décollement layer (e.g. shale or salt), and 10.0 to 32.0 m for the cover rock, both following a Gaussian distribution of particle size. Particle density is 2100 kg/m^3 for the décollement and 2600 kg/m^3 for the cover rock. The particle stiffness (both shear and normal) were assigned with a value of $1\text{e}7 \text{ N/m}$, which is equivalent to a Young's modulus value of 5 MPa for the bulk rock (Liu and Konietzky, 2018). The particles in the décollement were unbonded, whilst the overlying particles in the cover were assigned with a bond strength ranging from 1 to 5 MPa that fall within the range of typical values for sedimentary rocks (Liu and Konietzky, 2018) and can present rocks with a relatively low to high cohesions. Interparticle friction was set to 0.3 throughout the bonded domain, and 0 within the décollement to ensure its low strength (Morgan, 2015). The spectrum of combined parameters (décollement layer thickness and cover rock cohesion) resulted in a total of 15 different models.

The particles were packed by allowing an assembly of randomly-generated particles to settle to the bottom of model under gravitational force. The system was considered to have reached static equilibrium when the mean unbalanced forces within the system have dropped to a negligible value. We then trimmed the assembly to the desired thickness, which led to a small amount of

vertical elastic rebound and surface uplift. The trimming process was then repeated that allowed the system to be settled. At a critical point when no more than five particles could be removed at a new equilibrium, the packing process was considered finished.

The boundary conditions for the models were as simple as possible. The three elastic walls served as the confined boundaries for the particles, and the upper surface was free. The whole model was gravitationally loaded by 1 g. The hinterland wall (left side of Fig. 1b) advanced at a controlled, uniform rate towards the foreland to induce horizontal shortening and deformation in the system. The critical timestep proportional to $\sqrt{m/k}$ (where m is the mass of the smallest particle in the simulation, and k is the stiffness of the contact spring) that can govern the numerical stability of the simulations is 0.3 seconds. Itasca (1998) suggested that critical time increment should be multiplied by a safety factor, with the default safety factor being 0.8. The integration timestep is then 0.24 seconds. Six snapshots for each model were taken during the deformation process for structural analysis.

3. Results

3.1. Structural geometry and kinematics

3.1.1. Models with a thin décollement

The deformation of the particle assemblage with a bond strength of 1 MPa is characterised by the formation of a series of small detachment folds successively at the deformation front during the shortening process (Fig. 2a). From T1 to T5, numerous small, sinusoidal-shaped folds were developed throughout the entire layered sequence as a result of strata buckling. The folds exhibit the lowest dominant wavelength (predominantly < 564 m in the orange layer) compared to those

formed in other models. Each fold is associated with a minor dome developed at the basal décollement layer. The décollement plane is of high roughness across the entire section.

Similar to model 1, model 2 sequentially produced five detachment folds towards the foreland (Fig. 2b). Horizontal shortening was accommodated by the formation of new folds at the deformation front rather than modifications of existing folds. The folds are symmetrical and rather regularly spaced. In contrast to model 1, the folds produced in model 2 have much higher wavelengths, with an average wavelength of 830 m in the orange layer, whilst the fold number is significantly reduced. Each fold exhibits a box geometry, and has oppositely-dipping kink bands that did not experience rotation during continuous shortening. The fold cores are represented by domes in the décollement layer, which flowed to accommodate the geometric differences between the flat parts of the décollement and the folded layers above.

Model 3 produced three major folds (F1, F3 and F4) and two minor fold (F2 and F5) (Fig. 2c). Here, the minor folds are defined to have a much smaller fold amplitude than others and do not influence the superficial layers. Folds F1 to F4 were in turn generated towards the foreland from T1 to T5. Fold F5 that occurs on the left side of F4, formed later than F4. Differently from model 2, the existing folds experienced distinct modifications as shortening went on. Fold F1 that initially formed as a symmetrical, detachment fold- gradually became asymmetric, which is characterised by an anticlockwise rotation of the axial surface. Fold F3 formed initially as a symmetrical box fold during T2 to T3, however, it grew asymmetrically at T4 by the development of a secondary fold F3s at its forelimb. Fold F4 formed as a fault-propagation fold with a backthrust fault to accommodate the deformation. As the fault propagated and

accumulated displacement, the hangingwall rock became folded and the fold amplitude increased accordingly.

Model 4 produced two main folds (F1 and F3) and three minor folds (F2, F4 and F5) (Fig. 2d). Differently from all previous models, fault-propagation fold takes over detachment fold as the main fold type in this model. Both F1 and F3 developed by forethrusting to accommodate shortening. During T4 to T6, the axial surface of F3 rotated clockwise, whilst the hangingwall rock of the forethrust in F1 overrode the forelimb of F3 to result in a piggy-back arrangement as the fault displacement increased. Notably, a subvertical opening-mode fracture formed in the fold hinge of F3 at T5 as a result of tightening of F3 during shortening. The décollement particles involved in the folds were upwelling as the fold grew incrementally and marked the fault traces as linear thin bands.

Model 5 only produced two main folds to accommodate shortening (Fig. 2e). Tensile fractures occurred at the hinge of F2 at T4, and continued widening and propagating downward. The leftmost cover rock that contacts the driving wall underwent continued uplift and clockwise rotation during shortening, which met the backlimb at T5. The limited range of deformation in model 5 leaves a relatively wide undeformed foreland area.

3.1.2. Models with an intermediate-thickness décollement

Similar to the result of model 1, model 6 also produced a series of sinusoidal-shaped detachment folds successively towards the foreland (Fig. 3a). Differently, the folds produced in model 6

exhibit a much higher fold wavelength that reaches up to 1572 m, whilst the fold number is reduced to eight. Each fold is dome-cored and the domes are rather closely spaced.

Five detachment folds were generated in sequence in model 7 (Fig. 3b). All the folds were initially box-shaped and symmetric. However, significant fold tightening occurred in F2, F3 and F4 during T4 to T6, with the axis planes of F2 and F4 rotating clockwise, and the axis plane of F3 rotating anticlockwise. This led to their final asymmetric geometries. These folds also exhibit a trend of evolving into fault-propagation folds by simple shear. The folds have a rather irregular spacing compared to that in model 2. In particular, F2 and F3 are very closely spaced.

Model 8 only generated three folds, which are all fault-propagation folds (Fig. 3c). F1 and F3 accommodated shortening by forethrusting, and F2 by backthrusting. The thrusts accumulated fault displacement gradually, with fault geometries and dip angles keeping unchanged. At the final stage of T6, there is still a small fragment (1.36 km) of the foreland that remained undeformed and flat-lying.

Model 9 produced two main folds (Fig. 3d). The early-formed F1 and F2 are closely-spaced fault-propagation folds, which evolved to constitute a much larger fold. F3 formed at T4 as a fault-propagation fold with backthrusting. Later secondary fold F3s developed at the forelimb of F3. A much wider foreland area with a length of 4.52 km remain largely undeformed, i.e. the accommodation of shortening is achieved by the modifications of existing folds.

Only two fault-propagation folds were produced in model 10 (Fig. 3e). The early-formed F1 accommodated shortening by forethrusting, and exhibits a trend of becoming a fault-bend fold as F1 kept accumulating displacement. Differently, F2 accommodated shortening by a combination of backthrusting (T2 - T6), tensile fracturing in the fold hinge (T5 - T6) and secondary folding in the forelimb (T5 - T6). The flat-lying, undeformed layers in the foreland are 4.46 km long.

3.1.3. Models with a thick décollement

Nine detachment folds were produced in model 11, including two box folds (F2 and F5) and seven sinusoidal-shaped folds (Fig. 4a). F2 and F5 are bounded by two sinusoidal-shaped folds that have a lower amplitude than the box folds. Each fold is characterised by a dome as its core, which has a more distinct dome boundary and more regular shape than those in models 1 and 6. The early-formed F2 exhibits a trend of evolving into a fault-propagation fold.

Model 12 produced six folds successively towards the foreland (Fig. 4b). The first three folds formed as sinusoidal-shaped detachment folds, followed by the formation of F4 as a box fold at T2. F4 gradually became a fault-propagation fold during T3 to T6, which was accompanied with its symmetric fold geometry becoming less symmetric. F4 and F5 both contain forethrust faults that accommodated the shortening strain.

Model 13 only generated two folds, which are both fault-propagation folds (Fig. 4c). The early-formed F1 contains a forethrust fault, whose shape remained largely unchanged during fold growth. F2 formed at T3 as a rather symmetric box fold that subsequently evolve into a fault-propagation fold with backthrusting at T4. Meanwhile, tensile fractures occurred in the fold

hinge as a result of buckling of the uppermost hangingwall strata. At T5 secondary folds developed in the forelimb of F2 as another mechanism to accommodate shortening. The flat-lying layers in the largely undeformed foreland is 3.24 km long.

Similar to model 13, model 14 also produced two folds (Fig. 4d). F1 initially formed as a symmetric box fold at T1, which evolved into a fault-propagation fold with forethrusting. At T3, the thrust fault broke through the fold as it accumulated displacement and became a fault-bend fold. F2 initially formed as a fault-propagation fold with forethrusting at F4, and the thrust fault subsequently became a backthrust. Meanwhile, subvertical tensile fractures were generated in the fold hinge and propagated downward to the red layer. Secondary fold F2s occurred in the forelimb at T6. The foreland is as long as 4.94 km in this model.

Two folds were produced in model 15 (Fig. 4e). F1 formed as a fault-propagation fold at T1 with forethrusting, and evolved into a fault-bend fold from T2 to T3. F2 formed as a fault-propagation fold with a steep backthrust. The dip of the thrust fault decreased to a low angle at T4. The backlimb of F2 came into contact with the hangingwall rocks of F2 as the rocks were passively transported towards the foreland direction, which caused a significant truncation of the backlimb of F2. At F5, a secondary fold F2s developed in the forelimb of F2, followed by the formation and propagation of a forethrust fault at T6. The length of flat layers of the foreland is 5.90 km long.

3.2. Décollement and surface uplift

As described above, the folds that formed during horizontal shortening are predominantly dome-cored, and the domes exhibit varied width and height. Fig. 5 shows the plot of the maximum uplift of the décollement layer of each model during shortening. It is demonstrated that models with a thin basal décollement exhibit varied trends of décollement uplift (Fig. 5a). Dome grew firstly in model 1 that has the lowest bond strength during an early stage of shortening, followed by models with a higher bond strength in the cover, i.e. the higher the bond strength is, the later the first dome formed. The first dome in model 5 with a bond strength of 5 MPa occurred the latest when the shortening reached 8.79%.

The maximum décollement uplift in model 1, or the dome height, increased the slowest, whilst the domes in other models with a higher bond strength grew faster. The higher the bond strength is, the faster the dome grew. Notably, the maximum dome height did not increase continuously; instead, the value became steady and remained unchanged at a stage when new domes began to form. For example, the maximum dome height of model 5 stopped increasing when the shortening reached 17.59%, and remain unchanged until the amount of shortening became 24.43%. During this period, the second fold F2 formed. Meanwhile, the maximum dome height in both models of 3 and 4 exceeded model 5. After the amount of shortening exceeded 24.43%, the dome in F2 of model 5 continued to grow, whose height exceeded the maximum dome height in model 3 when the amount of shortening was 29.31%, and model 4 when the shortening increased to 31.27%.

At the end of the experiments, model 5 has the highest dome, whilst the maximum dome height in model 1 is the lowest. There is only one stationary stage during the increase of the maximum

dome height for model 5, because that only one fold, i.e. F2, formed after F1. There are two and three stationary stages for models 3 and 4 respectively, which correspond to the initiation of new folds during shortening. There is no significant increase in the maximum dome height in model 1 during the successive formation of multiple detachment folds.

Models 6 to 10 (Fig. 5b) and models 11 to 15 (Fig. 5c) exhibit similar features to model 1 to 5, regarding the relative timing of fold initiation and the maximum dome (or diapir) height. Here, diapir is defined to have pierced the overlying orange layer, whilst dome has not. Domes firstly formed in models with the lowest bond strength, and formed last in models with the highest bond strength. The higher the bond strength is, the maximum diapir height the model exhibits.

Fig. 6a illustrates the plot of bond strength versus the maximum décollement uplift of all models. The result shows that the higher the bond strength is, the higher the maximum dome (or diapir) height is. Similarly, the thicker the décollement layer is, the higher the maximum dome height is. The maximum surface uplift receives a similar influence of the bond strength and décollement thickness to the maximum décollement uplift (Fig. 6b).

Three fault-propagation folds in the equivalent positions, i.e. F3 in model 3 (Fig. 2c), F2 in models 8 (Fig. 3c) and 13 (Fig. 4c), exhibit similar geometries are compared regarding their growth history (Fig. 7). The result shows that the diapir in F3 (model 3) initiated the earliest, followed by F2 (model 8), whilst F2 (model 13) formed the latest. The diapir height of F3 (model 3) was exceeded by F2 (model 8) when the amount of shortening was 17.59%, and by F2 (model 13) when the shortening became 19.54%. The diapir in F2 (model 13) exceeded F2

(model 8) when the amount of shortening reached 25.41%. The final diapir height of F2 (model 13) is the highest, followed by F2 (model 8), whilst the diapir in F3 (model 3) is the lowest. Overall, F2 (model 13) grew the fastest, and F3 (model 3) grew the slowest.

4. Discussion

This section firstly discusses the relative importance of the cover rock cohesion and décollement layer thickness in the development of FAT belts by summarizing the modelling results, followed by comparing the results to a natural example of FAT belts, i.e. the Zagros FAT Belt, to examine their structural similarities.

4.1. Cover rock cohesion

It has been found that the mechanical properties of cover rocks can significantly affect structural evolution of FAT belt (Sepehr et al., 2006), especially the cohesive strength (Nilfouroushan et al., 2012; Morgan, 2015). The modelling results presented in this study demonstrate that the propagation rate of deformation is intimately associated with the particle bond strength, i.e. the cohesive strength of cover rocks. A low cohesion facilitated a rapid transfer of deformation towards the frontal, undeformed parts in the models, whilst a high cohesion resulted in a relatively low transfer rate. This can be demonstrated by the long undeformed frontal parts in the models by the end of the experiments (Table 2). With the same amount of horizontal shortening, the models with varied décollement thickness, but the same cohesion, exhibit similar extents of folding, indicating the dominant role of cover rock cohesion in the propagation rate of deformation rather than décollement thickness.

Vertically, the models with a higher cover rock cohesion experienced a greater maximum uplift, as well as the development of higher diapirs, comparing to the models with a lower cohesion (Fig. 6, Table 2). Hence, a high cohesion of the cover rocks favours accommodation of horizontal shortening through crustal thickening, i.e. vertical fold growth. Differently, for models with a low cover rock cohesion, the accommodation of shortening was mainly facilitated by more uniformly distributed, low-amplitude folds, which agrees with the study by Morgan (2015).

Structural style of fold belts has been suggested to be highly affected by the cover rock cohesion (Morgan, 2015). In this study, the models exhibit a trend of shifting from low-amplitude, sinusoidal folds to box folds, fault-propagation folds, and then to fault-bend fold with an increasing cohesion. Folds developed in models with a cohesion lower than 2 MPa are predominantly detachment folds with a symmetric geometry. However, the folds are asymmetric in models with a higher cohesion, due to the occurrence of thrusts in those folds that help accommodate shortening by incremental accumulation of fault displacement. Another difference between low and high cohesion models is the occurrence of opening-mode fractures in fold hinges in models with a cohesion no less than 3 MPa, as another type of structures for shortening accommodation.

The modelling results demonstrate that the number of folds generated is evidently influenced by the cover rock cohesion (Table 1). A higher cohesion resulted in a lower fold number. This is because that a higher cohesion favours strain localisation in fault-related folds through 1) accumulation of fault displacement, 2) development of secondary folds in fold limbs, and 3)

tensile fracturing in fold hinges. Hence, a less number of fault-related folds can accommodate the same amount of shortening as that accommodated by a larger number of detachment folds.

4.2. Décollement layer thickness

The décollement layer thickness has been suggested to be one of the strongest controls on structural style above the décollement (Jackson and Hudec, 2017). A thin décollement would restrict the volume of materials flowing into the rising folds from the décollement, and can hence inhibit or insufficiently sustain the growth of detachment folds (Stewart, 1996). In this case, thrusts would preferentially develop to accommodate shortening rather than strata bulking (Stewart and Coward, 1996). In contrast, a thicker décollement can provide sufficient material available to fill fold cores, and the redistribution of the weak materials in the décollement allows the development of detachment folds that can lead to decoupling of deformation at different structural levels (Farzipour-Saein et al., 2009).

In this study, models with the same particle bond strengths exhibit varied structural styles (Fig. 8), indicating the important control of the décollement thickness. This is mainly represented by the differences in the development of diapirs and the surface uplift (Fig. 6). Models with a thicker décollement produced higher diapirs comparing to those with a thinner décollement. The vertical growth of folds, with fold cores filled with remobilized materials from the thick basal décollement, led to a more pronounced uplift. Notably, the dominant folds in models 11 - 15 all contain the largest diapir, e.g. F2 and F5 in model 11, F4 in model 12, F2 in models 13 - 15. The unequal fold growth is considered to have been controlled by the size of diapirs as their fold cores. Moreover, the thickness of the décollement sheets intruded into the hangingwall of the

thrust faults in models that contain thrusts, is controlled by the thickness of the décollement thickness. For example, the thickness of such sheets is 182 m in F3 of model 2, 418 m in F2 of model 8, and 742 m in F2 of model 13. Hence, the thicker the décollement is, the thicker the sheets excised into the hangingwall of thrust faults are.

Compared to cohesion, the décollement thickness played a much less important role in controlling the propagation rate of deformation towards the foreland (Figs 2-4). The number of folds developed is influenced by both the cohesion and the décollement thickness. In models with a cohesion less than 3 MPa, fold number is much higher in models with a thinner décollement. However, in models with a cohesion greater than 3 MPa, the role of décollement thickness becomes less significant, because that the fault-related folds caused strong strain localisations in those folds, and fold number in all models are significantly reduced.

It has been suggested that increasing thickness of the décollement layer would give rise to an increase in the dominate fold wavelength (Sepehr et al., 2006). The dominate fold wavelength is believed to be approximately ten times the thickness of the décollement (Stewart and Coward, 1995). The results of models 1, 6 and 11 with the lowest cohesion show that the fold wavelength indeed increases as the décollement thickness increases, which agrees to the previous studies. This is due to the lack of sufficient materials from the thin décollement that restricts the fold size. Interestingly, the increase in the décollement thickness results in the shift of fold geometry from sinusoidal folds to box folds with tight cores and broad, flat crests, demonstrating that décollement thickness is capable of influencing the geometry of single folds.

4.3. Comparison to the Zagros FAT Belt

The discrete element models presented in this study generated a series of structures (Fig. 8) that are generally comparable to those observed in nature. The results also verify the theory of three stages in the development of a thrust from a box fold (Cosgrove, 2015), i.e. 1) initiation and amplification of a symmetric fold until the fold has been locked up; 2) rotation of fold limbs that causes the fold to become asymmetric; and 3) eventual development of a thrust on one of the limbs. Tighter, disharmonic folding in the inner units of a detachment fold that occur to accommodate space issues in fold cores (Mitra, 2003) have also been reproduced, e.g. F2 and F3 in model 4 (Fig. 2d), F1 and F2 in model 9 (Fig. 3d).

Although the models do not directly simulate structures of any natural prototypes, here we attempt to compare the models to the Zagros FAT Belt, to further verify the applicability of the models. The Zagros FAT Belt is one of the most intensively studied fold belts worldwide, with salts acting as a major control on the structural styles (e.g. Alavi, 1994; Bahroudi and Koyi, 2003; McQuarrie, 2004; Sepehr and Cosgrove, 2004; Molinaro et al., 2005; Sherkati et al., 2006; Farzipour-Saein et al., 2009; Lacombe et al., 2011). The Zagros FAT Belt, which lies along the northeastern margin of the Arabian Plate, is dominated by NW-SE trending folds and thrusts (Fig. 9a). A selected N-S cross-section from the southern Fars (Iran) shows that deformation in this area is characterised by multiple regularly-spaced detachment folds, with the Triassic Hormuz salt level serving as the regional décollement (Jahani et al., 2009; Callot et al., 2012) (Fig. 9b). Some of the folds exhibit an overall geometry of box folds, which are comparable to the models with a lower cohesion, especially model 2 (Fig. 8), regarding the structural geometry.

Notably, the detachment folding is suggested to have commenced during the initial stage of deformation since the early Paleozoic, i.e. just short time after the deposition of the Hormuz salt (Sherkati et al., 2006; Jahani et al., 2009). Hence, the overlying sediments could only possess a relative low cohesion during the early stages of folding, due to their incomplete consolidation and diagenesis. This agrees to the modelling results of models with a low cohesion that favours the generation of box-shaped detachment folds. Moreover, the thickness ratio of the Hormuz salt versus the overburden is relative low, similar to model 2. Models with a higher ratio, e.g. model 12, produced less regularly shaped and spaced folds with varied fold wavelengths and amplitudes, which are not compatible with those in the Zagros FAT Belt. Hence, our models reveal that the combination of a low cover rock cohesion and a low thickness ratio of décollement versus overburden would preferentially result in regularly-spaced box folds that are similar to the folds in the southern Zagros FAT Belt.

It should be noted that the models presented here are highly simplified and only show the first order structural similarities to the Zagros FAT Belt, without considering many other factors that may influence the structural styles in this area. For example, ductile creep of the décollement and brittle deformation in the cover could enhance the mechanical contrast between the décollement and the cover, which could jointly affect the structural styles of FAT belts. Moreover, the possibility of generation of opening-mode fractures and fracture aperture have been amplified in our models, because the models did not consider the influence of mechanical stratigraphy, i.e. a decreased cohesion upwards, on fracture development. To better simulate the structures developed in the Zagros FAT Belt, the numerical models should be implemented with the input

of more detailed regional geological data, such as bed thickness, mechanical stratigraphy, and spatial distribution and variations of these data.

5. Conclusions

This study utilized the discrete element method to simulate the development of fold belts, with varying basal décollement thickness and cover rock cohesion in the models, to yield new insights into their controls on structural styles of fold belts. We conclude the following:

- (1) The discrete element models with varied basal décollement thickness and cover rock cohesion produced a range of fold styles as a result of horizontal shortening, including sinusoidal folds, box folds, fault-propagation folds and fault-bend folds.
- (2) The modelling result suggests that a low cover rock cohesion would lead to rapid lateral propagation of deformation during horizontal shortening, resulting in more regularly distributed folds. A higher cohesion could promote vertical growth of existing folds, giving rise to more pronounced strain localisations.
- (3) A thicker décollement and a higher cohesion could result in a greater surface uplift and a higher diapir that serve as fold cores, but could reduce the number of folds.
- (4) A thicker décollement can provide sufficient materials to fill fold cores and contribute to the formation of larger folds. A higher cover rock cohesion favours strain localisations and generation of fault-related folds rather than detachment folds.
- (5) The modelling results are compatible with the southern Zagros Fold-and-Thrust Belt regarding the structural styles, indicating that the combination of a thin décollement and a low cover rock cohesion could preferentially produce regularly-spaced box folds. This study

demonstrates a strong influence of décollement thickness and rock mechanical properties on the structural styles of fold-and-thrust belts.

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Table 1. Parameters for the discrete element models.

Parameter	Décollement layer	Cover rock
Thickness (m)	50, 100 and 150	1200
Number of particles	4697, 9031 and 13728	12903
Particle radius (m)	5 - 10	10 - 32
Particle stiffness (N/m)	1e7	1e7
Contact friction	0	0.3
Bond strength (N)	0	1e6 - 5e6
Density (kg/m ³)	2100	2600
Damping	0.2	0.2

Table 2. Summary of results of the discrete element models.

Décollement thickness (m)	Model name	Bond Cohesion (MPa)	Number of folds	Fold type ^a	Max décollement uplift (km)	Max. surface uplift (km)	Length of undeformed area (km)
50	1	1	18	s	0.14	2.46	0
	2	2	5	b	0.52	2.54	0
	3	3	5	s, b, fp	0.84	2.88	1.34
	4	4	5	b, fp	1.22	3.26	2.16
	5	5	2	fp	1.38	3.34	5.12
100	6	1	8	s	0.42	2.52	0
	7	2	5	s, b, fp	0.64	2.74	0
	8	3	3	fp	1.34	3.30	1.36
	9	4	2	fp	1.64	3.28	4.52
	10	5	2	fp	1.76	3.84	4.46
150	11	1	9	s, b, fp	0.84	2.62	0
	12	2	6	s, b, fp	1.12	2.92	0
	13	3	2	fp	1.70	3.24	3.24
	14	4	2	fp, fb	1.88	3.60	4.94
	15	5	2	fp, fb	2.18	4.12	5.90

^a s = sinusoidal fold. b = box fold. fp = fault-propagation fold. fb = fault-bend fold.

Highlights

- Discrete element models were constructed to simulate fold belts with varied structural styles.
- The cover rock cohesion can significantly control the propagation rate of deformation.
- A thicker décollement and a higher cohesion could result in a greater surface uplift.
- A high rock cohesion favours strain localizations and generation of fault-related folds.
- A thin décollement and a low cover rock cohesion could preferentially produce regularly-spaced box folds.

(a)

(b)

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

(a)

(b)

Figure 6

Figure 7

Figure 8

Figure 9