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Influence of multiple decollement stratigraphy and growth strata on a detachment fold development: insights from 2D Discrete-Element Modelling and application to Pico del Águila anticline (External Sierras, Spanish Southern Pyrenees)

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Abstract: A 2D Discrete-Element Modelling approach is used to test the influence of multiple detachment levels and growth strata in the development of detachment folds. Two experiments are performed, each for testing one parameter. Multiple detachment levels create a contrast in structural style between the upper and the lower stratigraphic units. Growth strata make the structure more robust against gravitational instabilities and cause an increase of deformation in the internal and lower parts of the structure. The results are applied to the structure and evolution of the Pico del Águila anticline (External Sierras, Southern Pyrenees, Spain).

Keywords: numerical modelling, detachment, growth strata, Pyrenees, external sierras, Pico del Águila, fold, strain.

Detachment folds have been commonly described as a structure accommodating the hangingwall displacement related to a layer-parallel blind thrust (Poblet *et al.*, 1997), in which a weak decollement accumulates most of the deformation while the overlying sedimentary cover becomes folded above. Although the final geometry is strongly dependant on the depth to detachment level, the ratio between decollement and cover thicknesses, as well as the mechanisms that acted during the folding stages (e.g. limb rotation, limb elongation and hinge migration, among others; Poblet and Hardy, 1995), mechanical heterogeneities of the cover such as interbedding of competent-incompetent units are also able to influence the generation and evolution of a detachment fold. In addition, the presence of growth sediments can markedly influence the geometry of the structure, especially in the late stages of deformation. Considering both mechanical heterogeneities and growth strata influences, this work aims to generate and understand detachment fold structures using a 2D Discrete-Element Modelling approach, as it is a powerful tool with which to model complex folded and faulted geometriesstructural scenarios in two dimensions. The obtained results are directly applicable to the geometrical and mechanicalstructural evolution of the Pico del Águila anticline (External Sierras, Southern Pyrenees, Spain), as is shown by comparing the model results to the Pico del Águila structure.

Methodology: 2D Discrete-Element Modelling

The 2D Discrete-Element Modelling (2D-DEM) approach allows us to model an initially non-deformed rock mass as an assemblage of circular ele-

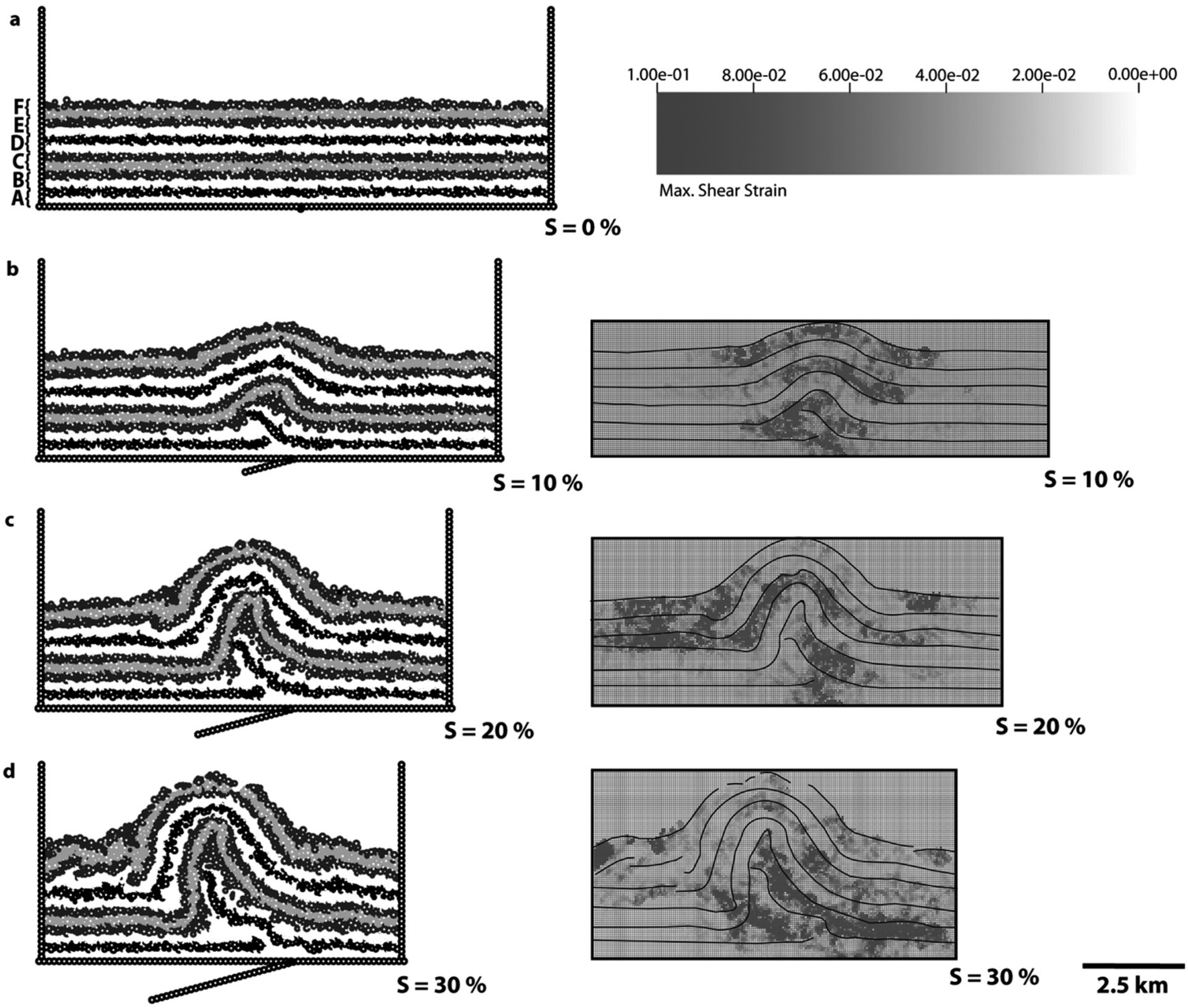

Figure 1. Geometrical and deformational evolution of Experiment 1. (a) Initial setup. Letters correspond to the SUs defined according to their mechanical properties (see text), (b) geometry and strain distribution after 1.25 km of shortening (10%), (c) idem after 2.5 km (20%), d) idem after 3.75 km (30%).

ments which interact in pairs as if connected by breakable elastic springs or bonds. The behaviour of the elements assumes that the particles interact through "repulsive-attractive" forces, of which attractive ones are positive and repulsive ones are negative. Particles are bonded up to the moment when the distance between them exceeds a certain threshold, at which the bond becomes irreversibly broken. Nevertheless, if the particle pair returns to a compressive contact, a repulsive force will act between them. When considering cohesionless materials, we assume that the elements are not connected by bonds, in other words, these are considered to be initially broken, in such a way that only the repulsive (negative) component of the elastic force is applicable. The total elastic force between a pair of elements, considering its application on one of them, is thus obtained by summing the normal and tangential forces on each contact/bond that links a specific particle i to its neighbours. Finally, a viscous damping term is also included in calculations of interaction between particles, as well as a gravitational effect due to gravity force, F_g. The viscous term attenuates dynamic phenomena, whereas F_g is only calculated in the z direction, taking into account the processes due to the Earth's gravity. To avoid unrealistic superimposed effects such as regular 60º dipping planes of weakness, homogeneous grid sorting of elements and other unnatural isotropy influences, the assemblage includes randomly-distributed elements of varying sizes. This reduces the likelihood of preferred planes of weakness and, thus, allows a non-artificially controlled deformation path.

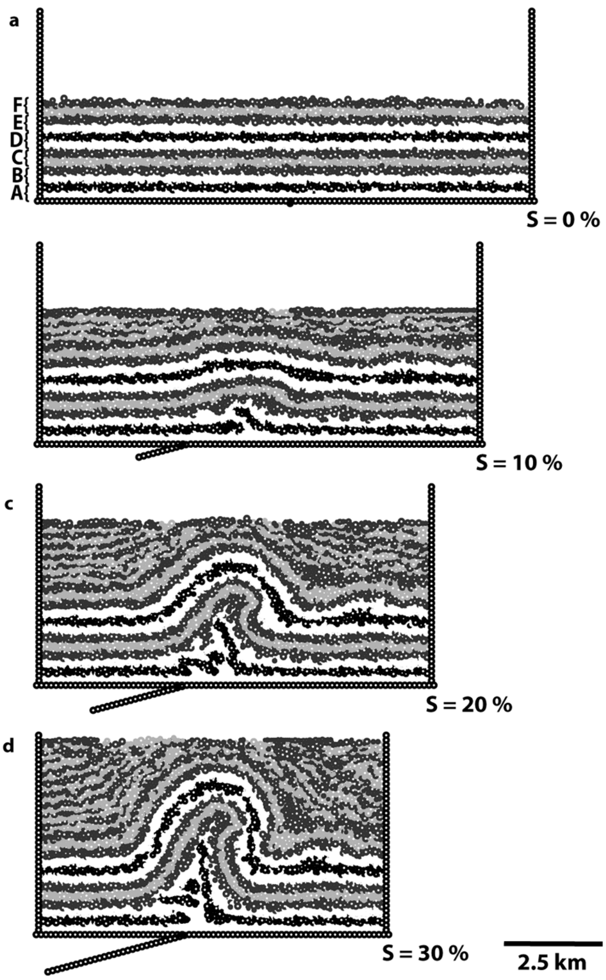

Figure 2. Geometrical evolution of Experiment 2. (a) Initial setup. Letters correspond to the SUs defined according to their mechanical properties (see text), (b) geometry resulting after 1.25 km of shortening (10%), (c) idem after 2.5 km (20%), (d) idem after 3.75 km (30%).

Experimental boundary and initial conditions

As stated, we apply a 2D-DEM technique to investigate the role of a multiple decollement stratigraphy as well as the effect of growth strata on the geometry and evolution of a detachment fold. Since we are engaged in a compressional tectonic setting, deformation is a result of shortening at a subduction slot in the base of the model, analogous to a digital sandbox. Despite this, the main improvement from these real sandbox models is that we can assign to materials a variety of mechanical properties such as cohesion or internal friction at our convenience. Consequently, we are able to set up a virtual stratigraphic sequence featuring the mechanical properties we might find suitable for our purposes. In this work, the initial element assemblage for all the experiments contained ca. 5500 elements with four different radii of 0.5, 0.4, 0.3 and 0.2 model units. These elements were positioned randomly inside an enclosed rectangular box (which is made of elements with a radii of 0.5 model units) and then permitted to settle to a state of equilibrium, in which their position remains almost constant, as does the gravitational potential energy. In this work, we assume that 1 model unit is equal to 250 m, rock density is homogeneous and equal to 2500 kg m^{-2}, both normal and shear elastic constants are equal to 5.5×10^{9} N m^{-1}, and the viscous term is 3×10^{7} N s m^{-1}.

The initial setup is 10 model units thick (~2.5 km) and 50 model units wide (~12.5 km), as shown in figures 1a and 2a. These values are appropriate for a thin-skinned compressional setting. All the pre-folding materials used are frictionless and cohesional, organized in stratigraphic units (SU) of two layers each. The cohesion values (breaking strains) of the sequence, from bottom to top, are as follows (see Figure Fig. 1a): SU A: 0.00; SU B: 0.06; SU C: 0.00; SU D: 0.06; SU E: 0.03; SU F: 0.01. In other words, SUs A and C are cohesionless and are thus expected to act as detachment levels. However, SUs B, D, E and F are cohesional, providing strength to the structure. It is important to highlight that growth strata are cohesionless and frictionless. The incremental displacement between time steps is 0.0025 model units, running each model for 2 000 000 time steps. This means that the total shortening accumulated is equal to 15 model units (3.75 km), equivalent to 30% of the initial length.

Results

As stated before, this work investigates the influence of multiple detachment levels and growth strata in the evolution of a detachment fold. To do so, we analyze two experiments, illustrating their geometry after 1.25 km (10%), 2.5 km (20%) and 3.75 km (30%) of shortening. In addition, a strain analysis is also carried out for the first experiment at each stage. The strain distribution is finally plotted in a *colour grid map* that relates shaded zones to areas of maximum deformation (shear strain) and *blank* zones to areas with no relative displacement (see scale of shear strain in figure 1).

Experiment 1: influence of multiple detachment levels

The first experiment (Figure Fig. 1) attempts to model a folded sedimentary sequence in which two detachment levels are involved: a basal detachment layer (SU A) and another one located in the middle of the sequence (SU C). Figure 1a shows the initial setup of the model, with the distribution of the different units according to their mechanical properties.

After 1.25 km of shortening (10%; Fig. 1b), the upper part of the sequence becomes gently folded while the basal detachment already shows a relatively high deformation expressed by means of a front directed reverse fault. The inner detachment appears to be geometrically stable, though accumulating a large amount of deformation as shown in the corresponding strain distribution plot. This also shows how deformation is concentrated all along the levels with lower cohesion (SUs A, C and F), especially in the areas with larger uplift. In the core of the anticline, SU B also features high deformation, affected by the fault that is detaching on SU A. After 2.5 km of shortening (20%; Fig. 1c), the layers defining the core of the structure haves definitely increased in dip and length, influencing the growth of the anticline by means of both limb rotation and limb lengthening. A slight disharmony is recorded in SUs D and E, due to the presence of the inner detachment, which probably acts as a barrier between the folded section above and the faulted section below. An incipient small backthrust is also generating in the frontal limb, apparently detaching on SU C since subjacent layers remain flat. Continuing shortening of up to 3.75 km (30%; Fig. 1d), the structure has reached the maximum deformation that it can accumulate by folding. Layers in the core are slightly overturned and the altitude amplitude of the structure (the amount of limb lengthening) has exceeded the stability threshold. In addition, the internal fault has been folded, although it has not affected the inner detachment. Several minor backthrusts have developed in the frontal limb, detaching on SU C. Thinning and collapse are common features in the outcropping crest of the anticline, since the structure is gravitationally unstable. At this stage, higher strain is accumulated along the back limb of the inner detachment, given that a new small structure is nucleating in. The core is also accumulating large strain by means of internal deformation, this probably start-

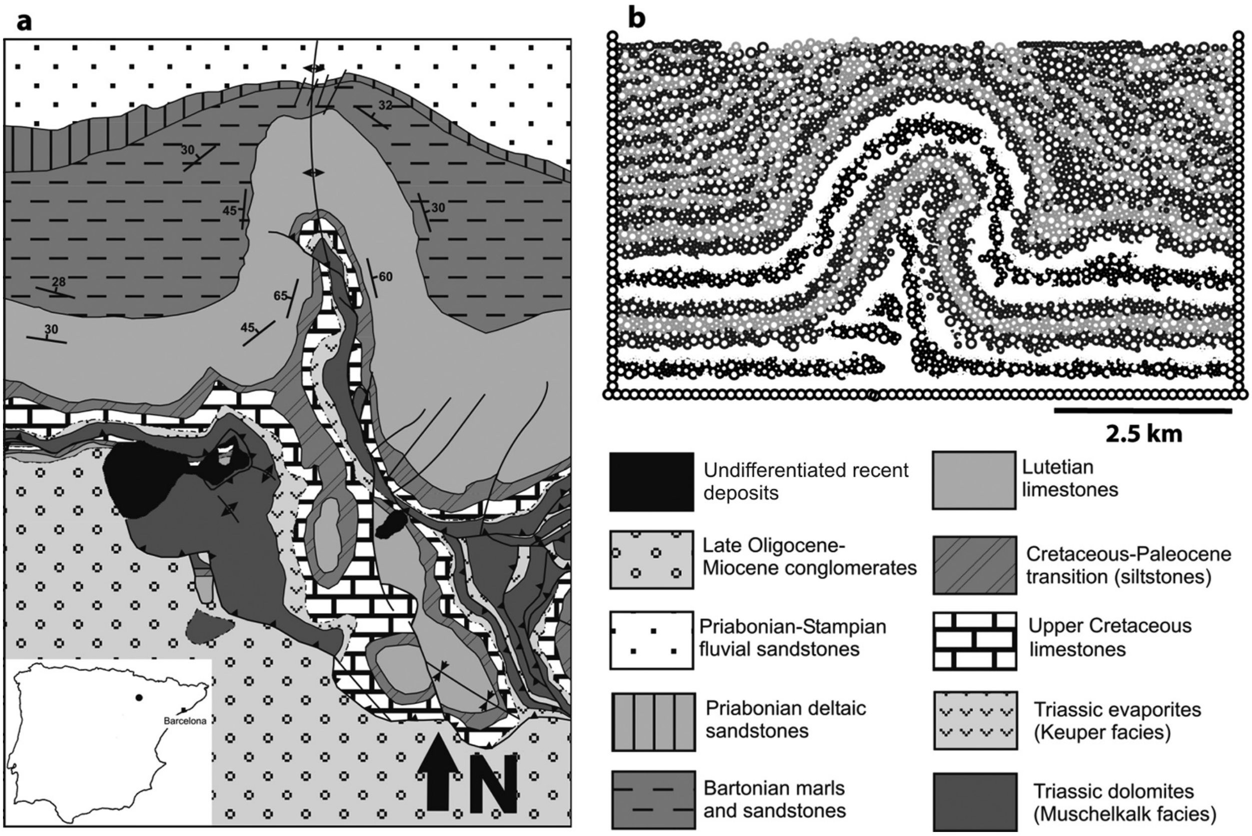

Figure 3. (a) Comparison between the geological map of the Pico del Águila anticline (modified after IGME, 1992), (b) result obtained from Experiment 2 after 3.75 km of shortening. Due to the geometry of the anticline and the intersection of the bedding with topography, the geological map of the Pico del Águila can be assumed as equivalent to a cross-section, comparison between (a) and (b) being possible.and a cross section of Pico del Águila (c) obtained from the 3D Structural Reconstruction of the fold (d).

ing to affect the frontal limb by means of incipient faulting.

Experiment 2: influence of growth strata

This experiment starts with the same setup as the previous one but includes sedimentation during deformation (Fig. 2). Figure 2a shows this initial non-deformed stage with the distribution of the units according to the mechanical properties.

Although the structural style of the pre-folding sequence after shortening 1.25 km (10%; Fig. 2b) is similar to the one observed in Experiment 1, there are some noticeable differences. The syn-folding sedimentation caused a decrease in the fold amplitude, due to both the syntectonic sedimentary load and the partial absorption of deformation by growth sediments. In addition, deformation is also propagating towards the moving wall, since a slight incipient anticline is also formed. After 2.5 km (20%; Fig. 2c), deformation has highly affected the inner part of the structure. The core has been faulted following a piggy-back thrusting sequence composed of three reverse faults (SUs A and B), whereas the inner detachment (SU C) has accumulated large deformation by reaching an obvious overturned geometry. In spite of this, the upper pre-folding levels show less deformation when compared with the equivalent stage of Experiment 1. Consequently, the extra sedimentary load of syntectonic sediments may cause the propagation of deformation to the inner parts of the structure, this being mainly absorbed by cohesionless units. In contrast, upper units are more gently folded due to this higher fatigue of the internal units. Finally, shortening up to 3.75 km (30%; Fig. 2d), both limb dip and limb length have increased their values, reaching a generalized overturned geometry in the back limb of the structure. Deformation in the core has been finally solved by a piggy-back thrusting sequence in which slip has markedly increased. The inner detachment has accommodated the deformation mainly by limb lengthening, whereas the upper units have grown mainly by means of limb rotation. As expected, growth sediments draw a double sedimentary prism, tapering towards the hinge of the anticline. This sedimentary body makes the structure more stable since neither collapse nor thinning in pre-folding units has been noticed at any stage of deformation.

Discussion

The results presented above are directly applied to the structure and evolution of the Pico del Águila anticline (Central External Sierras, Southern Pyrenees). Pico del Águila anticline is a symmetric kilometric scale parallel fold, plunging 29º towards N353. It is, therefore, a westwards-verging fold in which the Triassic-Lutetian sequence describes a concentric anticline, showing sub-parallel limbs. The uppermost part of the sequence, from Lutetian-Bartonian up to Priabonian, describes a cartographic scale double sedimentary prism that tapers towards the pre-folding sequence, drawing an obvious onlap over the Lutetian limestones. The stratigraphic sequence of Pico del Águila is characterized by the presence of at least two units that could act as detachment levels. The Upper Triassic clays and evaporites (Keuper facies) as well as the mudstones and siltstones of the Cretaceous-Paleocene transition (Garumnian facies) are excellent candidates to nucleate faults and folds due to their mechanical behaviour. In addition, both of them are affected by the internal reverse fault deforming the core of the structure. Despite this, field observations indicate that neither Keuper nor Garumnian facies are acting here as basal detachment levels but as inner ones, since both of them are suprajacent to other units which are also affected by the structure. This leads us to think about other subjacent non-outcropping units as possible basal detachment levels, the Middle Triassic clays and marls (M2 – Muschelkalk facies) being the most likely candidate.

Figure 3 indicates the similarities between Pico del Águila anticline and the results obtained by a 2D-DEM approach. Both field case study and model results show a nearly concentric anticline in the upper part of the sequence, whereas the structure becomes much more complex as one analyzes the internal parts at the lower units. In both examples, high internal strain and reverse faulting are the structural pattern with which to express the deformation in the inner parts of the structure. Furthermore, the syntectonic double sedimentary prism covers the crest of the anticline, hence providing a more stable structural construction.

Conclusions

A 2D-DEM technique has been used to determine the role of multiple detachment levels and growth strata in the construction of a detachment fold. It has proven useful to unravel the effect of both parameters. The first one causes a steep contrast in structure when comparing the style between the sequence above and below the inner detachment level. Above, folding is the common feature. Below, high internal deformation and reverse faulting characterize the structural style. The syntectonic sedimentary load makes the structure more stable against gravitational collapses, and causes an increase of deformation in the internal lower parts of the structure. All these results are directly applicable to the structure and evolution of Pico del Águila anticline.

Acknowledgements

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