DEM: Normal faulting 2. The effect of prograding footwall derived deltas on faulting in pre- and syn-kinematic stratigraphy

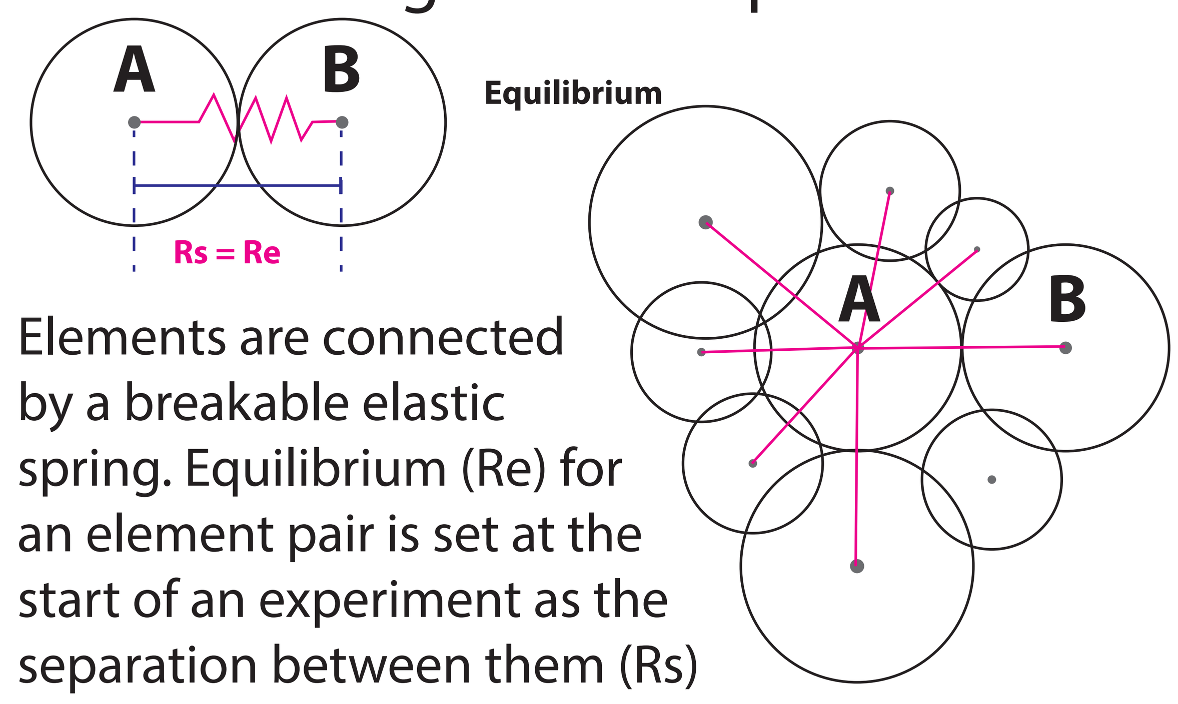
An understanding of the interaction between sedimentation and fault displacement and resulting stratigraphy is key to improve interpretation of seismic data. A modification of one parameter such as sedimentation impacts fault propagation in the syn-tectonic stratigraphy and, as a result, local accommodation space and subsequent deposition locations creating variation in overburden thickness which then affects faulting in the pre- and syn-tectonic layers. A complicated feedback loop that is often hard to unravel. Here, the effect of a footwall sourced prograding delta overlying a pair of domino faults is investigated where initial placement of the delta front and increase in the amount of sediment changes.
The intention of this data is not to provide full interpretation and discussion of the results but to provide an indication of the complexity within observed stratigraphy when the location of the delta front with respect to the two faults changes. When presented with only a static representation of stratigraphy it is sometimes tricky to understand what is observed and how it ended up like that, hopefully these movies and images will help.

A disrete element modelling method is used where the media has dimensions of 400 x 40 units containing 35,475 circular elements with radii between 0.25-0.50 unit. Elements interact as though connected by breakable elastic springs, where each link is assigned unique properties to introduce heterogeneity into the system (**Figure 1**). The initial breaking strain of the link between a pair of elements is defined as a percentage of the length (Re) that separates them (bst).

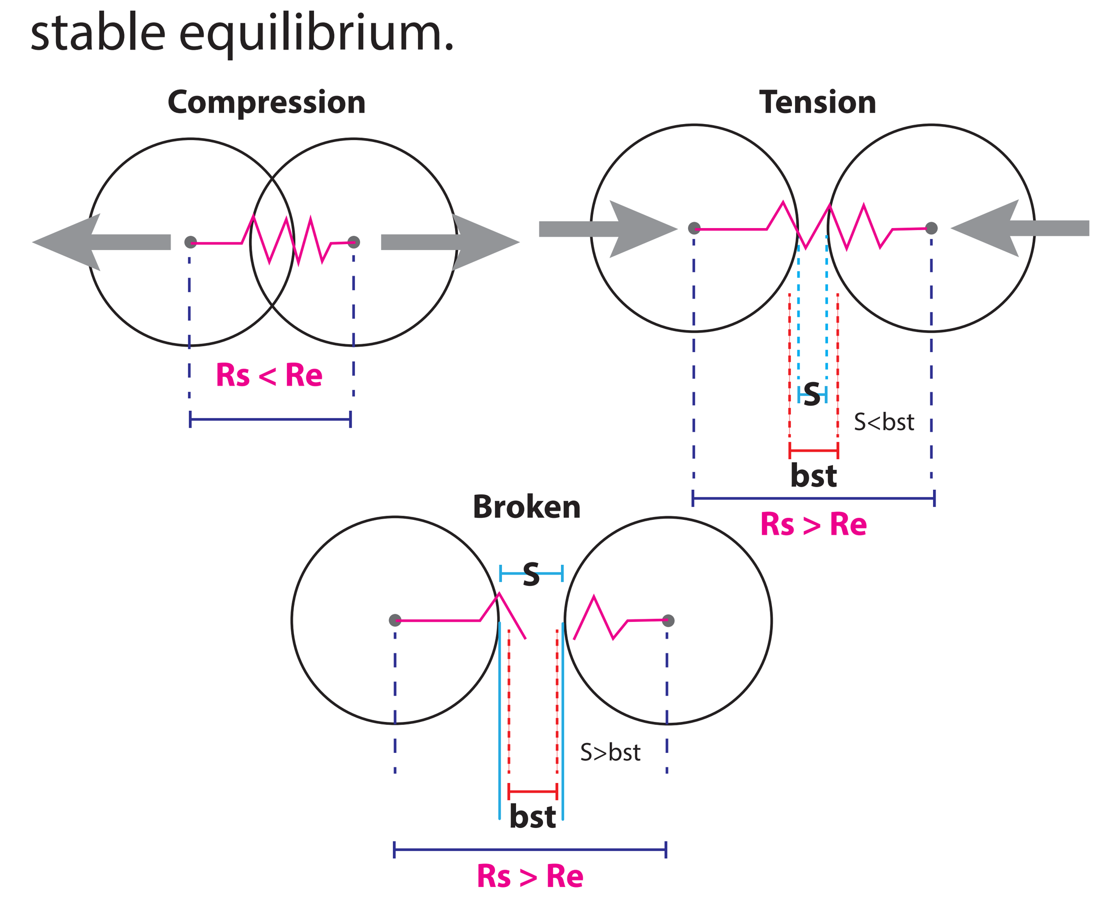
These experiments investigate the effect of deposition of sediment on faulting in both pre- and syn-tectonic layers. There is no variation in the strength of these layers. Sediment is added at intervals by placing elements to fill all empty space below a defined level. Elements that represent sediment are taken from a set of five files (dimensions: 750 x 4 units) with radii varying between 0.25-0.35 unit. Each file is selected at random and all elements that do not overlap existing ones by >15% of their summed radii are deposited. This ensures that elements in each sediment layer do not have aligned weaknesses. A sixth file is then used with radii of 0.15-0.40 unit to fill remaining void space.

There are a host of parameters that can be modified in these experiments for example;
* the material properties, thickness and number of pre-kinematic layers,
* the number of faults, their spacing and dip,
* displacement rates and timing of fault activity,
* sediment fill rate and properties,
* deposition of deltas (with varying foreslope dip and prograding, aggrading and retrogradational fills).

Experiments run to 3,000,000 timesteps and sediment is input 25 times (every 120,000 timesteps), divided into 5 intervals. Sedimentation starts at an initial height of 35 units after pre-tectonic layers have settled to gravity. The sediment source is on the left-hand boundary of the model and the inital delta front in the experiments is defined to start at 100, 150, 200, 250 and 300 units from the left-hand boundary. Propagation of the delta is determined from this boundary and is 2.5 units per sediment input where foreslope dip is 30°. Two sets of experiments are carried out in relation to delta front changes; one where deposition keeps pace with the left-hand footwall crest (Fault 1, **Figure 2**) with a rise of 0.25 unit/deposit and another where it exceeds it at 0.5 unit/deposit. Displacement on both faults is 1.0×10^{-5} unit/timestep where fault planes initial dip is 50° and reduces to 33° at the end of an experiment with a total displacement of 30 units.



Elements are connected by a breakable elastic spring. Equilibrium (Re) for an element pair is set at the start of an experiment as the separation between them (Rs) providing that the distance is less than their radii summed. In a media with elements of varying size this is set as the initial separation regardless of radii. This puts the inital media in a stable equilibrium.



Once an experiment starts the bonds around an element act to try and bring the links back to their equilibrium position through compressional (push the elements apart, Rs<Re) and tensional (pull the elements back together, Rs>Re) forces. If the separation (S) between an element pair in tension is less than a defined breaking strain/distance (bst) then the force acts to bring them back to the equilibrium separation. This is unique for each bond pair. If this distance is exceeded (S>bst), the bond is broken and no tensional force is experienced on the bond but a compressional one is permitted when the Rs<Re. The force exerted on an element is the sum of the forces on each bond multipled by the strength of the spring.
The constitutive equations of the modelling can be found in the following publication:

Discrete-element modelling of extensional fault-propagation folding above rigid basement fault blocks
E Finch, S Hardy, R Gawthorpe
Basin research 16 (4), 467-488
DOI:
https://doi.org/10.1111/j.1365-2117.2004.00241.x

Figure 1

Data is output every 40,000 timesteps to generate movies in the accompanying files (Time: 1 to Time: 75). **Table 1** shows the correlation between the number of timesteps, output image (Time_*), deposit number and topset height in units for a sediment increase of 0.25 and 0.50 unit/fill.

Experiments are named according to the location of the source, initial location of the delta front and increase in deposit height.

Table 1

End of Interval	1	2	3	4	5
Timesteps (million)	0.6	1.2	1.8	2.4	3.0
Output time	15	30	45	60	75
Deposit number	5	10	15	20	25
0.25 unit/fill	36.25	37.50	38.75	40.00	41.25
0.50 unit/fill	37.5	40.0	42.5	45.0	47.5

For example: FW.**100**.SLR.**0.25**
is an experiment where the initial delta front is at **100** units and the deposit height increases by **0.25** unit/fill.

Representative cross-sections of results are shown in **Figure 2**, where the syn-tectonic sediments are coloured according to **(a)** individual fills in alternating blue and yellow blocks to show the intervals and **(b)** five intervals. In the movie files sediments are coloured by layer.

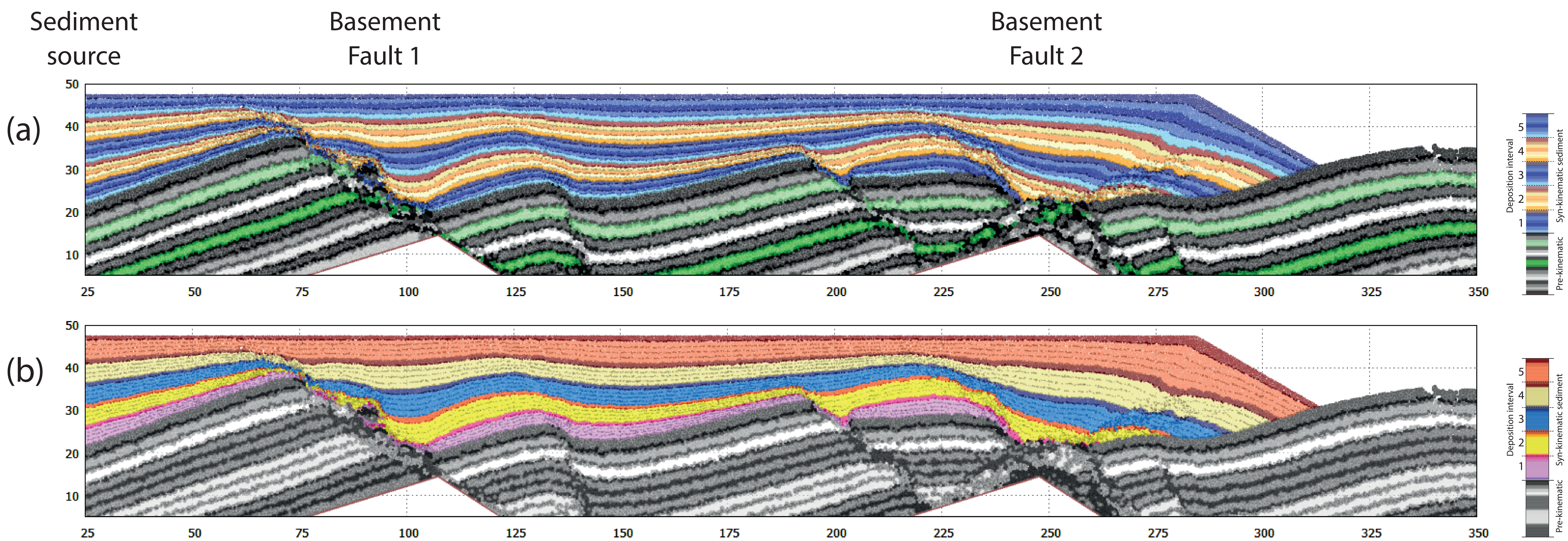


Figure 2

Comparison between fault geometries of experiments with an increase of deposition by 0.25 unit/fill are shown in **Figures 3** (individual layers) and **4** (intervals). Similarly experiments with an increase of 0.5 unit/fill are shown in **Figures 5** (individual layers) and **6** (intervals).

Files **FW.layers_0.25.pdf** and **FW.intervals_0.25.pdf** comprise of individual pages of figures showing the relationship between faults in the pre-kinematic layers and sediment at the end of each interval both for individual layers and the five intervals in experiments with an increase of 0.25 unit/interval. Similarly for files **FW.layers_0.50.pdf** and **FW.intervals_0.50.pdf** with a rise of 0.5 unit/fill.

Figure 3 Comparison between the final geometry of experiments where sediment is deposited in a prograding delta with a footwall-derived source over two normal faults. There are 25 individual layers of fill with an initial delta slope at (a) 100, (b) 150, (c) 200, (d) 250 and (e) 300 units from the left hand wall of the model. (f) presents results when there is a constant sediment fill and no delta front. Pre-kinematic layers are coloured green/grey and syn-kinematic sediments are in alternating intervals shaded blue and yellow. The height to which sediment is filled is 0.25 unit/fill.

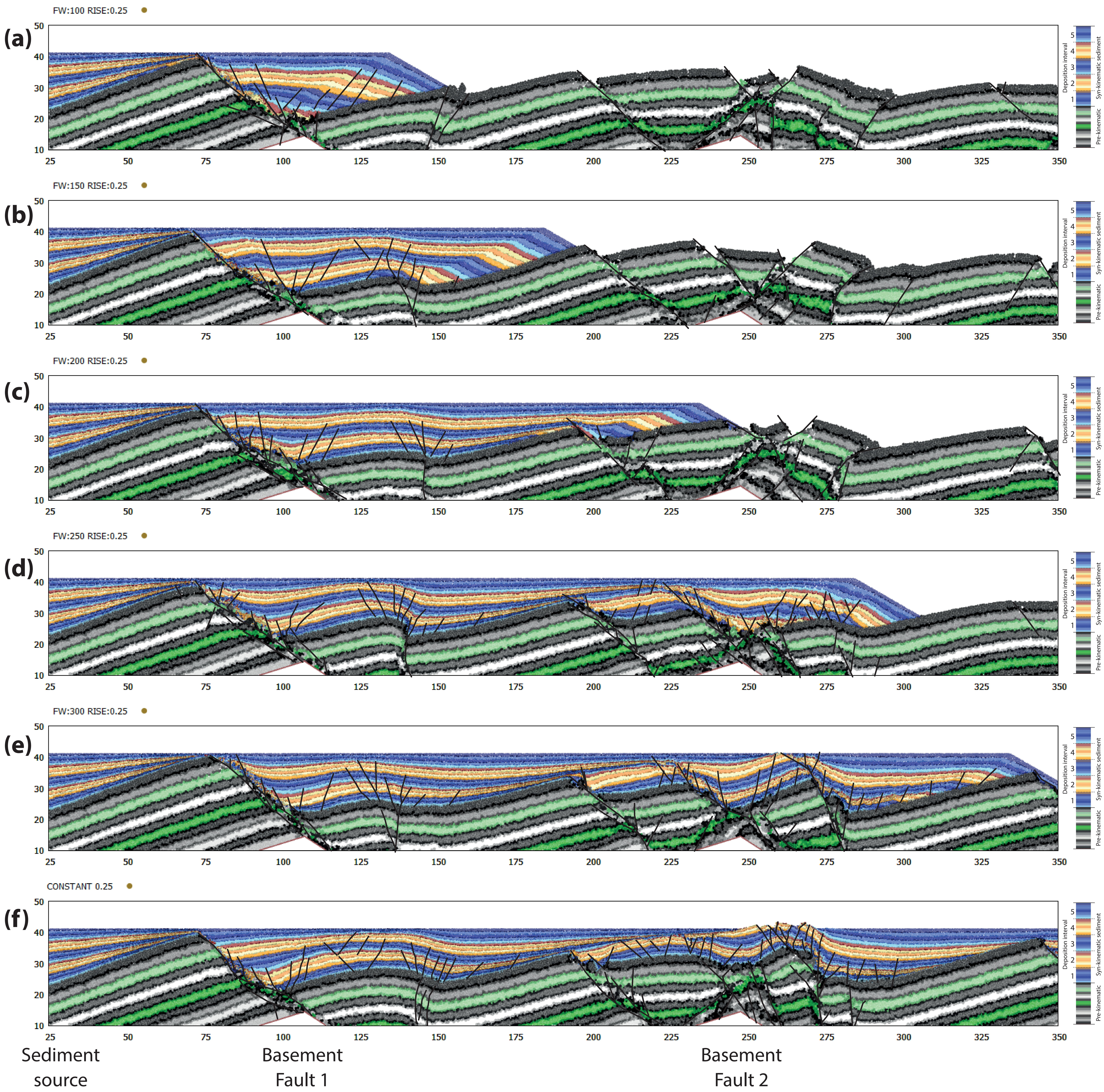


Figure 4 Comparison between the final geometry of experiments where sediment is deposited in a prograding delta with a footwall-derived source over two normal faults. This shows the 5 intervals of fill with an initial delta slope at (a) 100, (b) 150, (c) 200, (d) 250 and (e) 300 units from the left hand wall of the model. (f) presents results when there is a constant sediment fill and no delta front. Pre-kinematic layers are coloured green/grey and syn-kinematic sediments are in alternating intervals shaded blue and yellow. The height to which sediment is filled keeps pace with the height of the footwall crest of the left-hand basement fault (1) and is 0.25 unit/fill.

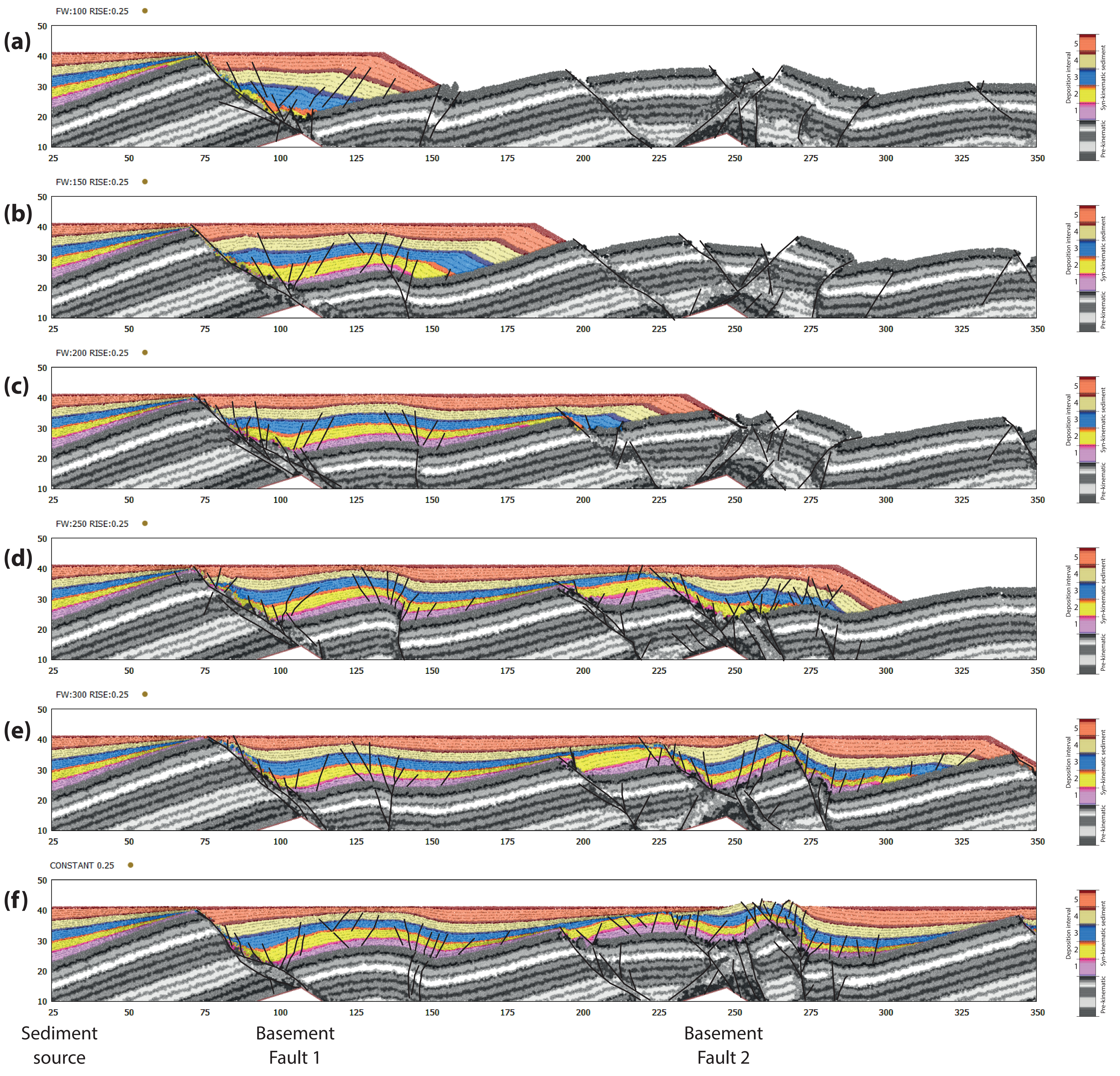


Figure 5 Comparison between the final geometry of experiments where sediment is deposited in a prograding delta with a footwall-derived source over two normal faults. There are 25 individual layers of fill with an initial delta slope at (a) 100, (b) 150, (c) 200, (d) 250 and (e) 300 units from the left hand wall of the model. (f) presents results when there is a constant sediment fill and no delta front. Pre-kinematic layers are coloured green/grey and syn-kinematic sediments are in alternating intervals shaded blue and yellow. The height to which sediment is filled outpaces the elevation of the left-hand basement fault (1) and is 0.50 unit/fill.

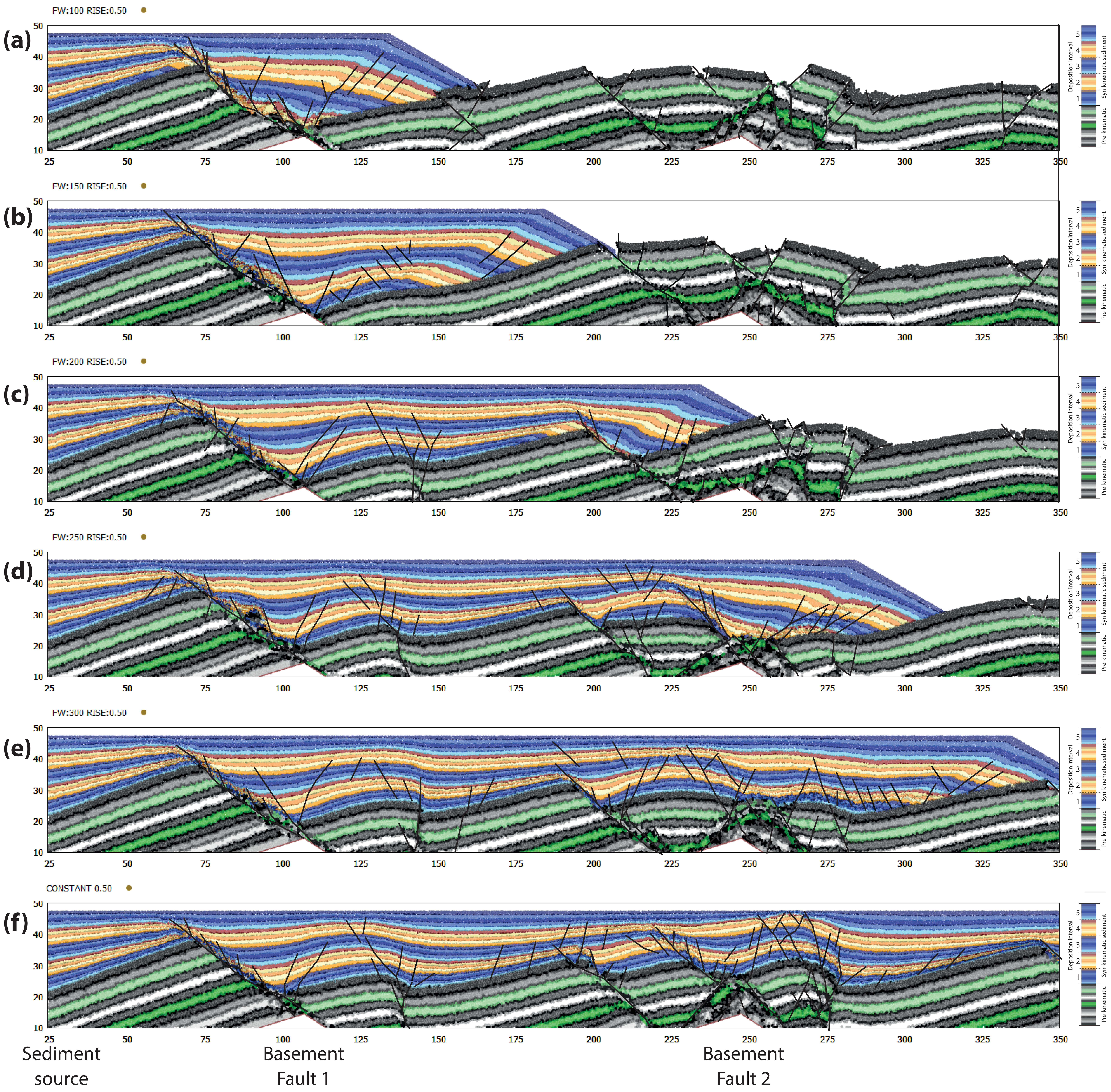


Figure 6 Comparison between the final geometry of experiments where sediment is deposited in a prograding delta with a footwall-derived source over two normal faults. This shows the 5 intervals of fill with an initial delta slope at (a) 100, (b) 150, (c) 200, (d) 250 and (e) 300 units from the left hand wall of the model. (f) presents results when there is a constant sediment fill and no delta front. Pre-kinematic layers are coloured green/grey and syn-kinematic sediments are in alternating intervals shaded blue and yellow. The height to which sediment is filled outpaces the height of the footwall crest of the left-hand basement fault (1) and is 0.50 unit/fill.