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3D Discrete Element Method Modelling of Fault Zone Internal Structure

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SUMMARY

Faults are often simplified as planar structures but are, in reality, complex zones comprised of multiple slip surfaces that contain variably deformed rock volumes, ranging from intact fault bound lenses to fault rock (breccia, gouge). This sub-resolution structure has a direct impact on the juxtaposition geometries across faults and ultimately their impact on fluid flow. We use a commercially available implementation of the Discrete Element Method (DEM), which represents rock as an assembly of cemented spheres, to model the propagation of normal faults through mechanically layered sequences. The fault zone evolution observed in the models demonstrates the main processes thought to be the cause of internal complexity in fault zone structure and the model faults replicate a range of features observed in normal faults at outcrop; these include multi-stranded fault zones, relay zones, normal drag, asperities and corrugated fault surfaces. Systematic variation in the internal structure of model faults with both changes in the lithological sequence and confining pressure suggest that this type of modelling can provide a basis for evaluating the likely complexity of fault zone structure and associated sequence juxtapositions.

Faults are often simplified as planar structures but are, in reality, complex zones comprised of multiple slip surfaces that contain variably deformed rock volumes, ranging from intact fault bound lenses to fault rock (breccia, gouge). This sub-resolution structure has a direct impact on the juxtaposition geometries across faults and ultimately their impact on fluid flow. Fault zone complexity and architecture will vary depending on the nature of the faulted sequence and the prevailing deformation conditions. Empirical constraints on the 2D and, in particular, 3D geometry and content of fault zones are, however, relatively sparse, in the sense that insufficient data are available on fault zones developed within multi-layered sequences, with different stacking patterns and rheological properties, and under different deformation conditions. Nevertheless, existing conceptual models for the formation of fault bound lenses, for example, suggest that their generation can often be explained by one of two processes (Childs et al. 1996): (i) Tip-line bifurcation in which a fault surface propagates through the rock volume and splits into two surfaces that enclose intact volume. (ii) Asperity bifurcation in which slip along a non-planar fault surface leads to the formation of a new fault strand that removes the fault plane irregularity. The newly formed fault bound lenses become progressively fractured with increasing fault displacement to become fault rock. However, as stated earlier, this and similar models for the formation of new fault strands, lenses and fault rock are conceptual and no data are available that can be used for assesing, for example, the likelihood that intact volumes of rock are contained within a fault zone that developed within a certain sequence at a given depth. Since this shortcoming will only partly be alleviated by future detailed outcrop investigations of faults, the aim of this study is to conduct numerical modelling using the Discrete Element Method (DEM), that could improve definition and prediction of the 3D geometry and growth of fault zones for a range of sequences and deformation conditions.

We use a commercially available implementation of the DEM which represents rock as an assembly of cemented spheres, to model the propagation of normal faults through mechanically layered sequences. The models are of a 5 x 5 x 4.2 m rock volume represented by 250,000 particles with a maximum particle diameter of 0.1 m so that individual particles represent volumes of rock, rather than grains. Brittle beds (sandstones) are modelled as bonded (i.e. cemented) particles, and the intervening weak beds (shales) as non-bonded particles. The rheological properties of the model materials (Young's modulus, unconfined compressive strength) are calibrated to those of rocks by varying the particle and bond properties. Bed thicknesses are varied, ranging from 0.3 to 0.6 m. Faulting is induced by movement on a normal fault at the base of the model which is grown to a throw 1.2 m. Over 50 models were run with different rock mechanical properties, different sequences and confining pressures to examine their impact on fault zone structure.

Figure 1 illustrates two stages of a growth sequence obtained from a 3D DEM model. The model shown is comprised of three sandstone beds, each 0.6 m thick, interbedded with shale beds of equal thickness. During the early stages of fault growth (throw < 0.1 m) a low-amplitude monocline develops and fractures form in the brittle sandstone beds. The complexity of the fracture patterns increases upwards, i.e. a single fracture develops in the lowermost bed whereas anastomosing fractures that enclose lensoidal volumes of intact rock form in the uppermost bed. With increasing displacement slip along these initial fractures leads to the formation of fault bound lenses (see L1 within Horizon A in Fig. 1a). In cross section, the trace of the fault strand forming the fault zone boundary in the footwall exhibits a kink within the shale bed located between the upper two sandstone beds, which forms an asperity (see cross section in Fig. 1a). With increasing displacement this asperity is sheared-off and a new fault strand develops in the footwall within sandstone bed B (Fig. 1b). With further displacement this newly formed fault bound lens (L2) moves downwards and rotates towards the hanging wall. At a final throw of 1.2 m (not shown) fault lens L2 is comminuted, whereas fault lens L1 largely remains intact, mainly because larger lenses require greater shear strain to become fault rock. In summary, this simple model illustrates the two basic modes of generating fault bound lenses, (i) tip-line bifurcation (L1) and (ii) asperity bifurcation (L2).

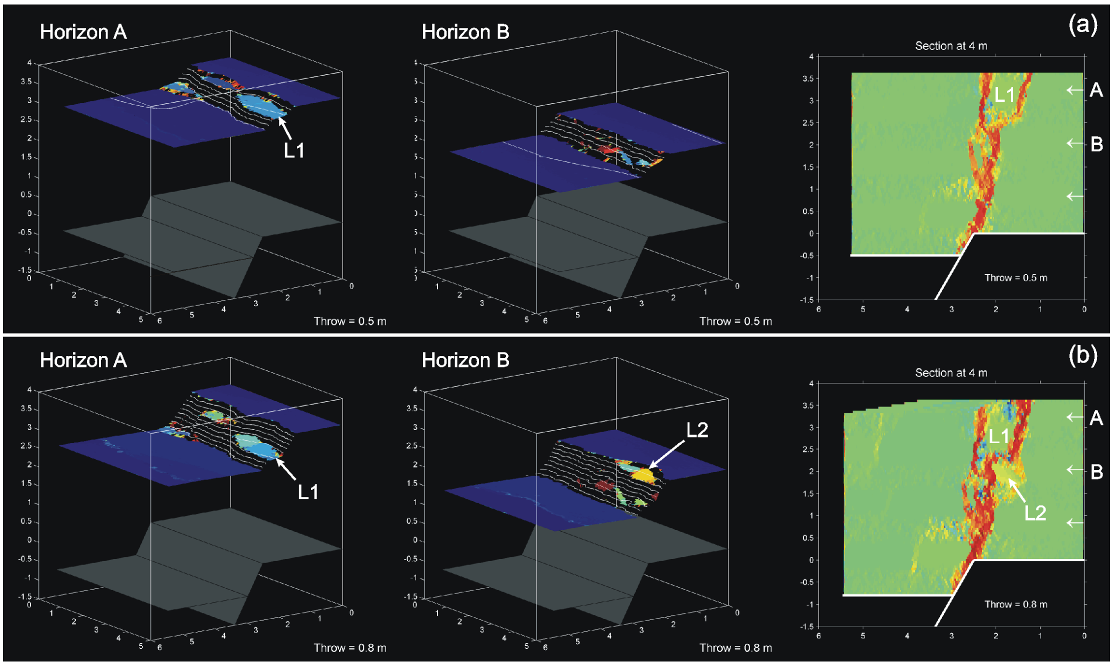

Figure 1 *3D DEM model at a throw of (a) 0.5 and (b) 0.8 m illustrating the formation of fault bound lenses. The horizon maps, taken through the centres of the upper two sandstone beds, are coloured for dip (blue is horizontal, red is ≥30°). White lines are structure contours in 0.1 m intervals. The cross-sections are normal to the strike of the pre-defined fault at the base (shown in grey) and are located at an along-strike distance of 4 m. The sections are coloured for displacement gradient (red areas are zones of elevated synthetic shear, blue antithetic). Two fault bound lenses, labelled L1 and L2, are arrowed in maps and sections and their formation is described in detail in the text.*

The fault zone evolution observed in the models demonstrates the main processes thought to be the cause of internal complexity in fault zone structure and the model faults replicate a range of features observed in normal faults at outcrop; these include multi-stranded fault zones, relay zones, normal drag, asperities and corrugated fault surfaces. These models, to our knowledge, represent the first time that the three dimensional internal structure of faults has been reproduced in numerical models. Systematic variation in the internal structure of model faults with both changes in the lithological sequence and confining pressure suggest that this type of modelling can provide a basis for evaluating the likely complexity of fault zone structure and associated sequence juxtapositions, which may be expected in different settings and its implications for fault-related flow in the subsurface.

References

Childs, C., Watterson, J. and Walsh, J. J. [1996] A model for the structure and development of fault zones. *Journal of the Geological Societ, London*, **153**, 337-340.