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Numerical modelling of the effects of fault slip on fluid flow around extensional faults: Reply

XING ZHANG and DAVID J. SANDERSON

Geomechanics Research Group, Department of Geology, University of Southampton, Southampton Oceanography Centre, Southampton SO17 1BJ, U.K.

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Chen and Lorig (this issue) suggest that different boundary conditions and modelling approaches from those of Zhang and Sanderson (1996) might be appropriate in the modelling of fluid flow around extensional faults. Their results are significantly different from ours, indicating the sensitivity of deformation and fluid flow to the boundary conditions applied to the model. However, we do not think that their approach is appropriate for the modelling of the movement of extensional faults, a view supported by comparison of the resulting models with natural systems.

We will address five points raised by Chen and Lorig:

(1) Chen and Lorig use a boundary element as an artificial boundary to their models, to simulate an infinite (or semi-infinite) extent of isotropic, linear and elastic material surrounding the modelled region of the fault. As a result, the fractured region around the normal fault is allowed to have large displacements and block rotation but is embedded in a continuum that is limited to small displacements and/or rotations. Such a boundary condition may be suited to modelling of an underground excavation with small far-field displacement, but not a faulted region where the extension is accommodated by major lateral motion (e.g. McKenzie, 1978; Le Pichon and Sibuet, 1981; Williams and Vann, 1987; Roberts *et al.*, 1990).

The deformation of the region surrounding the boundary element is greatly determined by K, the boundary element stiffness, and the two fixed point locations within the boundary element domain which are required to restrict the displacements of the nodes. The choice of these parameters imposes significant constraints on the deformation of the model. We do not think that the boundary element boundary condition represents a realistic geological setting for the modelled rock volume.

The stress boundary conditions that we used might not represent the stress state precisely along the vertical boundaries after large deformation, but these affect mainly the boundaries of the model, rather than the central area around the fault zone. This was why the length of our models was larger than the height, particularly in the hangingwall where greater deformation was expected.

(2) Chen and Lorig modelled the deformation of extensional faults by applying an internal velocity boundary condition parallel to the fault zone. In this way, the deformation of the fault zone is mainly controlled by the specific velocity distribution along the fault, as shown by their results (figs 2b and 4), rather than by the fault geometry, the associated fracture pattern and the stress state. Thus, deformation in their models is imposed by slip on the fault, with subsequent modification of the surrounding rock-mass (i.e. deformation, stress state, fracture aperture). It is not clear from their models whether stresses on the fault are sufficient to cause frictional sliding. In our models, fault slip is a consequence of the applied external boundary conditions (stress and basement velocity) such that the slip on the fault occurs where conditions for frictional sliding are met, which, in turn produces dilation and rotation within the jointed rock-mass.

We also modelled normal fault zones with jogs. Studies of active faults (Aki, 1979; Zhang *et al.*, 1991) show that oversteps and bends cause slip events to have complex spatial and temporal arrangements. Field evidence shows that the displacements of normal fault segments can be transferred by thickening, thinning, block rotation and void formation (e.g. Dunham, 1988; Peacock and Sanderson, 1991, 1994; Beach and Trayner, 1991; Chapman and Meneilly, 1991; Peacock and Zhang, 1994).

(3) Chen and Lorig question the attainment of equilibrium in our models. We used a very small timestep, Δt, so that the number of timesteps, N, was large, where $T = \Delta t N$, is the duration of the model, and the velocity of the basement block was set to be small. For each model, the unbalanced forces were checked, and equilibrium was demonstrated by plotting the unbalance forces and displacement histories (Zhang and Sanderson, 1996, fig. 12c).

(4) Our models do involve 'meaningful fluid flow' by application of a small hydraulic head across the model. For example, in our model A, the hydraulic pressure

along the top and bottom boundaries was set to 0 and 400 kPa, producing a gradient of 10 MPa km^{-1}, which was slightly higher than that for hydrostatic pressure (9.8 MPa km^{-1} with a gravity of 9.8 m s^{-2} and a fluid density of 1000 kg m^{-3} as used in our models). Thus, there was a slight pressure difference of 8 kPa between the top and bottom boundaries, which are 40 m apart. In this way, the applied hydraulic pressure was reasonably close to the hydrostatic pressure at a shallow depth, and the flow paths in the fractured rock mass could be examined (as in Zhang and Sanderson, 1996, fig. 7).

(5) Finally, the test of any model is its ability to reproduce natural behaviour. Our models produced dilation of sub-vertical joints in the hangingwall regions of faults or at bends in the fault surface, which closely resemble the steep vein systems seen in association with many natural extensional fault systems (e.g. Sibson, 1990). In contrast, the models of Chen and Lorig show extensive dilation of horizontal fractures in addition to significant 'edge effects' at their boundary element.

In our paper, we did not set out to explore fully the effects of boundary conditions and modelling approaches. We welcome the comments by Chen and Lorig, who produce some interesting alternatives to our models. We contend, however, that the boundary conditions in our models are more appropriate to the natural deformation around extensional faults, but concede the need to explore these more fully. We believe that our modelling shows that UDEC is a very suitable tool for the study of deformation and fluid flow in extensional fault regions and that our results demonstrate some important features appropriate to natural behaviour.

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