D-27 DAMAGE DEVELOPMENT ASSOCIATED WITH FAULTING

DAVID J SANDERSON¹, YOUNG-SEOG KIM² and XING ZHANG¹

¹Imperial College, TH Huxley School of Environment, Earth Science and Engineering,
London SW7 3BP, UK

²Southampton University

Damage zones

Fractures are developed around many faults and are interpreted to represent various types of damage related to fault development. This may involve increased density of fracturing and/or enhanced dilation to form veins. Three types of damage (Fig. 1a) are recognised:

Tip damage develops due to stress concentrations ahead of a propagating fault tip and forms a wedge-like pattern of damage. Typical damage zones at Mode II (shearing) tips are illustrated in Fig. 1(b).

Linkage damage develops in relay ramps and transfer zones between faults. Clearly as faults approach one another, the tip damage zones will overlap to provide linkage between unconnected fault segments (Fig. 1 c). Based on the work of Peacock and Sanderson (1994, 1995), different distributions of damage are considered typical of normal and strike-slip relays (Fig. 2).

Kinematic damage is produced by fracturing and dilation developed in response to deformation (particularly normal drag) induced in the wall-rocks of fault zones due to displacement (Fig. 1d). Kinematic damage often involves antithetic faulting that accommodates block rotation and is associated with the opening of jogs and other irregularities on the damage fractures and the main fault surface. Regions of high displacement gradient on a fault are often characterised by extensive damage.

Distributed damage along fault zones (Fig. 1 e,f) may be attributed to any combination of the above types. As a fault propagates earlier tip zones may be preserved as a zone of damage along the fault trace, which develops preferentially on the dilational side of the fault tip (Reches & Lockner 1994). Similarly, segment linkage and former relay ramps are commonly preserved as patches of damage along a fault (e.g. Fig. 1e). Fault zones with low displacement frequently consist of zones of distributed damage with no through-going displacement discontinuity (e.g. Fig. 1f). These zones are interpreted as Mode III (tearing) tips (Fig. 3) and are similar to en echelon tension gashes and classical Riedel shear patterns.

Clearly if these patterns of damage distribution up-scale to reservoir scales they provide a rationale for predicting sub-seismic fracturing and hence fracture controlled porosity and permeability. Faults within a reservoir can only be resolved by conventional seismic surveys to surfaces with a stratal separation of about 15m. These faults may be extended at their tips by considering the displacement profiles (Pickering *et al.* 1997). The resulting pattern may then be used as a basis for the prediction of areas of extensive damage based on the inferred stress field and the kinematics of the faults. Damage may result from the stresses responsible for the faults themselves or from periods of later reactivation under different stress fields. Such analysis may be quantified using numerical models with appropriate geomechanical behaviour.

Fig. 1 Examples of damage zones around faults; (a) damage types, (b) tip damage, (c) linkage damage, (d) kinematic damage, (e,f) distributed damage; b,c,e,f from Gozo, Malta; d from Kilve, Somerset, UK.

Fig. 2 Damage distribution at linkage zones between (a) normal and (b,c) strike-slip faults.

Fig. 3 Three dimensional conceptual model showing form and distribution of tip damage in sections through a strike-slip fault.

Numerical modelling

The kinematic evolution of damage zones for faults in multilayered sequences has been investigated using distinct element numerical modelling (UDEC code). Four situations representing a fault tip, continuous fault, and dilational and contractional jogs have been modelled. The resultant damage involves considerable localisation of the opening of fractures, and associate fluid flow, results from fault movement, particularly at fault tips and in association with jogs. The geometry of the fault segments and jogs determines the general pattern of damage, with distributed damage zones at fault tips and contractional jogs (Fig 4b), but more localized damage at pull-aparts and dilational jogs (Fig. 4a).

Fig. 4 Distinct element (UDEC) models of tensile (T) and shear (*) failure in a geomechanical model of a fractured limestone layer in a mudrock matrix. (a – left) shows a dilational jog with most of the damage being concentrated within the overstep; (b – right) shows much more distributed damage around a contractional jog (note lack of damage within the jog).

Dilation and fluid flow in damage zones

One particularly common feature of damage development is the dilation of fractures (e.g. Sanderson & Zhang 1999). This implies that much of the permeability is controlled by such damage and hence is important in the migration and production of hydrocarbons. Evidence of this damage is often seen as veining at the tips of faults and in fault zones (McGrath & Davison 1995).

Figure 5 shows a study of vein thickness along a traverse across three normal faults zones. Although veins generally open incrementally, it is instructive to think of them as providing a model for the variation in flow rate, which will be proportional to the cube of the aperture (thickness). The frequency of veins (i.e. intensity of fracturing) does not change within the fault zones (Fig. 5a), but their opening, as shown by steeper cumulative thickness gradients, does. The thickness distributions are markedly different for veins inside and outside the damage zones (Fig. 5b). This behaviour is typical of damage zones elsewhere (Roberts *et al.* 1999) and has been produced in numerical models by Sanderson & Zhang (1999), who demonstrate that most of the fluid flow is concentrated within such damage zones.

Fig. 5 is an 8m long traverse across three normal faults zones in a 0.25 m thick limestone bed to the east of Kilve beach, Somerset, UK. A total of 3.8 m of the traverse was within damage zones, with the remaining 4.2 m lying outside these zones. (a) The frequency of veins is fairly constant across the traverse, but the cumulative vein thickness gradients are steeper within the fault zones. (b) Log-log plots indicating a power-law exponent (D -value) within the damage zones of 0.5, compared with a value of about 1.5 outside.

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