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# Quadshear - A New Kinematic Model for Clay Smear Development

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## SUMMARY

A new kinematic model, based on the Trishear model, has been developed to simulate fault-propagation folding in ductile, clay-rich strata between two propagating faults, a process which often leads to the development of clay smears which can cause the fault to seal. The new model is used to determine the amount fault throw required for the continuous clay smears to break down, normalised to the bed thickness (this ratio is often known as the critical clay smear factor or CCSF). We find that the maximum length of continuous clay smear is primarily dependent on the position of the clay-rich bed in the stratigraphy, and the rate of propagation of the faults. The thickness of the clay-rich bed, the horizontal offset of the two propagating faults and the width of the fault-propagation folds have much less impact on the maximum length of continuous clay smear.

Clay smears often form when thin clay layers within a heterogeneous succession are sheared across a propagating fault zone. Unlike a fault gouge, a clay smear experiences no mixing with material from adjacent beds but is compositionally identical to the source bed. As long as the smear remains continuous, therefore, it can act as powerful seal across the fault zone. Many previous studies have therefore been undertaken to try to predict when clay smears are likely to be continuous. These typically focus on the Clay Smear Factor (CSF), the ratio between fault offset and source bed thickness, using field studies to determine a critical value of this ratio (the CCSF) above which smears are predicted to be discontinuous. However estimates of this critical value vary from 4 to 50 (Lindsay et al. 1993, Faerseth 2006).

In this study we develop a kinematic model to simulate the folding of ductile (clay-rich) layers between two propagating faults. This model, an extension of the Trishear model of Erslev (1993), is able to replicate the formation of smears as a result of fault propagation folding. We use this model to determine the controls on the breakdown of continuous smears (e.g. thickness of the source bed, position of the source bed within the stratigraphy, fault propagation rate and geometry). These models provide new insights as well as predictive tools on clay smearing and the CCSF.

**The Quadshear model**

The original Trishear model of Erslev (1993) simulates folding in the cover strata above an upward-propagating fault tip. It assumes that folding occurs within a triangular zone with a lower apex at the fault tip, and that two boundary conditions are satisfied: a) there is no volumetric strain, and b) there are no displacement discontinuities (i.e. the displacement at the edge of the trishear zone is equal to the fault slip vector). Subsequent studies (e.g. Zehnder and Allmendinger 2000) showed that there is no unique solution to these boundary conditions, and derived a number of velocity functions to fit the model.

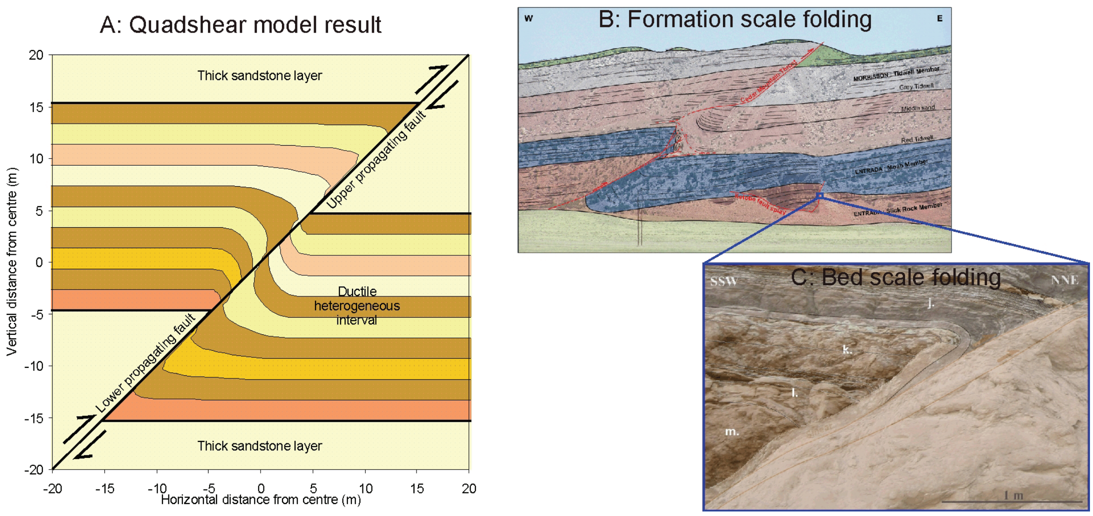


*Figure 1* *Folding of ductile layers between propagating fault tips at different scales, Utah.*

The Quadshear model simulates fault propagation folding in ductile strata between two propagating fault tips, one propagating up from underneath and one propagating down from above. The folding occurs within a quadrilateral zone with apices at the two fault tips and sinusoidal boundaries (apices other than at the fault tips would create displacement discontinuities, thus violating the second boundary condition). In the simplest version of the Quadshear model, the two propagating faults are coplanar. Quadshear models have also been developed for laterally offset propagating faults; these require either dilation or bed-parallel shear of material into or out of the fault zone to satisfy the first boundary condition.

The results of the Quadshear model show the beds in the ductile zone folded into the fault plane, with fold amplitude increasing towards the centre of the ductile zone (Fig 1A). Similar geometry can be observed in the field at a number of scales; Fig 1B and 1C show examples from the Cedar Mountain Fault, a reverse fault system in Utah, at the formation scale and the bed scale respectively.

**Controls on clay smear development**

Fig 2 shows an example of a c.4m interval of heterolithic strata between two thick sandstone units, from the Entrada Formation at the Cedar Mountain outcrop. As Fig 1C shows, these heterolithic intervals tend to act as ductile layers and fold into the fault zone, forming geometries similar to those predicted by the Quadshear model. We can therefore use the Quadshear model to predict the amount of throw the fault can undergo before the individual clay beds within the heteroltihic interval become completely separated (i.e. the maximum fault throw at which the clay smear is continuous). If we divide this by the bed thickness we get the Critical Clay Smear Factor (CCSF). We find that the largest control on CCSF is the position of the clay bed within the ductile interval: clay beds near the centre of the ductile interval will form much longer continuous clay smears (i.e. have a higher CCSF) than clay beds adjacent to the thicker sandstones, because of the prolonged folding before faulting.

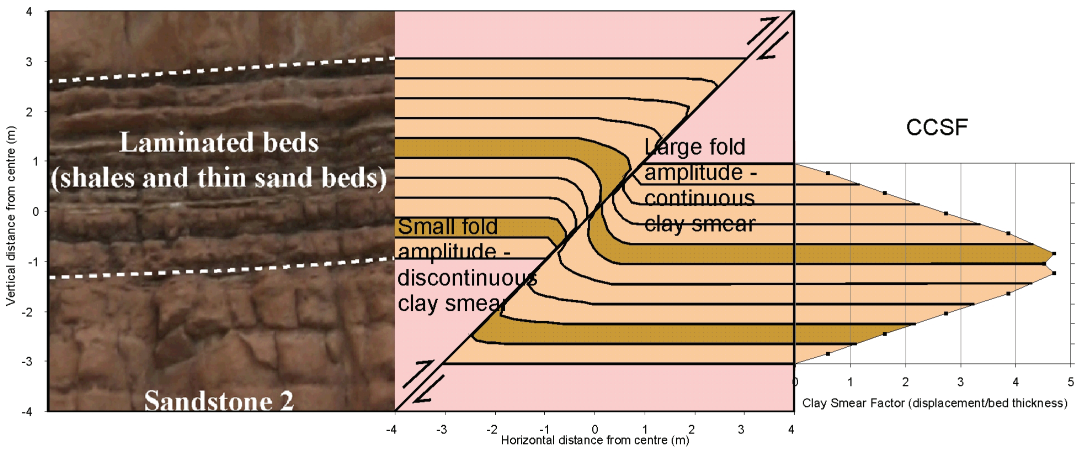


***Figure 2*** *Calculating the CCSF for different beds within a ductile interval.*

The other main factor that controls clay smearing is the fault propagation rate: slower propagating faults develop longer continuous smears than fast propagating faults. By contrast, the thickness of the source bed does not significantly affect the maximum continuous clay smear length; however since the CCSF is calculated as maximum continuous smear length divided by bed thickness, this will vary significantly with bed thickness. Surprisingly, neither the fault dip nor the lateral offset of the initial faults appears to have much impact on the CCSF. However the variations in CCSF due to source bed location, source bed thickness, and fault propagation rate, are sufficient to explain the range of CCSF values reported in the field.

**References**

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