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Distant off-fault damage and gold mineralization: The impact of rock heterogeneity

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ABSTRACT

Field observations have established that fault-related damage can occur at locations, far from the principal slip surface, which are well outside the fractured region currently predicted by models of fault damage. We use a finite element model to simulate fracture initiation due to fault linkage and show how variations in rock properties allow off-fault damage to develop at surprisingly large distances away from the main fault. Off-fault damage continues to grow even after two adjacent, closely spaced fault segments have interacted and linked. We demonstrate that this process was important for the formation of fracture-hosted gold deposits in the Mount Pleasant goldfield, Western Australia. The strength of lithological contacts also has a significant impact on off-fault damage location and intensity. Our approach may go some way to explaining the non-intuitive distribution of mineralization in certain mineral systems, as well as being applicable to predict subsurface fracturing and fluid flow in hydrothermal/geothermal reservoirs.

1. Introduction

Within a single lithology, properties can vary due to original deposition mechanisms, weathering and subtle changes in the original mineral composition, such changes can localize stress and initiate fracturing. Sandstones can vary in grain size, degree of micro-fracturing, number and orientation of deformation bands (Guo et al., 2009). A granite exposure may exhibit changes in mineralogy that will affect its mechanical properties. Such changes may be on a scale of a few centimeters or several kilometers, Glazner et al. (2004) suggest that such variation in granitic bodies is common at all scales.

It is now well understood that damage can develop along the full length of a fault, due to the roughness of the principal slip surface (Griffith et al., 2010), or at specific fault configurations such as tips and stepovers (Kim et al., 2003). It is widely stated that heterogeneity affects fracture initiation, propagation and termination (Blair and Cook, 1998; d'Alessio and Martel, 2004; Gudmundsson et al., 2010; Helgeson and Aydin, 1991; Tang et al., 2007). Previous numerical models investigating the effects of material heterogeneity have taken one of two approaches. Tang et al. (2000, 2007) simulate fracture evolution within a rock with an underlying random distribution of mechanical properties, they show that in heterogeneous samples initial location of micro-fractures is sensitive to local variations in material properties however once the micro-cracks have evolved into macro-cracks, which occurs well before the peak stress is reached, these macro-cracks become the dominant heterogeneity within the system and interact in a predictable way resulting in failure of the specimen. Other authors have modeled joint evolution in layered sedimentary sequences and shown that propagating fractures can be initiated, arrested or deflected at lithological boundaries (Bai and Pollard, 2000; Gudmundsson et al., 2010; Helgeson and Aydin, 1991). What is not well understood is the development of off-fault damage at substantial distances from the principal slip surface. For example, tip zone damage extends ~0.5 fault lengths beyond the tip of one fault on the island of Malta (Fig. 5 of Kim et al., 2003). Bistacchi et al. (2010) found off-fault damage proximal to a contractional jog, where two fault systems intersect in the Eastern Alps. Similarly, Cochran et al. (2009) postulated that long-lived off-fault damage 1.5 km from the Calico fault, California could be a dynamic effect, however, they did not consider how lithological variations may be responsible for the same damage.

Fault damage critically influences the formation of certain types of precious metal resource (Micklethwaite et al., 2010), the stress state of active fault systems (Faulkner et al., 2006), and the transmission of fluid through the crust where damage is directly linked to elevated permeability (Odling et al., 2004; Rowe et al., 2009; Sheldon and Micklethwaite, 2007). Hence, it is important to understand the circumstances under which it can occur at substantial distances from the fault. Is it possible that mechanical heterogeneity could be responsible for the development of the distant off-fault damage described by the authors above?

Here, we apply a novel finite element approach that both calculates the stress and strain fields associated with fracture networks and simulates the growth and propagation of fractures (Willson et al., 2007). We model fracture evolution and fault linkage at a stepover cutting variable

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lithological units. The approach is applied to a well-constrained case study site; fracture-hosted gold deposits in the Mount Pleasant goldfield, Australia, associated with a stepover in the Black Flag fault system (Micklethwaite and Cox, 2004, 2006). There are a large number of variables, many of which are interdependent, that effect gold mineralization, such as rock chemistry, fluid pH, redox and gold solubility, and fluid flux. In order to comprehensively model the full gold mineralization process one would have to develop a level of sophistication that is computationally and theoretically unachievable at the moment. Here we only model the first-order control, which is large-scale rock damage development leading to substantial transient permeability enhancement (on the scale of our models fluid flow can be considered a second-order variable). In doing so, we find that we can reproduce the known locations of gold deposits, and that changes in lithological variations enable fault-related fractures to develop at large lateral distances away from the principal slip surface, even after linkage of the stepover.

2. The Black Flag fault system

Gold mineralization along the Black Flag fault is associated with stepover-related damage. The damage intersects distinct changes in lithology and so represents an ideal case study for the application of our mechanical model, MOPEDZ. Previous approaches successfully related the distribution of gold mineralization to stress changes (Micklethwaite and Cox, 2004, 2006) and damage development (Sheldon and Micklethwaite, 2007) around the stepover using Coulomb failure stress change calculations and damage mechanics. However, these studies were unable to explain variations in the distribution of gold deposits within the damage zone; restricted as they were to treating the Black Flag fault as two unlinked segments and the host rock as an elastic isotropic medium.

The Black Flag fault is a dextral strike-slip fault, >50 km long, cutting Archean volcano-sedimentary and intrusive rocks. Mafic to ultramafic lavas are unconformably overlain by volcaniclastic and sedimentary rocks intruded by a mafic sill and the Liberty granite (Hagemann and Cassidy, 2001). The sequence is deformed into a shallow south-plunging antiform with the granite in its core, surrounded by the mafic sill and lavas (Fig. 1). Here the Black Flag fault forms a right-stepping, hard-linked stepover, ~2 km long (Micklethwaite and Cox, 2004), associated with a pronounced minima in the along strike displacement profile (Micklethwaite and Cox, 2004).

Gold deposit location has a skewed spatial distribution relative to the stepover (Fig. 1). Deposits are preferentially developed northwest of the stepover, stretching ~5 km from its midpoint, and importantly there is a concentration of mineralization around the margin of the Liberty granite (Cassidy and Bennett, 1993). Mineralization is hosted largely by veins linked to short, small displacement faults and shear zones (e.g. Gebre-Mariam et al., 1993), as well as in the weathering profile derived from underlying veins.

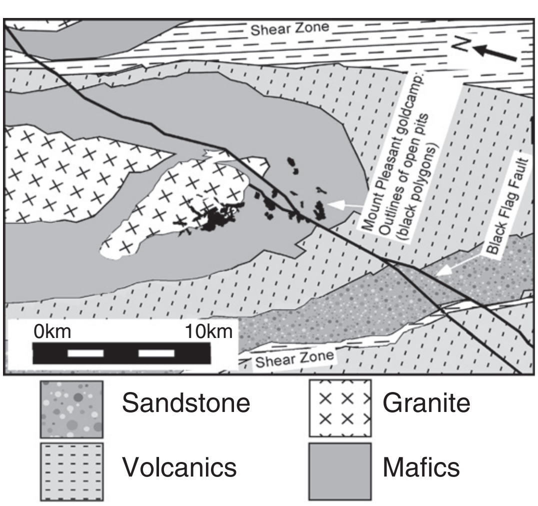

Fig. 1. Geological map showing the Black Flag fault in Western Australia cutting several lithologies. Gold mines associated with the fault are also shown.

3. Computational modeling

To examine the influence of lithology variation on fracture/fault evolution we performed computer simulations based on the MOPEDZ finite element model (described in Lunn et al., 2008; Willson et al., 2007). We estimate spatial and temporal fault evolution within a volume of rock with heterogeneous material properties. Faults are initiated by increasing the applied boundary stress (Fig. 2). To achieve a controlled mechanical failure, displacement boundary conditions are required; load control tends to result in rapid catastrophic failure, both numerically and in laboratory test rigs, whereas rigs which operate under displacement control result in reproducible failure patterns. Pre-processing using load control on the boundaries determines the size of the initial step to be used when running under displacement control at which point the ratio of σ_1 to σ_3 is known. After the first step (in which all 4 boundaries are displaced and failure is initiated) only the top and bottom boundaries are displaced (the left and right boundaries are maintained at a fixed load). This gradual displacement is carried out as a series of iterative steps that allow the fault structure to evolve. The magnitude of the boundary displacement in any one iterative failure step is controlled such that only a small number (<6) of cells fail in any one step (to maintain stability of the model).

Once the first fracture failure is initiated, subsequent failures are propagated by increasing the boundary displacement, while keeping σ_3 fixed. In MOPEDZ as an element fails (in either shear or tension) its material properties are altered (Appendix 1). Although the first failures are triggered by displacement of the boundaries, the alteration of the material properties of those failed cells causes a change in both the direction and the magnitude of local σ_1 and σ_3 near to those failures

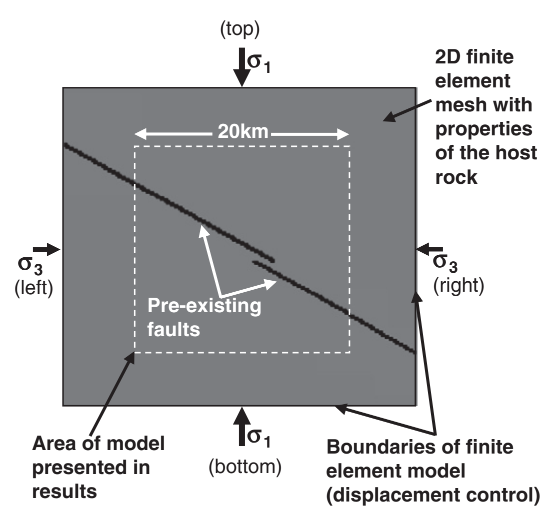

Fig. 2. Typical initial setup showing the orientation of σ_1 and σ_3 (simulated far-field stress), directions of σ1 and σ3 remain constant for all simulations. Gray area is host rock and black is host rock containing faults (n.b. the pixellated nature of the pre-existing joints is a product of the model). The model boundaries are under displacement control (size of the initial step determined prior to run with boundaries under load control), following the initial failure only the top and bottom boundaries are displaced. To avoid consideration of structures generated at the boundary only results for the central window (within the white dashed box) are presented. The number of mesh elements varies for the simulations presented in this paper but are always constrained such that each element in the finite element mesh represents an area approximately 150 m wide (all mesh elements are square).