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Influence of crystallised igneous intrusions on fault nucleation and reactivation during continental extension

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ABSTRACT

Continental rifting is commonly accommodated by the nucleation of normal faults, slip on pre-existing fault surfaces and/or magmatic intrusion. Because crystallised igneous intrusions are pervasive in many rift basins and are commonly more competent (i.e. higher shear strengths and Young's moduli) than the host rock, it is theoretically plausible that they locally intersect and modify the mechanical properties of pre-existing normal faults. We illustrate the influence that crystallised igneous intrusions may have on fault reactivation using a conceptual model and observations from field and subsurface datasets. Our results show that igneous rocks may initially resist failure, and promote the preferential reactivation of favourably-oriented, pre-existing faults that are not spatially-associated with solidified intrusions. Fault segments situated along strike from laterally restricted fault-intrusion intersections may similarly be reactivated. This spatial and temporal control on strain distribution may generate: (1) supra-intrusion folds in the hanging wall; (2) new dip-slip faults adjacent to the igneous body; or (3) sub-vertical, oblique-slip faults oriented parallel to the extension direction. Importantly, stress accumulation within igneous intrusions may eventually initiate failure and further localise strain. The results of our study have important implications for the structural of sedimentary basins and the subsurface migration of hydrocarbons and mineral-bearing fluids.

1. Introduction

Faults are a fundamental feature of extended continental crust; they accommodate strain, at various scales, through either the nucleation and growth of new normal faults or the reactivation of favourably-oriented, extant faults (e.g., Donath, 1961; Sibson, 1977, 1985; Byerlee, 1978; White et al., 1986; Faulds and Varga, 1998; Holdsworth et al., 2001; Walsh et al., 2001; Zhang et al., 2011). The architecture of normal fault arrays can therefore significantly influence the large-scale, long-term structural evolution of rift basins. Understanding fault nucleation, growth and reactivation processes has thus received considerable attention in the literature (e.g., Sibson, 1977, 1985; Walsh and Watterson, 1988; Walsh et al., 2001).

In addition to extensive normal fault arrays, sedimentary basins commonly contain temporally and spatially associated igneous intrusion complexes (e.g., Archer et al., 2005; Holford et al., 2012; Magee et al., 2013a). These are typically arranged into a pervasive network of interconnected magma conduits (e.g., sills and dykes) and reservoirs (e.g., sills and laccoliths), which may cross-cut, intrude along or be displaced by normal faults. To date, studies examining tectono-magmatic interactions in rift basins have focused on constraining syn-intrusive relationships and processes. These include analyses of how pre-existing faults may act as flow pathways for ascending magma (e.g., Valentine and Krogh, 2006; Abebe et al., 2007; Mazzarini, 2007; Magee et al., 2013a) or the mechanics and impacts of magmatically induced-faulting (e.g., Parsons and Thompson, 1993; Faulds and Varga, 1998; Corti et al., 2003; Grant and Kattenhorn, 2004; Rowland et al., 2007; Gudmundsson and Lotveit, 2012). This research has provided fundamental insights into how tectono-magmatic interactions influence the distribution of eruptive volcanic centres (e.g., Abebe et al., 2007; Gaffney et al., 2007) and economic ore deposits (e.g., Richards, 2001; Bédard et al., 2012), strain accommodation during continental rifting (e.g., Ebinger and Casey, 2001; Rowland et al., 2007; Calais et al., 2008), and the development of subsurface fluid flow pathways (e.g., Faulds and Varga, 1998; Holford et al., 2012).

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Although fault development and magma emplacement are key elements in basin and petroleum system evolution, very little attention has been paid to the impact that solidified igneous intrusions may have on subsequent tectonic events in rift basins (Faulds and Varga, 1998). Specifically, does the presence of crystallised igneous intrusions, which often have significantly different mechanical properties to the surrounding host rock (i.e. they represent elastic inclusions according to Gudmundsson, 2011), affect the reactivation potential of any extant faults they interact with? To address this question, we have developed a conceptual model for the mechanical interactions and processes that may occur between a normal fault array and fully solidified, gabbroic intrusions during extensional reactivation and examine two case studies where this model may apply. Our results suggest that the presence of mechanically competent (*sensu lato*) crystallised intrusions, relative to the host rock and any pre-existing faults, locally affects the temporal distribution of strain. During the early phase of extension, strain is accommodated by: (1) the reactivation of favourably-oriented extant faults, or possibly the nucleation of new faults, in areas that do not contain igneous bodies; and/or (2) differential dip-slip along fault strike, with displacement preferentially occurring on fault segments situated away from zones where the fault is exploited or cross-cut by an intrusion. This latter affect may result in the development of a fault-transverse fold or fault (oblique-slip). As extension continues, igneous rocks, which typically have relatively high Young' modulus values, may act to concentrate stress and therefore localise strain on intrusion-hosted fractures once failure occurs.

2. Theoretical framework

2.1. Fault nucleation and growth

Pre-existing tensional joints and cracks are pervasive throughout many rock types. When these weaknesses are oriented oblique to a horizontal σ_3 during crustal extension, perhaps due to their original orientation or post-formation rotation of the rock mass, they individually represent potential shear fractures (Gudmundsson, 2011). If the tensile stresses adjacent to these weaknesses exceed the tensile strength (T_0) of the host rock, then the cracks propagate and may link to form a large, through-going shear fracture; i.e. a fault (Gudmundsson, 2011). Other mechanical properties that influence fault nucleation and growth include: (i) the shear strength (τ_0), also referred to as cohesion (C), of a rock; (ii) the angle of internal friction (ϕ_i); (iii) toughness (i.e. both material and fracture toughness), which determines the amount of energy required to initiate a fracture; and (iv) stiffness (i.e. Young's modulus). To visualise the mechanical controls on fault formation and the stress conditions required, the first three parameters (i.e. T_0, τ_0, C) described above are commonly displayed on a Mohr diagram (e.g., Fig. 1). One disadvantage with this approach is that the Young's modulus cannot easily be incorporated. However, stiff units accommodate the majority of the tensile stress applied during loading and can consequently fracture first; this is well demonstrated for fault development within layered sequences of alternating, mechanically variable rocks (Peacock and Xing, 1994; Ferrill and Morris, 2003; Schöpfer et al., 2008; Gudmundsson, 2011).

Nucleation of and slip along faults relaxes the driving shear stress accrued during periods of fault quiescence. Faults therefore grow cyclically via discrete events during which the tip-line commonly propagates radially; i.e. the maximum displacement is located at the fault centre (e.g., Walsh and Watterson, 1988; Kim and Sanderson, 2005). However, faults are rarely exemplified by a single slip surface but rather consist of a fault core, containing the principle slip surfaces and fault rock, and a damage zone corresponding to an area of increased fracturing within the host rock. These two areas are henceforth referred to as the 'fault zone'. The mechanical properties of the fault zone will therefore differ from the host rock and so can be considered as elastic inclusions (Gudmundsson, 2011). Such fault zones are typically more compliant than the surrounding host rock and should, inherently, take up a lower amount of the applied stresses. Although this implies that intact host rock should fail prior to fault zone reactivation, the presence of pre-existing shear surfaces and elevated pore fluid pressures in fault zones means that fault growth typically supersedes fault nucleation, at least locally.

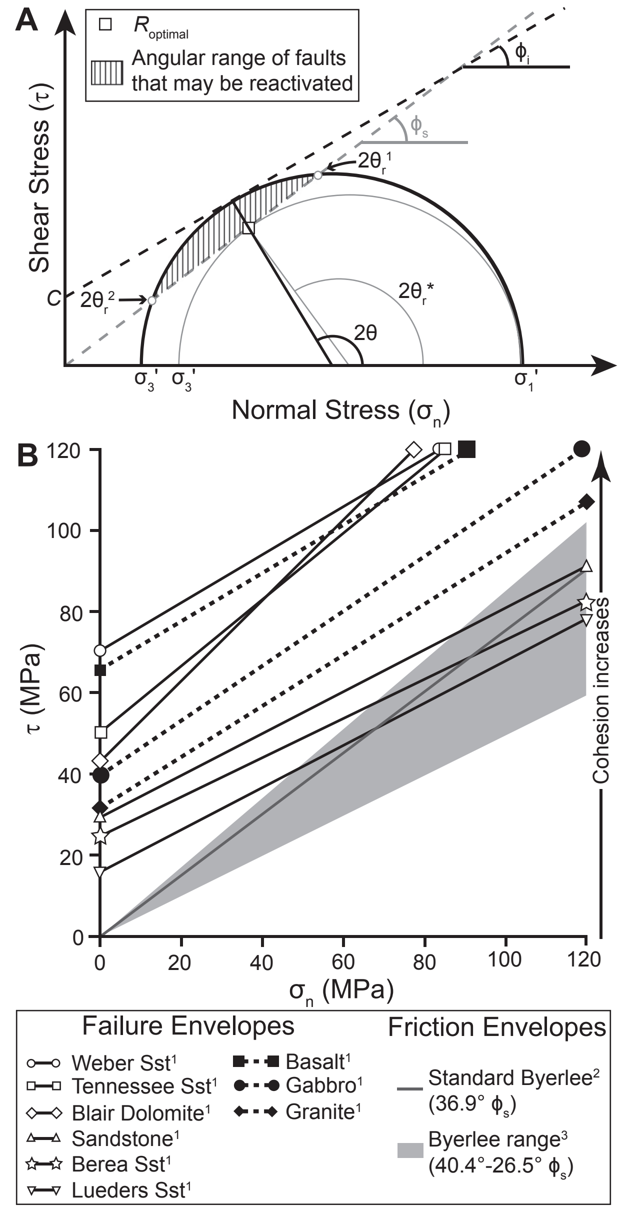

Fig. 1. (A) Mohr diagram describing the stress conditions required to initiate failure of an intact host rock (black lines) or reactivation of a pre-existing fault (grey lines). The black dashed grey line corresponds to the Mohr-Coulomb failure envelope and the grey dashed line is representative of the Byerlee friction envelope. (B) Failure envelopes for a series of intact rocks and pre-existing faults. Data collated from [1]Schellart (2000), [2]Sibson (1985) and [3]Byerlee (1978).

2.2. Fault reactivation

In their simplest form, extant faults can be considered as cohesionless planes that remain static due to frictional forces. Although they actually represent elastic inclusions within the host rock, this