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Propagation of brittle failure triggered by magma in Iceland

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Abstract

The architectures of normal faults at a divergent plate boundary in Iceland are examined by combining surface fault observations with cross-sectional studies at different structural levels to constrain a model of failure propagation. The structures of Holocene faults defining graben are analyzed to characterize the upper-most parts of ruptures. The shapes of faults resulting from growth and interaction of separate segments are used to better understand failure propagation inferred to occur in the intervening stages of displacement accumulation and lateral propagation. Pleistocene faults in volcanic sequences exhumed from 800 to 1000 m are analyzed to characterize deeper portions of failure that occurred beneath the central rift zone. Tertiary dikes exhumed from depths of 1300–1500 m are studied to infer how magma controls the failure initiation. Field studies in combination with a literature review indicate that the planar ruptures are likely to initiate at depth as magma-filled vertical fractures and lengthen upward and laterally. As failures propagate to higher crustal levels, they are likely to change into inclined normal faults. At near-surface levels, faults link with cooling joints and dilational fractures propagating downward from the surface. It is suggested that the inferred stages of fault propagation are characteristic for normal faults developed at spreading ridges.

Keywords: Normal fault; Fracture; Dike; Magma

1. Introduction

1.1. The geological problem

Analyses of the fault characteristics are critical to understanding the mechanics of fault growth, the evolution of fault populations, and the general systematics of brittle failure. Despite advances in understanding how faults evolve in space and time, many aspects of their development remain obscure, among those, their preferred direction of growth. Together with models for normal fault propagating upward from seismogenic levels (Langley and Martel, 2000; Peacock and Parfitt, 2002; Walsh et al., 2003), other models advocate that they propagate downward from the surface (Gudmundsson, 1992; Cartwright et al., 1995; Acocella et al., 2000). Understanding of the processes responsible for the propagation of fault

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planes is dependent on our knowledge of their geometry. Unfortunately the visualization of 3D fault shape and so the concept for their propagation is often hindered by limited exposure. Structural analyses of fracture patterns are commonly only possible on the surface or in a vertical cross-sections in seismic and mine data-sets, so that only small fractions of the whole failure plane geometry can be considered. This work integrates the characteristics of brittle failures seen on the surface with those that developed at different depths in the crust in the same tectonic conditions in order to reconstruct the stages of progressive fault propagation.

1.2. Previous research of failure propagation

Incremental growth of a fault can be represented as a radial propagation of its tip-line controlled by slip on the fault surface (Walsh et al., 2003). The amount of slip commonly varies along a fault trace and is often assumed to be highest at the site of the initial rupture (Gudmundsson, 1992; Childs et al., 1996). Faults grow by lateral propagation and by establishing connections with existing coplanar faults (Cowie, 1998). Fault segmentation also occurs in a vertical section so that segments have an overlap configuration parallel to the direction of slip (Childs et al., 1996).

A number of models aiming to account for how faults propagate have been suggested over recent years. Walsh and Watterson (1987) inferred that faults grow by a series of seismic slips over the semi-elliptical fault surface. The displacement on such fault accumulates from discrete slip events where fault length increases in constant increments. The model by Cowie and Scholz (1992) explains how an actively growing fault is loaded between earthquakes. In their model the stress at a fault tip depends on total displacement along the fault and the displacement profile maintains stress levels at the tip equal to the shear strength of the surrounding rock. Lin and Parmentier (1988) found that the shear stress intensity factor at the lower tip of an inclined growing fault is smaller than that at its upper tip due to the difference in lithostatic stress; this results in upward fault propagation being likely. An analogue model by Marchal et al. (2003) attributes upward fault growth to the linkage of en echelon secondary tip faults along the top tip line of the principal fault plane. Field research of structures in the Graben area of Utah Canyonlands National Park (Cartwright et al., 1995) and in the Ethiopian Rift system (Acocella et al., 2003) resulted in models of surface fault nucleation and downward propagation causing the surface tilting in the hanging wall. By contrast, studies by Peacock and Parfitt (2002) of the Koae fault system in Hawaii proposed upward fault growth accompanied by monoclinal folding.

1.3. What is known about fault propagation in Icelandic crust

1.3.1. Controls of magma

Magma intrusion at depth has been shown to be capable of initiating graben on the surface. Pollard et al. (1983) computed the elastic displacements and stresses in an isotropic, 2D half-space driven by a magma-filled blade-like dike. They showed that dike emplacement produces significant changes in the local stress over the top of the dike and predicted the height, inclination and depth of subsurface dikes from ground displacement profiles measured within central rift zone (CRZ) of N Iceland. They proposed that inclined faults in the CRZ form because of stresses induced by dike injection and fissure eruption. However, their analysis accounts for neither the presence of vertical, dip–slip faults observed throughout Iceland, nor for the effects of far-field stresses, which must also play role in inducing normal faults. One of their conclusions was that subsidence over a dike is followed by upward displacement as a fissure breaches the surface which contradicts field observations (Tryggvason, 1984; Einarsson, 1991). The dike-induced faulting model of Rubin and Pollard (1988) and Rubin (1992) accounts for the activation of normal faults dipping 45–60° at the surface, on a scale appropriate to the entire width of the CRZ. This model emphasizes, however, that without pre-existing faults, dikes alone cannot account for graben subsidence. According to the model, faults cannot be vertical at the surface but must have dips low enough so that they intersect the subsurface dike.

Geodetic leveling data in Iceland from 1966 to 1980 indicated that surface displacement related to dike intrusion may reach 1 m (Tryggvason, 1984). The surface shear strain correlates with seismic activity when inflow of magma at depth and subsidence of the plate boundary are balanced by tectonic extension