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The mechanics of intersecting echelon veins and pressure solution seams in limestone

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ABSTRACT

Many studies that describe the formation of echelon vein arrays relate the causative stresses implicitly to the deformation, reliant on simple shear kinematics, such that the vein-to-array angle and the array width are the primary physical quantities. In contrast, we identify twelve physical quantities to describe echelon veins in two dimensions, including coeval, vein-intersecting, pressure solution seams. A finite element method is used to reproduce vein shapes in linear elastic and elastic-perfectly plastic model limestone. Model vein geometries are designed using values within the range of geometries measured from echelon veins at Raplee Anticline and Comb Monocline, Utah.

Four physical quantities are significant for describing echelon vein shapes: vein spacing, vein-array angle, limestone elastic stiffness, and closing of orthogonal pressure solution seams. Pressure solution seam closing influences the mechanical interaction between adjacent veins, and for a range of conditions, causes a nearly linear vein opening distribution (triangular shapes) and encourages straight vein propagation, both of which approximate field measurements. Model results show that small spacing of veins with seams and large vein-array angles promote straight vein traces in limestone with stiffness typical of laboratory measurements, given the physical geologic conditions inferred from the burial history of the limestone strata.

1. Introduction

Arrays of echelon veins with intersecting echelon pressure solution seams are common features in deformed limestone rocks (Fig. 1). *Echelon*, commonly termed *en échelon* in structural geology literature, refers to the step-like geometry of closely spaced, similar length veins or seams. Here, the term *array* refers to the arrangement of vein and pressure solution seam midpoints along an approximately straight line over decimeter to meter distances. The systematic geometries of these vein and seam arrays has encouraged structural geologists to relate their formation to a tectonic stress state (e.g. Roering, 1968; Jackson, 1991; Wiltschko et al., 2009). Inferences about the physical processes for opening and propagation of echelon veins in conjunction with pressure solution seams are mostly made from field maps and descriptions (Roering, 1968; Beach, 1975; Jackson, 1991; Peacock and Sanderson, 1995; Willemse et al., 1997; Kelly et al., 1998; Smith, 1999; Wiltschko et al., 2009).

Motivated by geologic field measurements and interpretations of echelon veins and seams in limestone at Raplee Ridge, Utah, our hypothesis is that echelon vein shapes are the result of deformation in limestone caused by remote tectonic stress, fluid pressure on the surfaces of echelon veins, closing of pressure solution seams that intersect contemporaneously opening veins, and plastic yielding of limestone near vein tips. Mechanical models can relate these applied stresses and material behavior to the shapes of veins (displacements of the vein surfaces) explicitly through material constitutive relations. In a mechanical model, physical quantities, like vein-array angle, can be varied to record their effect on vein aperture and stresses near vein tips. The ranges of acceptable values for the physical quantities are constrained by values that result in model vein shapes closely approximating measured vein shapes, given the values are defensible with geologic reasoning.

A large number of scientific studies invoke a simple shear kinematic method to describe the formation of echelon veins (e.g. Bons et al., 2012; Lisle, 2013; Seyum, 2015; and publications cited therein), as introduced by Ramsay (1967). Models using this

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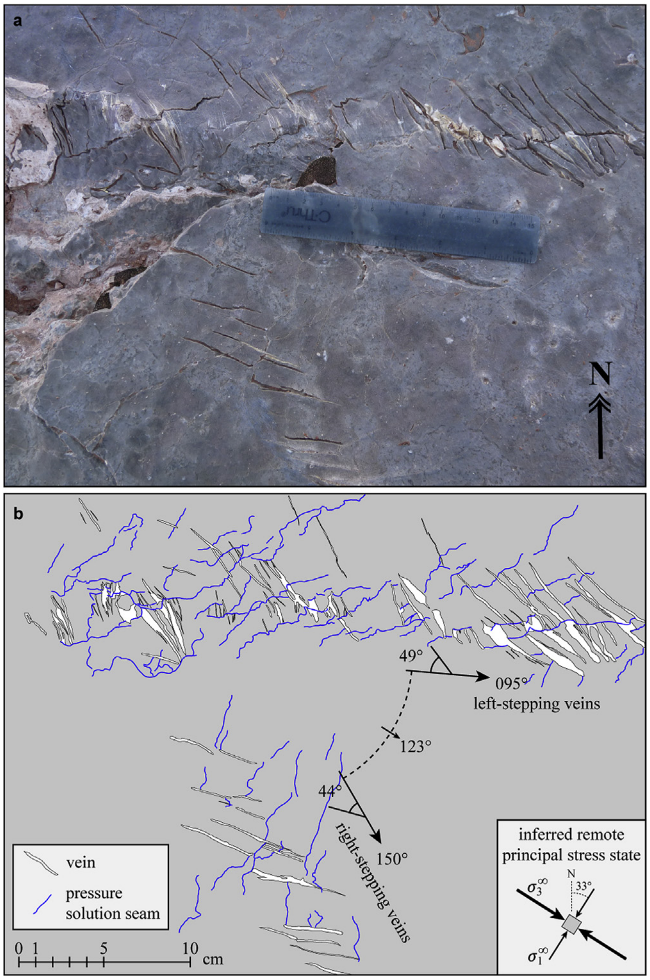

Fig. 1. a) Conjugate arrays of left-stepping and right-stepping echelon veins and pressure solution seams on the top surface of the McKim Limestone, north Raplee Anticline. UTM coordinates are 12S 606477m 4120593m, northern hemisphere. b) A map of the veins and seams that includes array trace orientations, orientation of the line that bisects the array traces, vein-array angles, and an inferred remote stress state. The remote least and greatest compressive stresses are σ_1^∞ and σ_3^∞, respectively. Compression is negative.

method treat veins as passive markers: as imaginary lines that rotate and lengthen within the shear zone (Fig. 2a, b). In a simple shear kinematic model, the angle of shear and the shear strain are estimated from the change in orientation of echelon veins, ignoring perturbations of the local strain field (Fig. 2d) (Seyum, 2015). Vein opening is inferred to be parallel to the axis of greatest extension at 45° to the shear direction within the simple shear zone (Ramsay, 1967, pp. 83–88). Subsequent shearing rotates the passive marker that is a proxy for the veins, and each additional increment of vein propagation is perpendicular to the direction of greatest extensional strain; thereby forming sigmoidal vein shapes. Echelon vein positions, modes of fracturing, the number of veins initiated, vein lengths, echelon vein spacing, and vein opening cannot be explained using a kinematic analysis (Fig. 2b) because no choice is made of the material properties that control the deformation response to the applied stresses.

A complete physical model for this geologic phenomenon includes a geologically appropriate constitutive relationship between applied stresses and the resulting strain that, with other geologic and mechanical constraints, would reproduce the observed geometries. The underlying relationships are Cauchy's laws of motion, which are based on conservation of mass and momentum (Pollard and Fletcher, 2005, pp. 269–273).

Studies of echelon fractures that use two-dimensional deformation models based on the laws of motion include Dey and Wang (1981), Pollard et al. (1982), Rogers and Bird (1987), Du and Aydin (1991), Fleck (1991), Olson and Pollard (1991), Mandal (1995), Ramsay and Lisle (2000, pp. 711, 715, 766–769, 1044–1046), and Chau and Wang (2001). Ramsay and Lisle (2000) use three distinct finite element models to: (1) show how the stress field is deflected across a narrow zone of linear elastic material that is relatively softer than the surrounding elastic material, to infer the orientation of echelon veins in a shear zone; (2) show how stress in a linear elastic material is distributed near echelon vein tips; and (3) describe sigmoidal vein shapes in a viscous material that is deformed in simple shear. Rogers and Bird (1987) illustrate the complexity of stress distributions surrounding a geometrically irregular set of echelon dikes using a boundary element model with isotropic, linear elastic material. Dey and Wang (1981) record changes in magnitude of the maximum tensile stress at the tip of a crack in an array with changes in the initial crack positions. Pollard et al. (1982) model propagation paths of echelon cracks and show that interaction between overlapping cracks causes curved propagation paths, increasing aperture near crack centers, and decreasing aperture near the crack tips. Chau and Wang (2001) describe interactions between echelon cracks and the limits on straight crack growth patterns using an analytical solution to solve for the critical ratios of crack length and crack spacing for a variety of boundary configurations. Du and Aydin (1991) use an analytical solution to show how the position of the maximum stress intensity near the tips of echelon cracks varies with distance and angle between neighboring crack tips. The results suggest that an array of echelon veins would promote the growth of new veins at the array ends with the same echelon step arrangement. Mandal (1995) uses an analytical solution for the stress field in an elastic material containing cracks to show how echelon crack spacing, or mechanical interaction of neighboring crack tips, affects the direction of crack propagation. Fleck (1991), using dislocation theory, and Olson and Pollard (1991), using a boundary element model, show that the crack surface displacements can be calculated given the stiffness of the material, and similar to Pollard et al. (1982), Chau and Wang (2001), and Mandal (1995), show that crack propagation is a function of the near-tip stress field and the near-tip stress field is perturbed by neighboring cracks.

We build on these published numerical methods and results for model echelon vein formation by introducing closing of orthogonal, intersecting pressure solution seams, assigning an elastic-plastic material constitutive relationship to the limestone host rock, and comparing model results to vein and pressure solution seam array structures measured at Raplee Ridge, Utah.

In the remaining text, *fracture* is used as a generic term without any specification of relative motion of those surfaces. The term *joint* refers to dominantly opening mode fractures identified in the field. *Vein* is a term used for a fracture that has been filled with mineral precipitates. The term *crack* is used when referring to a displacement discontinuity in mechanical models and consists of two surfaces. Model cracks are compared to veins observed in the field. *Pressure solution seam* refers to the field identification of a two-dimensional trace in limestone along which we infer soluble grains within the rock were dissolved and transported in solution, and insoluble grains remain. A *model seam* refers to the mechanical model representation of a pressure solution seam.

In this paper, we introduce a mechanical description for the formation of echelon veins and orthogonal pressure solution seams. The numerical model input values are derived from field-measured geometries of veins and seams, published values for