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Predicting the width and average fracture frequency of damage zones using a partial least squares statistical analysis: Implications for fault zone development

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A B S T R A C T

We introduce the partial least squares (PLS) statistical analysis that quantifies and predicts the observed relationships among normal fault slip, fracturing associated with the fault, and lithology. We describe the systematic process for constructing a multivariate PLS model that predicts the average fracture frequency and the width of fracture-dominated fault damage zones from fault, lithologic and fracture data. Conversely, the model can also predict normal fault net slip for a defined lithology given the average fracture frequency and width of a fracture-dominated fault damage zone, hereafter defined as a fracture intensification domain (FID). Fracture, fault and lithologic data were collected in the Mohawk Valley of New York State from outcrops in the Upper Ordovician Utica Group and Lorraine Group. Data collection was focused on faults with observable slip, associated FIDs, and no observable lateral restriction. Our statistical analysis used three variables to describe the geometry of the FID: FID width (FID_W), average fracture frequency within the FID (FID_f), and the power law regression exponent (FID_R) of the least squares trend line. We incorporated additional data from literature and tested multiple PLS models in order to refine the analysis using quality indicators provided by the PLS summary statistics output. Variables included in the final predictive model included FID_w, FID_f, fault slip, grain size and clay percent. Fault slip and grain size were found to have a positive covariance with FID_W while clay percent had a negative covariance. Fault slip, grain size and clay percent all showed a negative covariance with FID_f. Results from this research indicate that increasing fault slip leads to wider FIDs and lower average fracture frequency within the FID. The lower average fracture frequency in wider FIDs is primarily attributed to an increase in the length of the low-frequency FID tail away from the associated fault. A possible secondary influence reducing fracture frequency is due to the progressive development of a fault core at the expense of the adjacent damage zone and the consumption of the highest-frequency fractures adjacent to the fault surface.

1. Introduction

Fracture system variations arise from diverse driving mechanisms including lithology (e.g., Childs et al., 2007; Lézin et al., 2009), pore fluid pressure (e.g., Lash and Engelder, 2009), tectonic history (e.g., Engelder and Geiser, 1980; Geiser and Engelder, 1983; Zhao and Jacobi, 1997; Whitaker and Engelder, 2005), and local stress field deviations (e.g., Dyer, 1988; Rawnsley et al., 1992; Jacobi and Xu, 1998; Sagy et al., 2001; Jacobi, 2002; Jacobi and Fountain, 1996, 2002; Lin et al., 2010). Fracture systems that develop in the perturbed stress fields around faults can display elevated frequency and increased complexity compared to regions outside the anomalous stress field. This anomalous fracturing, regarded as part of a fault damage zone (e.g., Savage and Brodsky, 2011; Johri et al., 2014), has additional factors that affect their development such as fault type and net slip (e.g., Cowie and Scholz, 1992; Kim et al., 2004; Faulkner et al., 2010). Choi et al. (2016) advocated limiting

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qualitative descriptions of damage zones by integrating descriptive terminology, including fault core, and inner/outer damage zone (e.g., Kim et al., 2004), with quantitative analyses that would improve comparisons among damage zone datasets. Choi et al. (2016) proposed defined the width of a damage zone by analyzing changes in slope of cumulative fracture frequency data. The present paper adds to the developing quantitative methodologies for damage zone analysis through the use of partial least squares (PLS) predictive modeling.

The PLS method was chosen due to its ability to quantify the influence of individual predictor variables which may be correlated with one another, as has been established in several fields such as chemometrics (Kramer, 1998). In our case, testing multiple combinations of predictor and response variables provides a means of quantifying the influence of structural and lithologic variations on the width and average fracture frequency of fracture dominated fault damage zones, (hereafter defined as fracture intensification domains, Jacobi and Xu, 1998; Jacobi, 2002; Jacobi and Fountain, 1996, 2002).

Fracture intensification domains (FIDs) are fault-parallel zones defined by fracture set(s) with elevated fracture frequency compared to the fracture frequency in regions outside the FID (e.g., Jacobi and Xu, 1998; Jacobi and Fountain, 1996, 2002; Jacobi, 2002). Since faults are commonly located within, or adjacent to, the area of elevated fracturing, FIDs could be considered the fracture subset of fault damage zones (e.g., Choi et al., 2016). In the northern Appalachian Basin of New York State, the FID-defining fracture set is commonly the master set, i.e., this set is the oldest set based on fracture abutting relationships and/or the cross-cutting sequence of veins (e.g., Hancock, 1985), although some FIDs display fracture sets older than the defining high frequency fracture set. The fracture set defining the FID is parallel to the FID trend in most of the FIDs in the Devonian section of central and western New York State (e.g., Jacobi, 2007), whereas the defining fracture set of some FIDs is highly oblique to the FID trends in the Ordovician black shales in the Mohawk Valley region of New York State (e.g., Jacobi, 2011). In this research, we only consider FIDs that are defined by fault-parallel fractures.

Results of our analysis can be applied to modeling fluid flow in aquifers and in oil and gas reservoirs. Modeling fluid flow in fractured rock associated with faults can prove difficult if the fracture characteristics of fault-associated fractures are poorly known due to covered intervals or if the fault is only observed remotely, such as in a seismic reflection profile (e.g., Kearl et al., 1998; Abdelaziz and Merkel, 2012; Kumar, 2012). The multivariate nature of fluid dynamics in fractured bedrock creates the need to quantify characteristics such as the width of fault damage zones and fracture frequency associated with the fault in order to produce more accurate models of the hydraulic system. The PLS model that we present can accurately predict the width of an FID and average fracture frequency for an area of interest if the fault throw, grain size, and clay content are known. Conversely, given the width of an observed fracture zone associated with a hidden fault and the average fracture frequency within the zone, the PLS analysis presented here can predict the net slip on the concealed fault. With the ability to calculate the width of intensely fracture bedrock associated with faults, improvements can be made to monitoring and remediation techniques for environmental scientists and modeling of hydraulic fracturing.

2. Geological setting

Fracture, fault, and lithologic data were collected in the Mohawk Valley, a region located generally south of the Precambrian crystalline rocks of the Adirondack Mountains and north of the Silurian/Devonian sedimentary rocks of the Catskill Mountains in New York State (Fig. 1). In the Mohawk Valley field area, Ordovician black shale and overlying siliciclastic sediments were deposited over a Cambrian-Ordovician carbonate bank along the Laurentian passive continental margin (e.g., Landing, 2012). The Mohawk Valley has traditionally been viewed as Taconic-aged (Ordovician) collisional foredeep, dominated by normal faults (e.g., Bradley and Kidd, 1991; see review in Jacobi and Mitchell, 2002); although recent work suggests strike-slip and thrust movements have also occurred along the faults (e.g., Jacobi et al., 2015).

Events of the Ordovician Taconic orogeny reflect the initiation of a series of microcontinent/microcontinental-floored arc collisions with the eastern (present coordinates) margin of Laurentia, culminating in the collision of Laurentia and Gondwana during the Carboniferous/Permian Alleghanian orogeny (see review in van Staal et al., 1998; Hatcher, 2010). In New England, the Taconic continent-magmatic arc collision initiated about 520-505 Ma when the Iapetus Ocean began eastward subduction (Kim and Jacobi, 2002). The resulting Shelburne Falls arc (Karabinos et al., 1998; Kim and Jacobi, 2002; Macdonald et al., 2014) underwent peak igneous activity approximately at 480-470 Ma (Macdonald et al., 2014). Prior to the recognition of the Shelburne falls arc, the older eastward subduction models involved only one long-lived arc, the Bronson Hill arc, which lies east of the Shelburne Falls arc (e.g., Jacobi, 1981; Stanley and Ratcliffe, 1985; Bradley and Kidd, 1991). The more recent models suggest that the Bronson Hill arc is younger than the Shelburne Falls arc (e.g., Karabinos et al., 1998; Kim and Jacobi, 2002; Macdonald et al., 2014), and was generated from about 460 to 445 Ma by westward subduction. Based on the earlier Taconic eastward (present coordinates) subduction tectonic models with a single Taconic arc, faulting in the Mohawk Valley region occurred when the Laurentian continental margin passed over a peripheral bulge and into the trench at 460-445 Ma (e.g., Jacobi, 1981; Stanley and Ratcliffe, 1985; Bradley and Kidd, 1991). In the more recent Taconic models with two arcs and westward subduction, the relatively late timing of the Mohawk Valley faults suggests they developed primarily during subsidence of a retroarc foreland coeval with late (460-445 Ma) Taconic westward subduction (Macdonald et al., 2014). This subsidence resulted from retroarc thrust loading (Macdonald et al., 2014), perhaps associated with flat slab subduction (Jacobi and Mitchell, 2016).

3. Data collection

3.1. Outcrop analysis

Field work for the present research focused on locating outcrops proximal to the major fault trends (Fig. 1) in order to identify minor faults with observable displacements and zones of locally intense fracturing. Although data are biased toward minor faults, results of this analysis should apply to fault systems with larger magnitudes of slip due to the fractal scaling of faults and fractures for both general structural geology (Mitchell and Faulkner, 2009; Schueller et al., 2013) and specific fracture studies completed in New York State (e.g., Zhao and Jacobi, 1993; Xu et al., 1999; Jacobi and Baudo, 2000).

Data were collected from outcrops presented in Fig. 1 (white circles) with lithologies ranging from black shales in the Flat Creek and Indian Castle formations of the Utica Group to interbedded shales and greywackes in the overlying Frankfort and Schenectady formations of the Loraine Group (e.g., Mitchell et al., 1994; Baird and Brett, 2002). The outcrops used for this study are sufficiently separated (on the order of km) and the fault throws sufficiently small (on the order of a meter) that interference among fault stress fields is not an issue.