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Thrust fault nucleation due to heterogeneous bedding plane slip: Evidence from an Ohio coal mine

Ciel Elizalde [a,*], W. Ashley Griffith [a], Tim Miller [b]

[a] Department of Earth and Environmental Sciences, University of Texas at Arlington, P.O. Box 19049, Arlington, TX 76019, USA
[b] East Fairfield Coal Company, P.O. Box 217, North Lima, OH 44452, USA

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ABSTRACT

Shales often form the roof and floor rocks of coal mines in the Appalachian Basin. From a geologic perspective, these mines offer outstanding 3D exposures of fresh rocks, otherwise only accessible via boreholes or heavily weathered surface outcrops, and present an excellent opportunity to directly observe pristine in situ natural fractures in shale. In Carroll County, Ohio, small thrust faults that predate mining operations are well exposed within the roof rocks and develop near areas where gradients of coal–shale contacts are steepest, causing ground instability. We hypothesize that bedding contact surfaces served as natural displacement discontinuities that perturbed the local stress state, resulting in localized thrust fault development. Using borehole and in-mine survey data, we digitally constrain bedding contact geometry to model slip along this interface and resolve related stress perturbations. Our modeling results suggest that inherited non-planarity of contact surfaces influenced the nucleation of secondary faults. Simulation results as constrained by the integrated field and modeling approach taken in this study help us to better understand the relationship between subsurface stress perturbations and the formation of secondary fractures. For mining purposes, recognizing subsurface stress heterogeneities due to variable bedding geometry within a regional stress field can improve our predictive capabilities of underground structural hazards.

1. Introduction

In the Appalachian Basin, an Andersonian thrust-faulting regime has influenced the structural deformation of sedimentary cover leading to intense faulting and folding (Engelder et al., 2009) and this deformation is the source of ground instabilities in coal mines throughout the region (Phillipson, 2003, 2005). East of the Alleghany Front (Fig. 1), prominent lineaments in the Appalachian Valley and Ridge Province are often the surficial manifestations of subsurface structures caused by intense rock deformation attributed to the Alleghanian Orogeny (Gwinn, 1964; Jacobi, 2002; Plankell, 2000). Farther west into the Appalachian Plateau (Fig. 1), a transitional region between the intensely deformed Valley and Ridge Province to the east and the far less deformed inner craton to the west, this surface expression becomes far less pronounced as broad folds and blind thrust faults are the predominant structural features (Phillipson, 2005). The lack of surface expression in some locations often makes it difficult to identify subseismic faults at depth and this can lead to unpredictable underground structural hazards.

Several authors have identified common decollement structures within the roof rocks of underground coal mines and these often include bedding-parallel faulting with locally developed thrusts (Milici et al., 1982; Molinda, 2003; Molinda and Mark, 2010; Phillipson, 2003, 2005). The bedding-parallel faults have been interpreted to initiate at bedding contact surfaces that undergo slip and eventually ramp upward into the roof rocks as small thrust faults. The implementation of geologic mapping during mining has been advocated to predict areas of unstable ground conditions due to such faults (Phillipson, 2003, 2005). In the present study, we examine the hypothesis that slip on bedding discontinuities controls the spatial distribution of thrust faults in the overlying strata. In doing so, we show that the utilization of simple elastic discontinuity models to predict stress perturbation due to bedding plane slip proves a further useful step.

In eastern Ohio, the roof rocks of the Carroll Hollow underground coal mine show a similar decollement scenario to those described by Phillipson (2003, 2005). Slip is indicated by slickensides on bedding contact surfaces of the roof rocks, and thrust faults appear to nucleate as a result of slip along those bedding discontinuities and subsequently ramp upward into the overlying strata (Fig. 2). In some areas of the mine, these secondary faults can be as small as 2 m with only 10s of centimeters of offset; however, some fault traces have been projected to span for 100s of meters with less than a meter offset. Qualitative in-mine observations led to the preliminary conclusion that thrust faults were located where several of the most steeply dipping contact surfaces occur, suggesting a possible spatial relationship between the bedding

* Corresponding author.
E-mail addresses: cielelizalde@gmail.com (C. Elizalde), wagriff@uta.edu (W.A. Griffith), efairfield@cboss.com (T. Miller).

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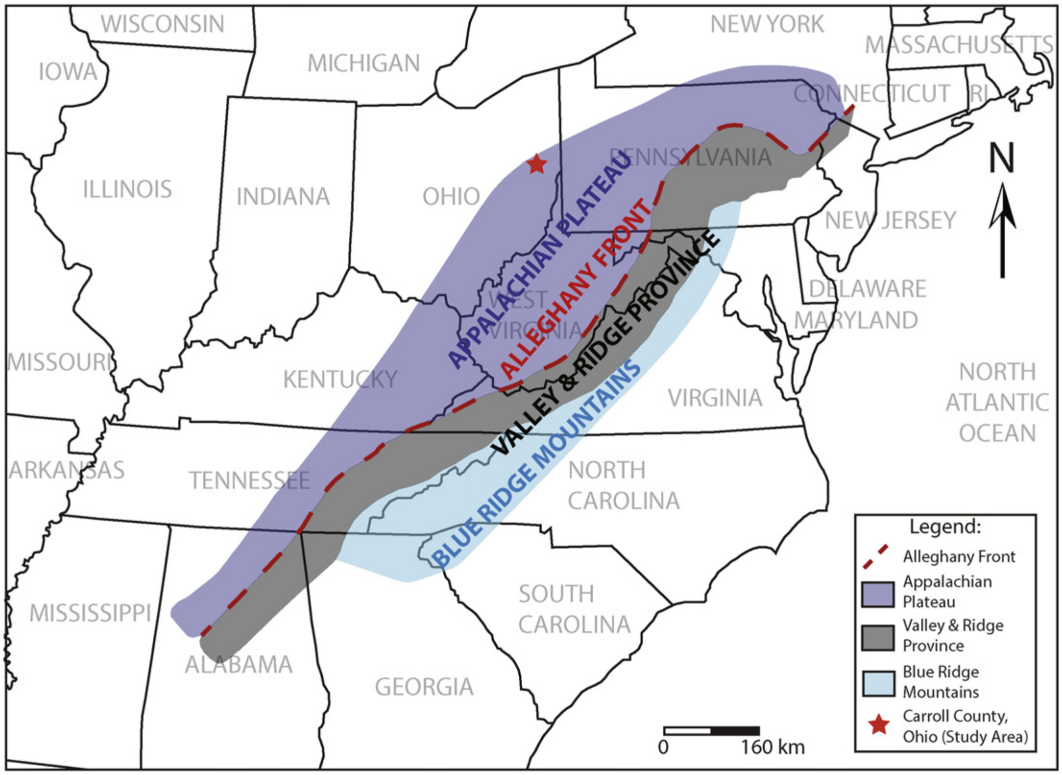

Fig. 1. Location of relevant Appalachian provinces in the eastern United States (modified from a base map courtesy of the United States Geological Survey). The image shows the Valley and Ridge Province (dark gray) as well as the Blue Ridge Mountains (light gray) located to the east of the Alleghany Front (dashed line), and the Appalachian Plateau (medium gray) to the west. Note that the study area (star) is located in eastern Ohio; on the western Appalachian Plateau.

geometry and thrust fault development. The contact surfaces associated with observed bedding-parallel slip are present between the lower Middle Kittaning (No. 6) coal seam (MKCS) and the overlying Washingtonville shale. The MKCS is immediately overlain by a thin shale layer (~40 cm thick), which is a lower member of the Washingtonville shale, and forms the immediate roof rocks. The upper contact of this lower shale member is formed by thin clay and siderite layers (~1 cm thick). These thin layers serve as natural structural discontinuities with overlying shale layers (Griffith et al., 2014) and are often the source of detachments that lead to roof falls.

Slip on natural discontinuities can significantly perturb the local stress state in Earth's subsurface (Barton and Zoback, 1994; Hafner, 1951; Maerten et al., 1999; Newman and Griffith, 2014; Pollard and Segall, 1987; Segall and Pollard, 1980). Numerous studies show that mechanical interaction between faults can influence the local stress state within the surrounding rocks, and that this can lead to the development of secondary faults and linkage of adjacent fault segments (Aydin and Schultz, 1990; Crider and Pollard, 1998; King and Nabelek, 1985; Maerten et al., 2000; Willemse, 1997). These stress perturbations can be extremely heterogeneous when sliding takes place on non-planar discontinuities (Griffith et al., 2010). The static stress perturbation due to fault slip, commonly expressed as the Coulomb stress change, can be used to identify areas of increased propensity for secondary brittle failure in surrounding rocks, as well as identifying possible locations of aftershocks and triggered earthquakes, hydrothermal mineral deposits, and hard-linkage between adjacent or overlapping faults (Harris, 1998; Li et al., 1987; King and Nabelek, 1985; King et al., 1994; Micklethwaite and Cox, 2004; Stein and Lisowski, 1983; Stein et al., 1992). This approach has also been used to study the spatial development of smaller secondary faults and joints at the subsurface (Bellahsen et al., 2006; Kattenhorn et al., 2000; Maerten et al., 2002).

This study has two objectives: 1) to determine the spatial relationship (if any) between bedding contact geometry and the occurrence of thrust faults, and 2) to determine whether or not such a relationship is causative. The coal-shale contact surfaces are idealized as a single, large displacement discontinuity and the thrust faults as smaller incipient secondary faults that presumably formed due to slip on one of the natural discontinuities above the coal seam. We then build three-dimensional models using the Boundary Element Method (BEM) to simulate slip and calculate static stress changes on the rocks above the relevant contact surfaces. We investigate the propensity for brittle failure by calculating change in strain energy density (SED) and Coulomb stress (S_C); both commonly used failure indicators in rock mechanics (Cooke and Kameda, 2002; Crider and Pollard, 1998; Du and Aydin, 1996; Griffith and Cooke, 2004; Jaeger et al., 2007; King et al., 1994; Micklethwaite and Cox, 2004). The results show that areas with increases in SED and S_C are spatially consistent with mapped thrust fault locations, suggesting a mechanical relationship between slip on non-planar bedding surfaces and secondary fault development. The modeling approach used in this study could help improve underground mining conditions and also sheds light on the nucleation of thrust faults at the subsurface.

2. Background

2.1. Previous work

Numerous geologic factors influence ground control problems in underground coal mines (Ellenberger, 1979; Hill, 1986; Milici et al., 1982; Moebs and Ellenberger, 1982; Moebs and Stateham, 1984; Molinda and Ingram, 1990; Molinda, 2003; Molinda and Mark, 2010; Nelson and Bauer, 1987; Phillipson, 2010). Such geologic factors often include rock heterogeneities (comprising stratigraphic layers or "stackrock", paleochannels, and clay veins), intense rock deformation, and faults and joints. Phillipson (2003) has described the effects of intense rock deformation related to regional tectonic stresses and the instability that it presents to underground coal mining. In particular, he points out that the presence of slickensided surfaces in Appalachian Basin