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Geometrical analysis of deformation band lozenges and their scaling relationships to fault lenses

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ABSTRACT

Deformation bands can influence fluid flow in sandstone hydrocarbon reservoirs and therefore, understanding the geometrical attributes of individual bands and their patterns is a critical step in quantifying their connectivity. We present a geometrical study of deformation band lozenges, which are rock volumes contained between deformation bands, and fault lenses, which are rock volumes bounded by slip surfaces in fault cores. We investigate the statistical trends among data sets for deformation band lozenges and fault lenses in sandstones from the Moray Firth (Scotland) and southeastern Utah (USA), and explore their potential correlation to other attributes of the fracture pattern and petrophysical properties. The aspect ratio of lozenges, that represents the ratio of length or height to the maximum thickness of a lozenge, displays an oblate-shaped geometry in relation to fault-zone orientation. The length–thickness scaling relationships of lozenges are statistically similar to lenses. The scaling relationships show a slope break between lozenges bounded by deformation bands and lenses bounded by slip surfaces in the fault core. This break is inferred to mark the boundary between the lozenge domain and lens domain, and is likely due to a deformation transition from distributed strain for deformation bands to localised strain for slip surfaces. Furthermore, the integration of geometrical analysis with an understanding of scaling properties can help to make better predictions of fractures and fault properties in subsurface reservoirs.

1. Introduction

Deformation bands are planar structures that record strain localization due to faulting in porous rocks such as sandstones (e.g. Aydin, 1978; Antonellini et al., 1994; Fossen and Hesthammer, 1997; Fossen et al., 2007). Numerous studies have focused on the geometry of deformation bands in sandstones (e.g. Antonellini and Aydin, 1995; Fossen and Hesthammer, 1997; Schultz and Fossen, 2002; Schultz and Balasko, 2003; Shipton et al., 2005; Okubo and Schultz, 2006; Eichhubl et al., 2010) and carbonates (Tondi et al., 2012). In most studies, the geometrical analyses were confined to 2D rock exposures, and a robust 3D geometrical model of deformation bands has therefore not yet been presented. However, a recent study by Brandes and Tanner (2012) investigated the three-dimensional geometry of deformation bands and showed that the true shapes of the bands may be concavely arcuate in horizontal trace, but linear in dip section.

The term lozenge has been used to refer to the shape of various geological features for over 200 years. In structural geology, the term lozenge refers to an elongate block of rock bounded by shear zones or fractures (Graham, 1980; Simpson, 1983; Woodcock and Fischer, 1986; McClay and Bonora, 2001; Weinberg et al., 2004; Carreras et al., 2005; Fusseis et al., 2006; Baldwin et al., 2007; Kuiper et al., 2011; Ponce et al., 2013). Most existing works use the term lozenge for 2D features, with only a few studies having considered the 3D shapes of lozenges (e.g. Bell, 1981; Choukroune and Gapais, 1983). A tectonic lozenge is scale-independent over a certain range of sizes, and describes a 3D elongate body of rock surrounded by relatively more deformed rocks (Ponce et al., 2013). Here, we use the term lozenge to refer to the volume of less deformed sandstone situated between two strands of a composite deformation band, while lenses are rhomboidal-shaped rock bodies bounded by slip surfaces and breccias (Candela and Renard, 2012). These lozenge and lens fault-zone structures are common, but their origins have not been widely addressed in the literature. The geometries of lozenges and lenses provide important constraints for understanding fault-zone development. Lenses can consist of undeformed host rock, intensely fractured host rock or only fault rocks (Gabrielsen and Clausen, 2001; Berg and Skar, 2005). Lenses are characterized by a high density of deformation bands and ladder fractures in the host rock. Previous work has suggested that the

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development of lenses is controlled by a number of factors such as the orientation of the fault plane, magnitude of the fault displacement and host rock lithology (Lindanger et al., 2007; Bastesen et al., 2009).

Deformation band lozenge and fault lens datasets were collected from outcrops that provided sub-horizontal and sub-vertical rock faces (Fig. 1). Cataclastic deformation bands were mapped and quantified in outcrops of aeolian sandstones of the Entrada Formation near Bartlett Wash and Goblin Valley in southeastern Utah (USA) and the Hopeman Formation in Moray (Scotland). The first locality is in Bartlett Wash Canyon at the footwall of the Bartlett Fault which towards east interacts with the

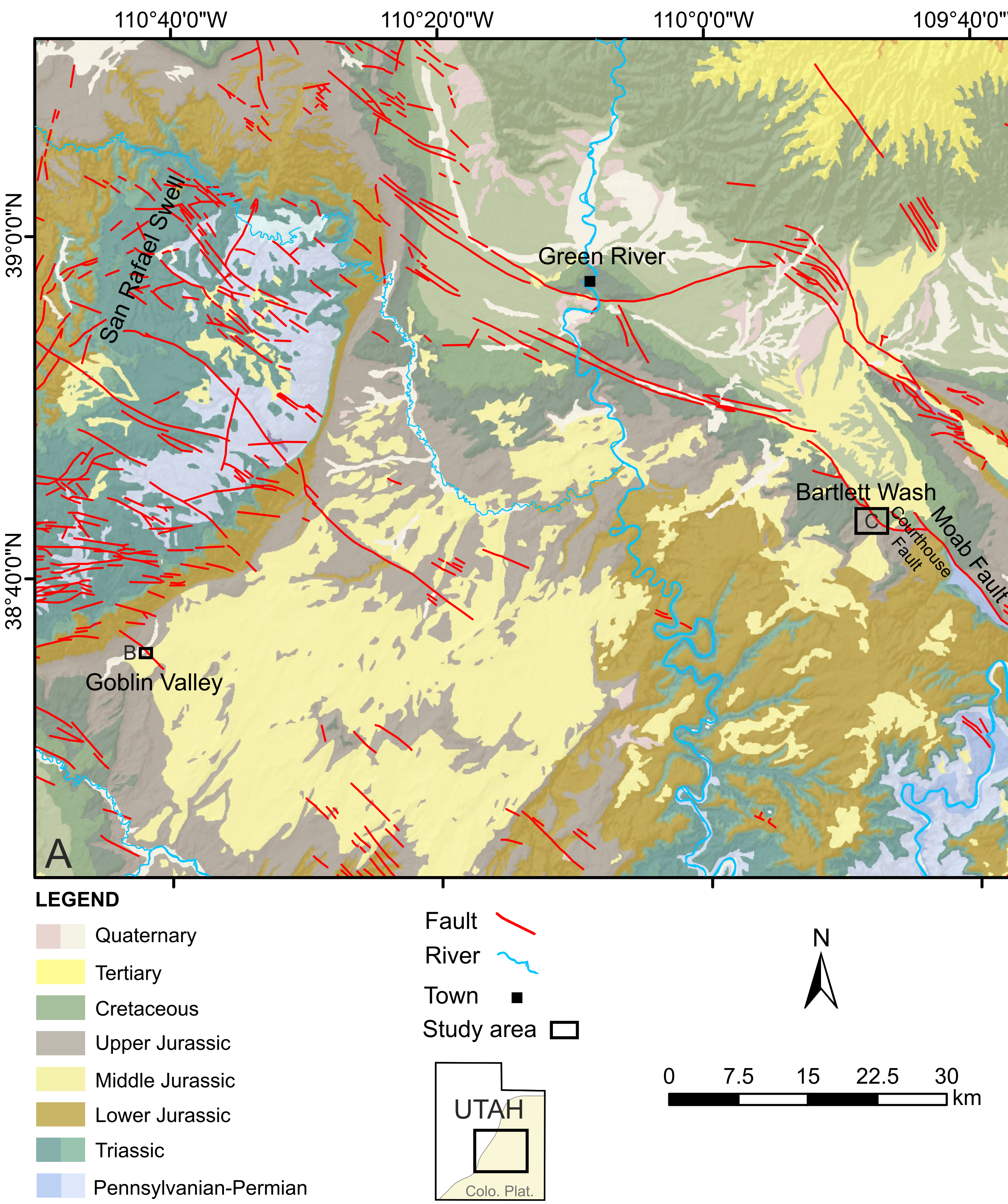

Fig. 1. (a) Geologic map of the study areas in Utah (USA) showing the Moab Fault, Courthouse Fault and San Rafael Swell (after Hintze et al., 2000). The study areas are indicated by black boxes. (b) Aerial photograph showing Bartlett Wash Canyon and the exposed Slick Rock Member (Entrada Formation) at the footwall of Bartlett Fault, SE Utah (USA); (c) aerial photograph showing Entrada sandstone exposures near Goblin Valley, Utah (USA); and (d) aerial photograph of Hopeman sandstone in the Moray Firth (Scotland).