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Progressive evolution of deformation band populations during Laramide fault-propagation folding: Navajo Sandstone, San Rafael monocline, Utah, U.S.A.

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ABSTRACT

Monoclinal fault propagation folds are a common type of structure in orogenic foreland settings, particularly on the Colorado Plateau. We have studied a portion of the San Rafael monocline, Utah, assumed to have formed through pure thrust- or reverse-slip (blind) fault movement, and mapped a particular sequence of subseismic cataclastic deformation structures (deformation bands) that can be related in terms of geometry, density and orientation to the dip of the forelimb or fold interlimb angle. In simple terms, deformation bands parallel to bedding are the first structures to form, increasing exponentially in number as the forelimb gets steeper. At about 30° rotation of the forelimb, bands forming ladder structures start to cross-cut bedding, consolidating themselves into a well-defined and regularly spaced network of deformation band zones that rotate with the layering during further deformation. In summary, we demonstrate a close relationship between limb dip and deformation band density that can be used to predict the distribution and orientation of such subseismic structures in subsurface reservoirs of similar type. Furthermore, given the fact that these cataclastic deformation bands compartmentalize fluid flow, this relationship can be used to predict or model fluid flow across and along comparable fault-propagation folds.

1. Introduction

Porous sandstones tend to develop strain localization features called deformation bands at relatively low strains (Aydin, 1978; Antonellini et al., 1994; Aydin et al., 2006; Fossen et al., 2007). These tabular strain localization structures form by rotation, sliding and crushing of grains, featuring individual thicknesses of less than 1–2 mm, which coalesce into thicker clusters. Individual deformation bands accommodate millimeter-scale offsets that can reach decimeter-scale cumulative offsets in clustered systems. Due to the high porosity required for deformation bands to form (≥15%), they are often associated with (but not restricted to) continental sandstones and burial depths of less than 4 km (Cashman and Cashman, 2000; Shipton et al., 2002; Aydin and Ahmadov, 2009; Brandenburg et al., 2009; Soliva et al., 2013). Deformation bands are interesting for a number of reasons: soon after formation, they "lock-up" and multiply due to strain hardening, recording successive stages of deformation (Davis, 1999b). The strain is usually variably distributed within a deformed volume of porous sandstone (Jamison, 1989) and as they tend to be porosity- and permeability-reducing structures in high quality reservoirs (at micro and meso-scale), they have the potential to either baffle or redirect fluid flow (Antonellini and Aydin, 1994; Fossen and Bale, 2007), creating permeability openings/pathways (Tindall and Davis, 2003; Rotevatn et al., 2009). Deformation band characteristics are thus important for the prediction and assessment of sandstone reservoirs in groundwater/hydrocarbon production, as well as CO_2/water injection (e.g., Sternlof et al., 2006; Rotevatn et al., 2013).

Deformation bands have primarily been described from the extensional regime, where they tend to localize around larger normal faults or form clusters that are interpreted as fault precursors (Aydin, 1977; Aydin and Johnson, 1977, 1978; Antonellini et al., 1994; Hesthammer et al., 2000; Ahlgren, 2001; Shipton and

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Cowie, 2001; Torabi and Fossen, 2009; Tueckmantel et al., 2010; Schueller et al., 2013). In contrast, studies of deformation bands formed in the contractional regime are less commonly reported in the literature (cf. Davis, 1999b; Cashman and Cashman, 2000; Wibberley et al., 2008). Solum et al. (2010) and Brandenburg et al. (2012), based on observations from the East Kaibab monocline on the Colorado Plateau, suggested that contraction-induced deformation bands may be more broadly distributed away from faults, while the ones formed during extension are more localized (i.e. narrower damage and process zones of main faults), hence affecting fluid flow in a different way. Other studies (Ballas et al., 2012a; Soliva et al., 2013) analyzed deformation bands formed during contraction and extension phases in the South-East Basin in southern France, suggesting that whereas contraction-induced deformation bands are more widely distributed, extension-related deformation bands affected paleofluids to a greater extent. On the contrary, Saillet and Wibberley (2013) found no noticeable relationship between tectonic regime and band permeability for the same region.

These contrasting results indicate that tectonic regime is only one of several factors influencing the role of deformation bands in reservoirs (e.g., Fossen and Rotevatn, 2012); wider spatial distribution of deformation bands throughout contractional structures seems to be a common observation, but more information is needed to explore more closely the role of deformation bands during shortening of porous sandstones, and to characterize and evaluate their effects on fluid flow.

In this study we focus on a particularly well-exposed example of folded porous Navajo Sandstone on the Colorado Plateau, the Laramide San Rafael monocline in southeastern Utah, which is particularly well suited for studies of deformation band formation in a contractional setting. Structural mapping along several parallel canyons that transect the structure allows us to compare differently dipping forelimb sections, and compare the distribution and characteristics of deformation bands with respect to dip or fold tightness. Because deformation band development depends on strain (Bésuelle, 2001), the relationship between strain and deformation band type, organization and distribution can be assessed in this field example. Our observations allow us to propose a sequence of deformation band development through time. The main aim of this study is thus to elucidate how strain, in the form of potentially flow-altering deformation bands, is distributed in contractional folds. This is achieved through the following set of objectives, which are i) to describe and characterize deformation bands formed during contractional folding in terms of geometry, distribution and petrophysical properties, ii) to propose a model for the formation and evolution of deformation bands during such folding, and iii) to establish a relationship between forelimb dip (interlimb angle) and deformation band density, ultimately allowing us to iv) discuss applications with respect to analog reservoir settings.

2. Geologic setting

The study area lies in the Colorado Plateau of the southwestern U.S.A.; a region characterized by relative crustal stability and thick-skinned tectonics, mainly in the form of basement uplifts (Davis, 1999b). The focus of this study, the San Rafael monocline (SRM) is located 25 km west of Green River in Utah, forming the eastern flank and the most steeply dipping layers of the doubly-plunging asymmetric San Rafael Swell (SRS), ~120 km long and 60 km wide (Fig. 1). The SRM exhibits maximum inclinations of ~65°, flattening laterally both to the north and south, where it evolves into gentle homoclines, strikes approximately N20°E in its northern part, and N50°E in its southern part. The structure is interpreted to have formed during the well-documented Late Campanian-Eocene Laramide contractional deformation event, the youngest reverse reactivation of high-angle normal faults in the Precambrian basement (Rigby, 1987; Neuhauser, 1988; Johnson and Johnson, 2000; Bump and Davis, 2003; Fischer and Christensen, 2004; Cross, 2009). The SRM has been interpreted as a forced fold (Stearns

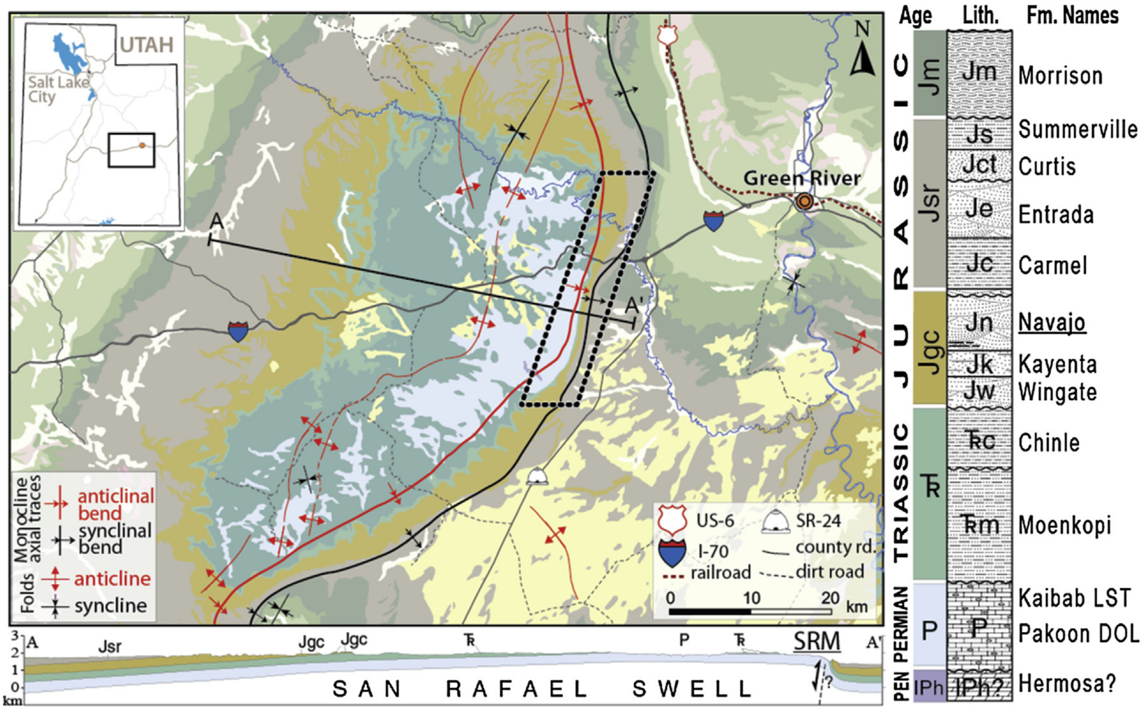

Fig. 1. Stratigraphic column, geologic map and cross section of the San Rafael Swell and San Rafael monocline (SRM). Units as old as Permian outcrop in the fold core (light blue). Sub-region with contraction-deformation band populations is delimited by the dashed polygon along the steepest segment of the monocline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)