Journal of Structural Geology 79 (2015) 42–56

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

The unusual 3D interplay of basement fault reactivation and fault-propagation-fold development: A case study of the Laramide-age Stillwell anticline, west Texas (USA)

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A R T I C L E   I N F O

Article history:
Received 30 March 2015
Received in revised form
30 June 2015
Accepted 3 July 2015
Available online 7 July 2015

Keywords:
Stillwell anticline
Fault reactivation
Fault-propagation fold
En echelon
Kinematic modeling

A B S T R A C T

Subsurface fault geometries have a systematic influence on folds formed above those faults. We use the extraordinarily well-exposed fold geometries of the Laramide-age Stillwell anticline in west Texas (USA) to develop a strain-predictive model of fault-propagation fold formation. The anticline is a 10-km long, NW-trending, NE-vergent, asymmetric fold system with an axis that displays a map-view left-stepping, en echelon pattern. We integrated field observations, geologic and structural data, cross-sections, and 2D kinematic modeling to establish an unusual 3D two-stage model of contractional fold formation, including: 1) reverse reactivation of a pre-existing, NW-striking, SW-dipping, left-stepping, en echelon normal fault system in Paleozoic basement rocks to generate monoclinal flexures in overlying layered Cretaceous carbonate rocks; and 2) the formation of a subsequent flat-ramp fault system that propagated horizontally along a mechanically-weak, clay-rich Cretaceous unit before ramping up at the hinge of the pre-existing monocline system. Strain is focused within the forelimb of the system, in front of the propagating fault tip, and is accommodated by a combination of interlayer slip, flat-ramp faulting, and fracturing proximal to planes of slip. This strain predictive model can be applied to similar, less-well-exposed contractional systems worldwide and provides a new, unusual example of Laramide-age contractional deformation.

1. Introduction

Many studies have demonstrated that fault geometries have a strong and systematic influence on the shapes of folds above to those fault systems (e.g., Suppe, 1985; Mitra, 1990; Erslev and Rogers, 1993; Rowan and Linares, 2000; Almendinger and Shaw, 2000; Wilkerson et al., 2002; and Savage and Cooke, 2003; Jabbour et al., 2012). Where fault systems are unexposed or only poorly defined, workers can utilize geometries of overlying folds to resolve the geometries of those fault systems; these subsurface fault geometries have significant impacts on the assessment of seismic hazard and the evaluation of fluid flow in the subsurface. In this investigation, we combine field-based data collection, structural analysis of complex map-view fold geometries, cross-section construction and analysis, and two-dimensional forward kinematic modeling to develop a viable fault-propagation fold evolution that reveals vital information about subsurface structure.

Our investigation of the Stillwell anticline, an unusually well-exposed northwest-trending structure in the northern Sierra Del Carmen of the Trans-Pecos region of west Texas, also provides new data that improve our understanding of variations in Laramide deformation along the geologically-complex orogenic belt (Fig. 1). Although contractional deformation associated with the Late Cretaceous – Early Paleogene Laramide orogeny has been well-studied in Montana, Wyoming, Colorado, and New Mexico, where workers have clearly demonstrated basement involvement in the formation of folds and faults (e.g., Chapin and Cather, 1983; Gries, 1983; Jacob and Albertus, 1985; Woodward, 1986; Miller et al., 1992), few studies examine Laramide structures in areas further south, especially near the eastern margin of Laramide deformation (Cobb and Poth, 1980; Muehlberger, 1980; Moustafa, 1983, 1988; Muehlberger and Dickerson, 1989; Carpenter, 1997).

We here provide a model of fault-propagation fold evolution that explains the formation of the complex Stillwell anticline system in the context of previous studies of similar systems (e.g.,

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http://dx.doi.org/10.1016/j.jsg.2015.07.003
0191-8141/

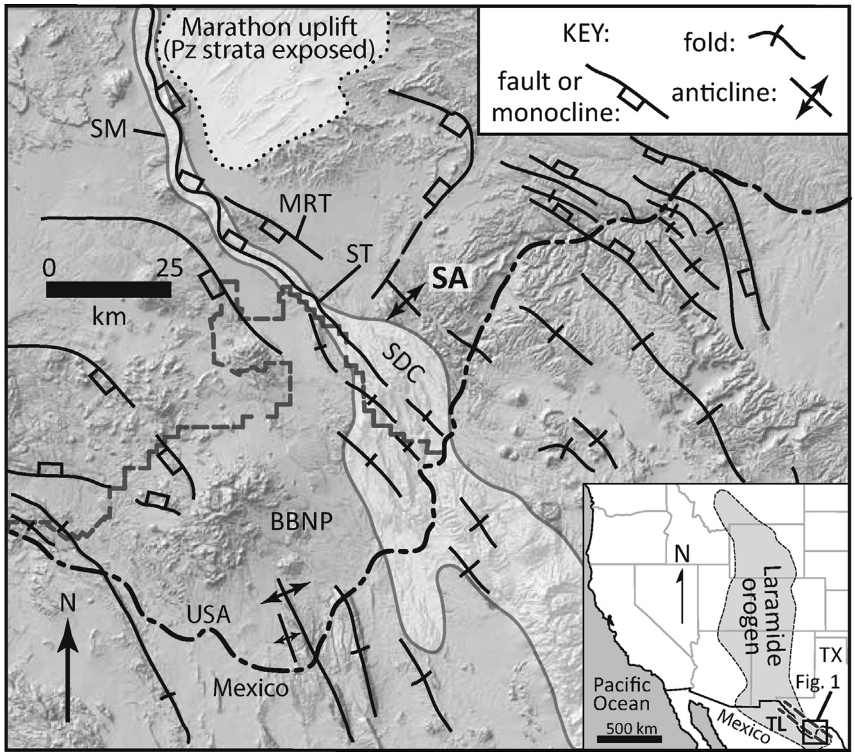

Fig. 1. Shaded relief map with major Laramide-age faults and folds of the Big Bend region, with inset (lower right) showing distribution of deformation associated with the Laramide orogen and the approximate boundaries of the Texas Lineament (TL). The Sierra del Carmen (SDC) and the Santiago Mountains (SM) are shaded in light gray. Big Bend National Park (BBNP) is outlined by a dashed, dark gray line. The Santiago thrust (ST) and the Maravillas Ridge thrust (MRT) are subparallel to the Stillwell anticline (SA). For most Laramide age folds, fold type is not differentiated. The rectangle on thrust faults/monoclines indicates the upthrown side of the fault/monocline system. Distribution of Laramide-age faults and folds modified from Muehlberger and Dickerson (1989) and Page et al. (2008). Laramide orogeny modified from Miller et al. (1992). Approximate boundaries of the Texas Lineament modified from Muehlberger (1980).

Suppe, 1985; Mitra, 1990; Suppe and Medwedeff, 1990; Erslev and Rodgers, 1993; Hardy and Ford, 1997; Mercier et al., 1997; Allmendinger, 1998; Jabbour et al., 2012). Our results suggest that the Stillwell anticline system formed in an unusual way relative to most other contractional fold systems worldwide. The documented anticline geometries were formed by two temporally-distinct styles of folding associated with Laramide-age compression: 1) initial compressional stresses reactivated a left-stepping, en echelon, high-angle basement fault system in pre-Mesozoic basement units, resulting in monoclinal structures in the layered carbonate rocks above the upward propagating faults; and 2) continued compression across the region resulted in the initiation of a separate, spatially- and temporally-distinct fault – propagation event, with a subhorizontal fault that propagated along a mechanically weak unit before ramping up at the hinge of the earlier monocline, creating a complex, but well-defined, fold geometry that varies along the axial trace of the system.

Importantly, we document outcrop-scale contractional strain of layered carbonates in the context of fault-propagation fold formation, tying the intensity of faults, interlayer slip, and fractures to the zone of greatest shear strain in front of the propagating fault tip. The predictive model we present here deepens our understanding of coupled fault-fold formation and provides a new and unusual example of how strain can be accommodated on the margins of continent-scale contractional deformation (Fig. 1). This model can be applied to coupled fault-fold systems worldwide, especially where data are not as complete.

2. Background

2.1. Pre-Laramide tectonics of Big Bend region

The Stillwell anticline is located within the Texas Lineament, an 80-km wide, northwest-trending zone of deformation (e.g., Albritton and Smith, 1957; Sears and Price, 1978; Muehlberger, 1980; TL in Fig. 1) thought to be fundamentally influenced by earlier plate-scale tectonic events which affected the Big Bend Region beginning in the Middle Proterozoic (e.g., Sears and Price, 1978; Muehlberger, 1980; Maler, 1990; Page et al., 2008; Thomas, 2011). The orientation of transform faults relating to Neoproterozoic rifting are subparallel to the NW-trending lineament (Thomas, 1991; Poole et al., 2005), which is considered a fundamental crustal weakness that juxtaposes the original craton to the northeast against accreted terranes to the southwest (e.g., Muehlberger, 1980; Page et al., 2008; Thomas, 2011). Late Paleozoic extensional deformation and uplift resulted in high-angle, northwest-striking normal faults to the north and northwest (e.g., Muehlberger, 1980 *and refs. therein*; Henry, 1998). During this period of Late Paleozoic deformation, the Big Bend region was part of the uplifted Diablo platform, adjacent to the Delaware basin (e.g., Henry, 1998; Goldhammer and Johnson, 1999; Page et al., 2008), but any normal fault systems associated with this event are obscured in the Stillwell anticline region by the deposition of Mesozoic marine strata.