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Fault zone processes in mechanically layered mudrock and chalk

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A 1.5 km long natural cliff outcrop of nearly horizontal Eagle Ford Formation in south Texas exposes northwest and southeast dipping normal faults with displacements of 0.01–7 m cutting mudrock, chalk, limestone, and volcanic ash. These faults provide analogs for both natural and hydraulically-induced deformation in the productive Eagle Ford Formation – a major unconventional oil and gas reservoir in south Texas, U.S.A. – and other mechanically layered hydrocarbon reservoirs. Fault dips are steep to vertical through chalk and limestone beds, and moderate through mudrock and clay-rich ash, resulting in refracted fault profiles. Steeply dipping fault segments contain rhombohedral calcite veins that cross the fault zone obliquely, parallel to shear segments in mudrock. The vertical dimensions of the calcite veins correspond to the thickness of offset competent beds with which they are contiguous, and the slip parallel dimension is proportional to fault displacement. Failure surface characteristics, including mixed tensile and shear segments, indicate hybrid failure in chalk and limestone, whereas shear failure predominates in mudrock and ash beds – these changes in failure mode contribute to variation in fault dip. Slip on the shear segments caused dilation of the steeper hybrid segments. Tabular sheets of calcite grew by repeated fault slip, dilation, and cementation. Fluid inclusion and stable isotope geochemistry analyses of fault zone cements indicate episodic reactivation at 1.4–4.2 km depths. The results of these analyses document a dramatic bed-scale lithologic control on fault zone architecture that is directly relevant to the development of porosity and permeability anisotropy along faults.

1. Introduction

Understanding natural deformation processes in fine-grained sedimentary strata has become increasingly important with the growing development of shale and self-sourced reservoirs for oil and gas production. The Cenomanian to Turonian Eagle Ford Formation (deposited between about 94 and 88 Ma) in south Texas (USA) has long been recognized as oil and gas source rock, and is a major self-sourced (unconventional) oil and gas "shale" reservoir (Fig. 1; Haymond, 1991; Robinson, 1997; Martin et al., 2011; Bodziak et al., 2014). The Eagle Ford Formation also is an important aquitard that separates the overlying Austin Chalk from the underlying Buda and Edwards Limestones, and is considered part of the upper confining unit for the Edwards Aquifer system that provides water for much of south central Texas (Livingston et al., 1936; Maclay and Small, 1983; Maclay, 1989; Ferrill et al., 2004). Although often referred to as shale, the Eagle Ford Formation throughout the subsurface oil and gas play of south Texas is a heterolithic carbonate-rich unit composed of thicker mudrock with relatively thin interbeds of chalk, limestone, and volcanic ash. At the regional scale, the productive Eagle Ford Formation through much of the play is essentially a gentle homocline dipping south or southeast, and productive well depths vary from as shallow as approximately 1219 m, dominated by liquid production, to 4267 m, dominated by dry gas production (U. S. Energy Information Administration, 2014). Despite the apparent simplicity of this play, the geologic setting in the productive Eagle Ford trend includes numerous normal faults that resulted from Cretaceous and Tertiary regional extension around the margin of the Gulf of Mexico basin (Treadgold et al., 2010; Ferrill et al., 2014b; McGinnis et al., 2016). Faulting in the Eagle Ford trend includes the Balcones fault system, which is at the up-dip limit of the Gulf Coast extensional system and is coincident

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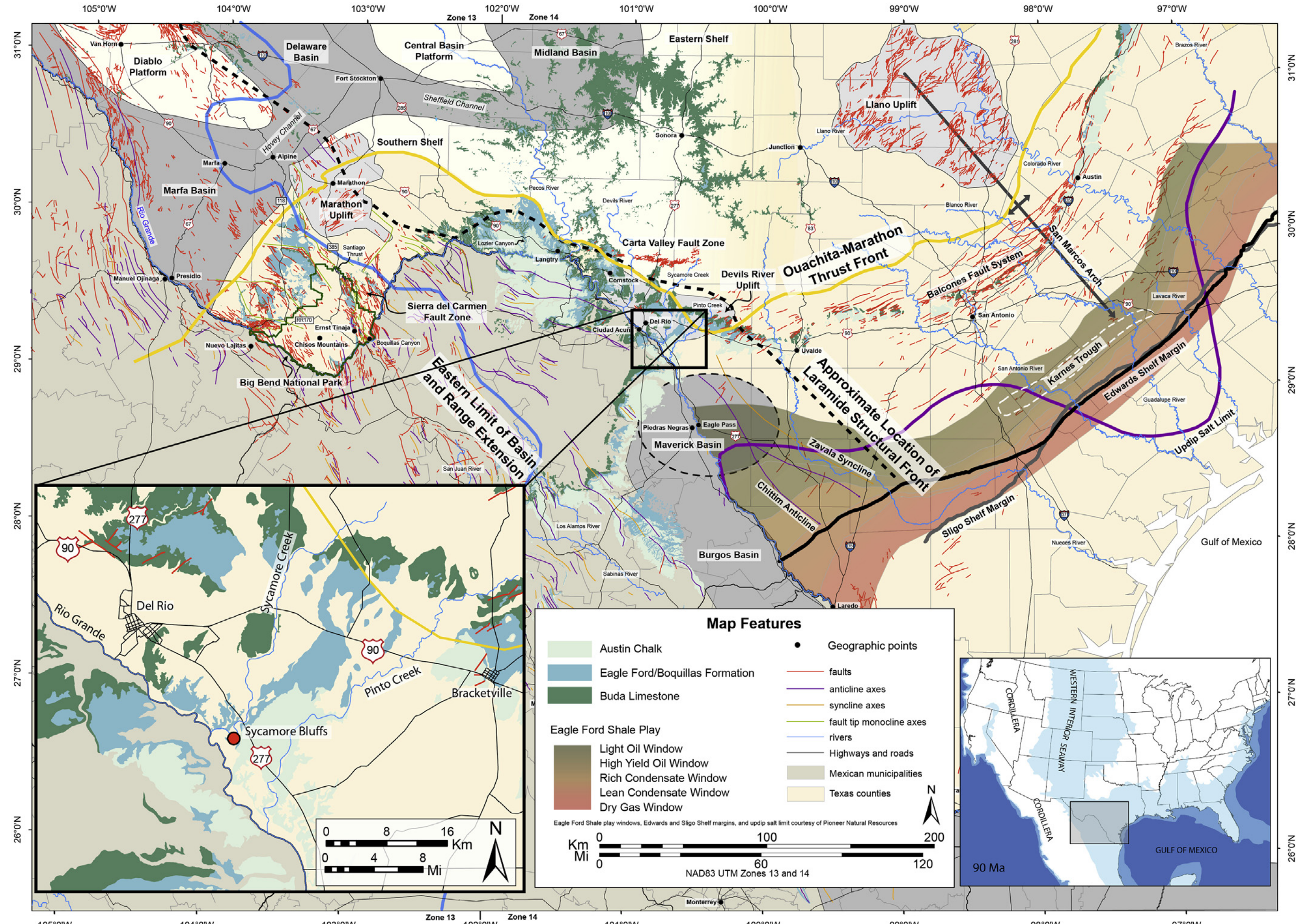

Fig. 1. Structural and tectonic synthesis map with inset showing details of study area, with red dot indication location of the Sycamore Bluffs exposure. Inset on the bottom right is the regional paleogeography of North America showing flooded continental margin and Western Interior Seaway at the time of Eagle Ford Formation deposition indicated by light blue color (modified from Blakey, 2011). Boquillas Formation is the lateral equivalent of the Eagle Ford Formation.

with much of the Eagle Ford Formation outcrop belt (Ferrill et al., 2014a). The Eagle Ford Formation is a low-permeability source-rock reservoir within which induced hydraulic fracturing is used to generate and enhance fractures through which oil and gas can be produced (Donovan and Staerker, 2010; Hentz and Ruppel, 2010; Basu et al., 2012; Bodziak et al., 2014; Busetti et al., 2014; Gale et al., 2014; Smart et al., 2014). Consequently, natural fractures can have a significant influence on oil and gas production within the Eagle Ford Formation (Treadgold et al., 2010; Basu et al., 2012). Induced hydraulic fracturing is the result of the interaction between a fluid driven pressure increase in the reservoir and the *in situ* stress field, mechanical properties of the strata (mechanical stratigraphy), and pre-existing natural deformation (Ferrill et al., 2014a). Mechanical stratigraphy represents the mechanical properties of the rock, thickness of the mechanical layers, and frictional properties of the boundaries between mechanical layers within a stratigraphic section (Groshong, 2006; Ferrill and Morris, 2008; Ferrill et al., 2017). Variations in mineralogy, depositional texture, porosity, and degree of cementation influence the rock strength (tensile and compressive strength, friction angle, cohesion) and stiffness (Young's modulus) which in turn govern how a rock layer or multilayer responds to natural tectonic deformation (e.g., tensile versus hybrid versus shear; e.g., Hancock, 1985; Reches and Lockner, 1994; Sibson, 1998, 2000; Ramsey and Chester, 2004; Engelder et al., 2009; Ferrill et al., 2012a, 2014b; Petrie et al., 2014; McGinnis et al., 2015; Giorgetti et al., 2016) as well as induced hydraulic fracturing (Gale et al., 2014; Smart et al., 2014). Mechanical stratigraphy has been found to influence fault nucleation and growth (Ferrill and Morris, 2003, 2008; Roche et al., 2012a, 2012b, 2013; Kettermann and Urai, 2015; Giorgetti et al., 2016; Kettermann et al., 2016), fault zone processes (Jamison, 1979; Young, 1982), and fault geometry and network characteristics (Ferrill and Morris, 2003; Morris et al., 2009b), and is considered key for correctly interpreting geologic structure (McGinnis et al., 2016). Analysis of microseismic data (Busetti et al., 2014) and geomechanical modeling (Smart et al., 2014) of induced hydraulic fracturing indicates that a substantial amount, and in some cases the bulk, of induced failure is in shear (faulting) or hybrid mode rather than tensile (extension fracture) mode, and also indicates that pre-existing faults may reactivate during induced hydraulic fracturing (Smart et al., 2014).

In this paper, we analyze normal faults in heterolithic mudrock, chalk, limestone, and volcanic ash in the Eagle Ford Formation in south Texas within a 1.5 km long natural cliff exposure. These faults provide analogs for both natural and hydraulically-induced deformation in the productive Eagle Ford Formation – a major unconventional oil and gas reservoir in south Texas, U.S.A. – and other mechanically layered hydrocarbon reservoirs. The faults are