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Mechanical Stratigraphy of Bed-Bound Mode I Extension Fractures in the Eagle Ford Formation, Del Rio Area, West Texas

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ABSTRACT

A set of well-developed, bed-bound natural fractures of the Eagle Ford in the Del Rio (Texas) area formed in response to far-field compressive stresses. These NE–SW oriented fractures are best developed in, but not restricted to, tabular limestone beds at the base of the Upper Eagle Ford where the formation consists of cm- to dm-scale interbeds of limestone and marlstone. Where definable, mean fracture spacing is less than bed thickness; in some cases, fracture spacing shows a log-normal distribution. They are observable in outcrops that stretch ~120 km (75 mi) from the NW to SE (Sycamore Creek to Antonio Canyon) and at other locations in between.

Their NE–SW orientation has led to confusion about the mechanisms responsible for their formation. That orientation is approximately parallel to the strike of extension fractures developed in Mesozoic and Tertiary strata of the southern Texas Coastal Plain. Fractures with that orientation are observable in outcrops of the Austin Chalk in the San Antonio area. On the other hand, the fractures are perpendicular to fold hinge lines of the Sierra Madre Occidentale to the southwest of the outcrop belt in Mexico and the Chittum Anticline in the subsurface of Texas to the southeast of the outcrop belt. Plumose structures on fracture faces imply fracture growth parallel to bedding, indicating that they formed in response to compressive stresses (σ_1 horizontal).

INTRODUCTION

Natural fractures can affect fluid flow (hydrocarbons, water) and drilling and completion practices in many ways (e.g., Lorenz and Cooper, 2020). As such, natural fracture characterization is an important part of applied subsurface analyses. One of the important aspects of fracture characterization is defining the origin of the fractures—how did the in situ stress field at the

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time of formation interact with the mechanical stratigraphy of the rocks to cause brittle failure? Addressing this question facilitates prediction of fracture characteristics away from available well control and can help with definition of current and previous tectonic stresses.

Previous studies of these fractures (e.g., Ferrill et al., 2014; Gottardi and Mason, 2018) suggested they may be part of a NW–SE Tertiary extension of the Gulf Coast area. Fractures with nearly identical orientations are present in outcrops of the Austin Chalk, northeast of the Eagle Ford outcrops discussed here and did indeed form in response to Gulf Coast extension. In this study, the bed-bound natural fractures in the Eagle Ford Formation exposed in outcrops in the Del Rio area of West Texas (Fig. 1) are interpreted to have formed as mode 1 extension fractures in response to NE–SW oriented Laramide compressive stresses

STUDY AREA AND METHODS

Natural fractures in the Eagle Ford are exposed in three areas: (1) Antonio Canyon, (2) along Highway 90 east of Langtry, and (3) along Sycamore Creek east of Del Rio. In these and other outcrops of this area, the Eagle Ford is composed primarily of interbedded marlstones and limestones; the relative proportions of each lithology varies stratigraphically in the for-

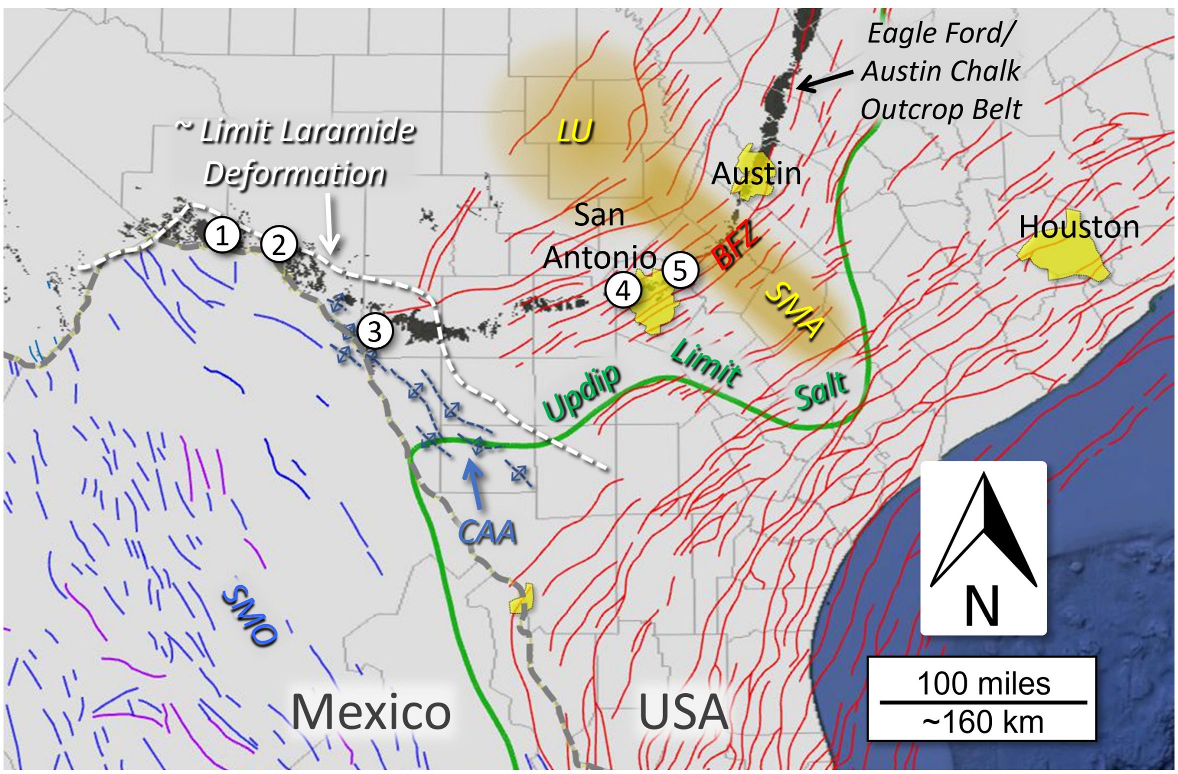

Figure 1. Location map. Natural fractures in the Eagle Ford described herein are from locations 1–3. Locations of Austin Chalk outcrops in the San Antonio area are shown as locations 4 and 5. Red lines show locations of normal faults of the South Texas coastal plain, the Balcones Fault Zone (BFZ) in the San Antonio/Austin area, and other normal faults to the northwest of the outcrop belt. Blue and magenta lines in Mexico represent the orientations of anticlines of the Sierra Madre Occidentale (SMO). Anticlinal axes of the Del Rio Fold Belt and Chittum Anticline (CAA). Based on imagery from the U.S. Geological Survey GIS server, Ewing (1987), and Padilla y Sanchez et al. (2013).

mation as do bed planarity, continuity, grain size, and other lithological variables. Previous descriptions and interpretations of the Eagle Ford stratigraphy in this area are summarized in Hart et al. (2020).

At each location data collected includes fracture strike orientations, bed-thickness measurements, and the fractures have been characterized with respect to orientation relative to bedding, fracture-surface morphology (fractography), and other features. In this paper, the focus is on fracture orientations and fractography of natural fractures that formed in limestone beds.

For comparison, natural fracture orientations measured in outcrops of the Austin Chalk in the San Antonio area are also presented. These data were collected and presented by Hart et al. (2020). Ferrill et al. (2017) also described and interpreted fracture orientations in the Austin Chalk in the San Antonio area.

RESULTS

Figure 2 shows selected images of natural fractures in the Eagle Ford. At all three locations, natural fractures in the limestones are bed bound, terminating at the upper and lower bed contacts. Natural fractures can be present in the marlstones, but their spacing is different and fractures are not continuous from the limestones into the marlstones. Fractures are either perpendicular to bedding (locations 1 and 2) or at a high angle to it (location 3). Fracture spacing in the limestones is broadly related to bed thickness but the relationship is not one-to-one. Lognormal fracture spacing distributions are present in some of the limestone beds.

Plumose structures (Fig. 2E) are present on fracture faces at locations 1 and 2 but are not observed at location 3. Their low abundance or apparent absence at locations 1 and 3 is probably due to weathering of those outcrops compared to the relatively fresh exposures along Highway 90 (location 2). The plumose structures indicate fracture propagation parallel to bedding, and are clear indicators that the fractures formed in response to bed-parallel compression. Hart and Cooper (2021) reported well-developed plumose structures on natural fractures in lithologically and chronostratigraphically equivalent rocks of the Bridge Creek Limestone in the San Juan Basin of New Mexico.

Figure 3 shows the orientations of the Eagle Ford fractures and compares them to the orientations of fractures in the Austin Chalk near San Antonio (numbered locations keyed to map locations in Figure 1). The consistent orientations of the fractures in the two formations/areas could be considered evidence that they formed in response to the same/similar stress fields. However, that consistency is coincidental: the Laramide compression in the Del Rio area is at a right angle to the Tertiary extension orientation that is expressed near San Antonio (Fig. 1). Normal faults, having well-developed dip-slip indicators on the fault planes, are present at both the Sycamore Creek (location 3) and Cibolo Creek (location 5) outcrops. At location 3, the natural fractures described herein are not parallel to the faults (e.g., Ferrill et al., 2014, their figure 4), whereas they are at location 5 (Hart et al., 2020).

The preferential development of natural fractures in the limestone beds of the Eagle Ford is a function of Hooke's Law, which dictates that for bed-parallel compression the stresses carried by each bed will be different. The stiffer limestones will carry more stress than the interbedded, more compliant marlstones, making the limestones more prone to fracturing. This concept is illustrated in Figures 4A and 4B. Figure 4C illustrates the differences in Young's modulus for limestones and marlstones. Fracture terminations at bed boundaries result from these mechanical property and stress contrasts, as well as the harder to define degree of coupling between the beds.

CONCLUSIONS

A regionally developed set of NE–SW striking natural fractures is present in outcrops of the Eagle Ford in the Del Rio area of West Texas. The fractures are bed bound, and are better de-

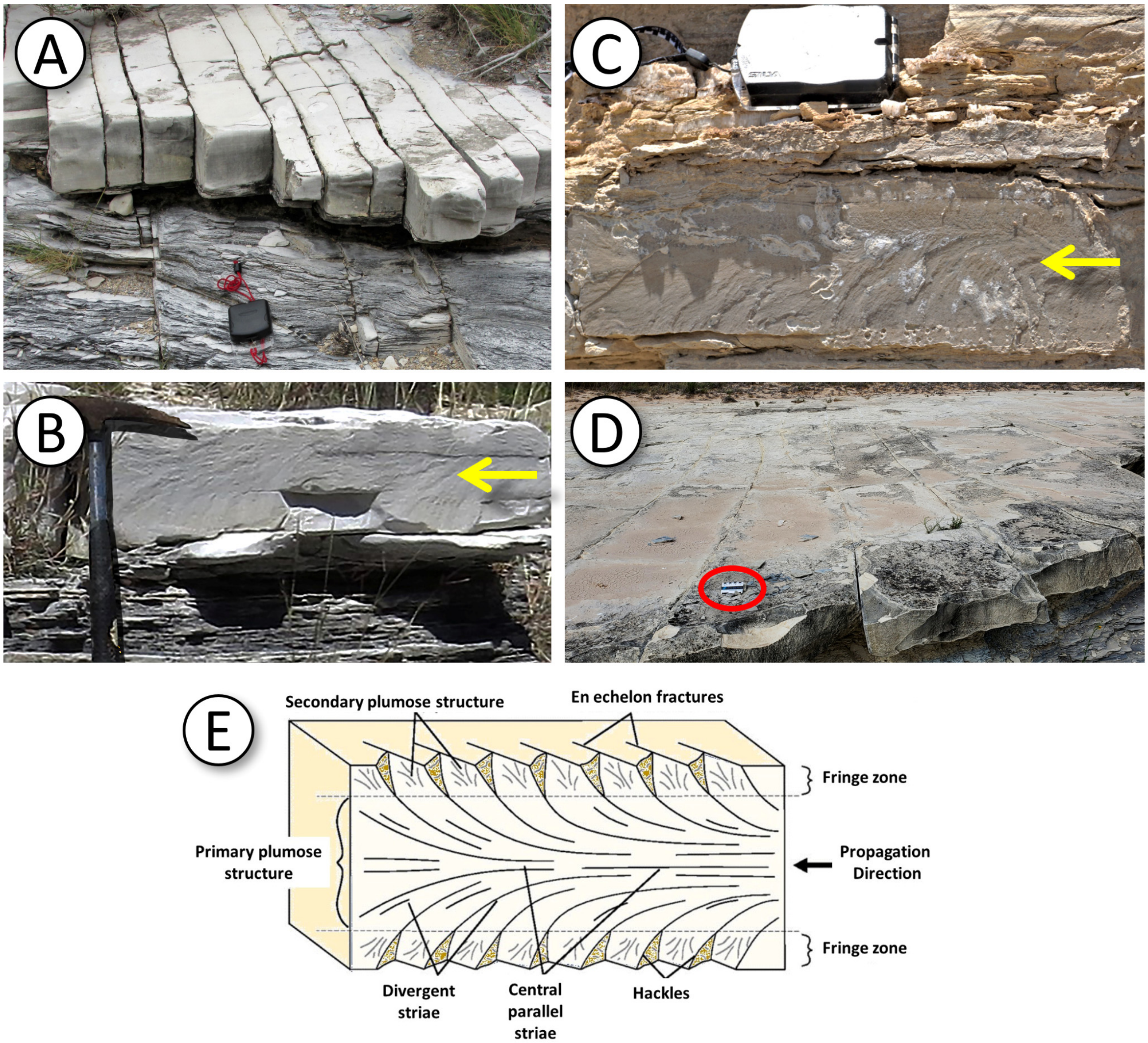

Figure 2. Outcrop photos of mode 1 extension fractures in the Eagle Ford. (A) Parallel fractures in the limestone bed (top) do not extend into the underlying marlstone. Antonio Canyon (location 1 in Figure 1). (B) Plumose structure on a fracture plane indicating fracture growth parallel to bedding and from right to left. Antonio Canyon (location 1 in Figure 1). (C) Plumose structure on a fracture plane indicating fracture growth parallel to bedding and from right to left. West Langtry (location 2 in Figure 1). (D) Bed bound, parallel to curviplanar natural fractures in a limestone bed. Scale bar (red oval) is ~3" long. Sycamore Creek (location 3 in Figure 1). (E) Schematic illustration of plumose structure on a fracture surface indicating fracture growth parallel to bedding and from right to left.

veloped in limestone beds than in the interbedded marlstones. That fracture set has developed in response to Laramide compression acting on a stratigraphic unit composed of beds having different elastic properties (i.e., Young's modulus).

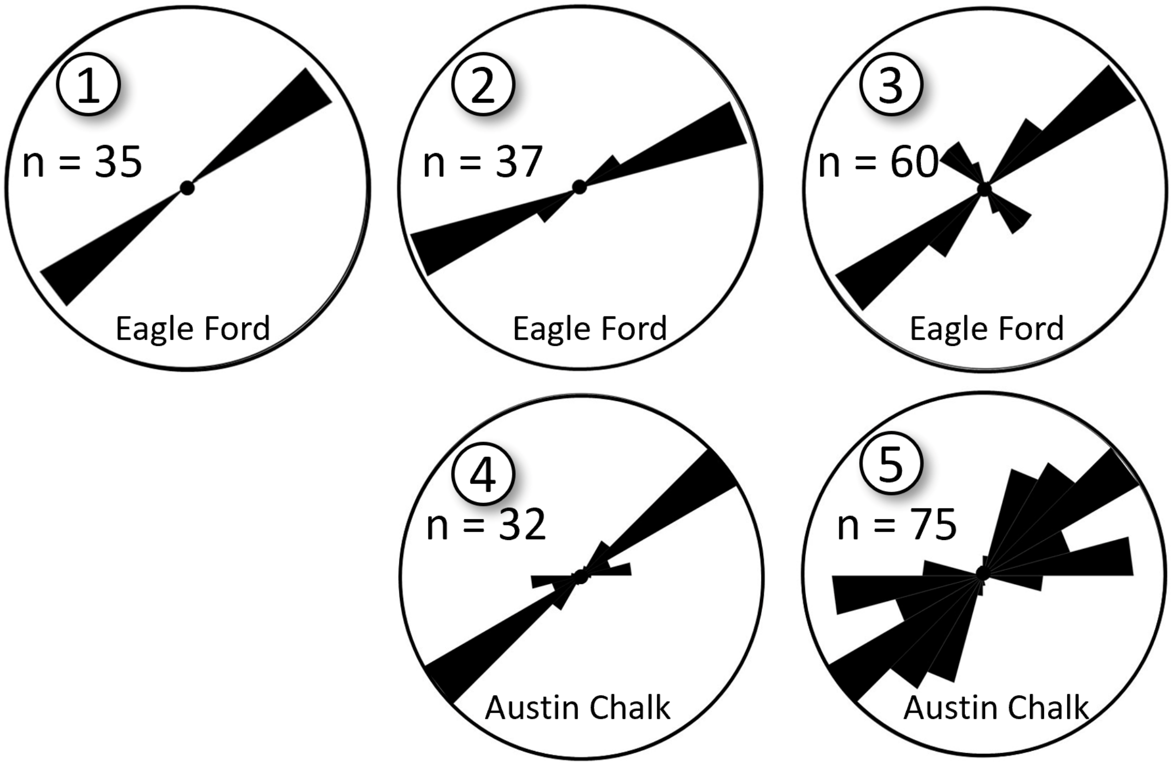

Figure 3. Rose diagrams of fracture orientations. Numbers refer to locations in Figure 1. Fractures in the Eagle Ford at locations 1–3 have approximately the same strike as fractures in the Austin Chalk at locations 4 and 5, but correlation does not mean they are genetically related. The Eagle Ford fractures from the Del Rio area have formed in response to Laramide compression, at right angles to the squeezing direction. The Austin Chalk fractures in the San Antonio area are associated with Tertiary normal faulting. Fracture orientations at location 1 are from a single bedding plane, elsewhere fracture orientations have been measured on multiple beds.

This short paper is a subset of the data collected and incorporated into the fracture characterization work but hopefully emphasizes the need for detailed fracture characterization work in a variety of fundamental and applied analyses. For example, proper characterization of stress fields and mechanical property contrasts should be a key input for hydraulic fracture design.

ACKNOWLEDGMENTS

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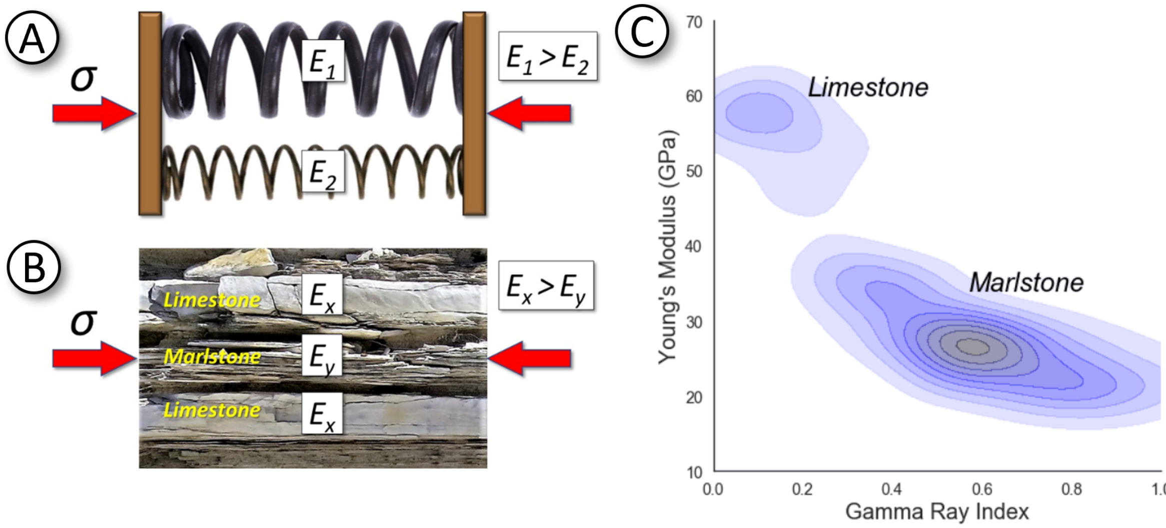

Figure 4. Differences in Young's modulus (E) between two layers affect natural fracture development. (A) The two springs have different values of E. The heavier/stiffer spring at top will feel more of the compressive stress (σ) than the thinner spring because of differences in Young's modulus. (B) Outcrop exposure of limestones and marlstones at Antonio Canyon (location 1 in Figure 1). The limestones have higher E than the adjacent marlstones and so felt higher compressive stress during Laramide compression. (C) Kernel density plot showing the relationship between Young's modulus and lithology (as defined by the gamma-ray curve, a proxy for clay content) in the Eagle Ford. Limestones have higher Young's moduli than interbedded marlstones. Parts A and B are reproduced from Hart et al. (2020) and Part C is reproduced from Hart and Cooper (2021).

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