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Influence of Structural Position on Fracturing in the Austin Chalk

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ABSTRACT

Outcrops of Upper Cretaceous Austin Chalk in south-central Texas (San Antonio area) were investigated to produce a baseline assessment of fracture network characteristics and relationships with respect to regional structural position. This area represents the nearest outcrop exposures of Austin Chalk to significant active drilling in the Eagle Ford Formation and overlying Austin Chalk. These Austin Chalk exposures are within the Balcones Fault System, which is the updip portion of the Gulf of Mexico marginal fault system. In the study area, the fault system consists of a right-stepping en echelon array of generally northeast-striking normal faults, within a major relay structure—the San Antonio relay ramp—between the Haby Crossing Fault to southwest and the Balcones Escarpment Fault to the northeast. Similar extensional fault patterns exist in the subsurface Austin Chalk in the exploration and production area. Reconnaissance field investigations at 36 stations within a ~20 km by 40 km region in the San Antonio area document significant variability in failure modes (extension versus shear failure), fracture orientations, and fracture intensity (or spacing). Incompetent beds within the Austin Chalk localize fracture terminations and in some cases have caused fault (shear fracture) dip change (refraction). Our observations indicate that fracture network characteristics are related to mechanical rock properties and structural position, with fault and fracture orientations and timing relationships reflecting stress rotation and structural overprinting within the San Antonio relay ramp. These observations are directly relevant to subsurface interpretation and hydrocarbon production from the Austin Chalk, particularly for exploitation of the Austin Chalk as a self-sourced or conventional fractured reservoir.

INTRODUCTION

The Upper Cretaceous Austin Chalk lies stratigraphically above the Eagle Ford Formation and is experiencing renewed focus as a target for horizontal drilling and hydraulic fracturing. The Austin Chalk, which has historically been exploited as a conventional fractured reservoir producing from natural porosity and permeability (Corbett et al., 1987, Pearson 2010, 2012; Pearson et al., 2011), is now being explored as a "hybrid unconventional reservoir," relying on natural porosity and permeability combined with induced hydraulic fracturing to generate new fracture porosity and permeability to release hydrocarbons (possibly self-sourced) trapped in microscopic pores in the fine-grained rock (e.g. Ferrill et al., 2014a). This renewed focus on the Austin Chalk allows companies to leverage their existing leases, wells, and surface infrastructure purchased for the Eagle Ford Formation and currently held by Eagle Ford production.

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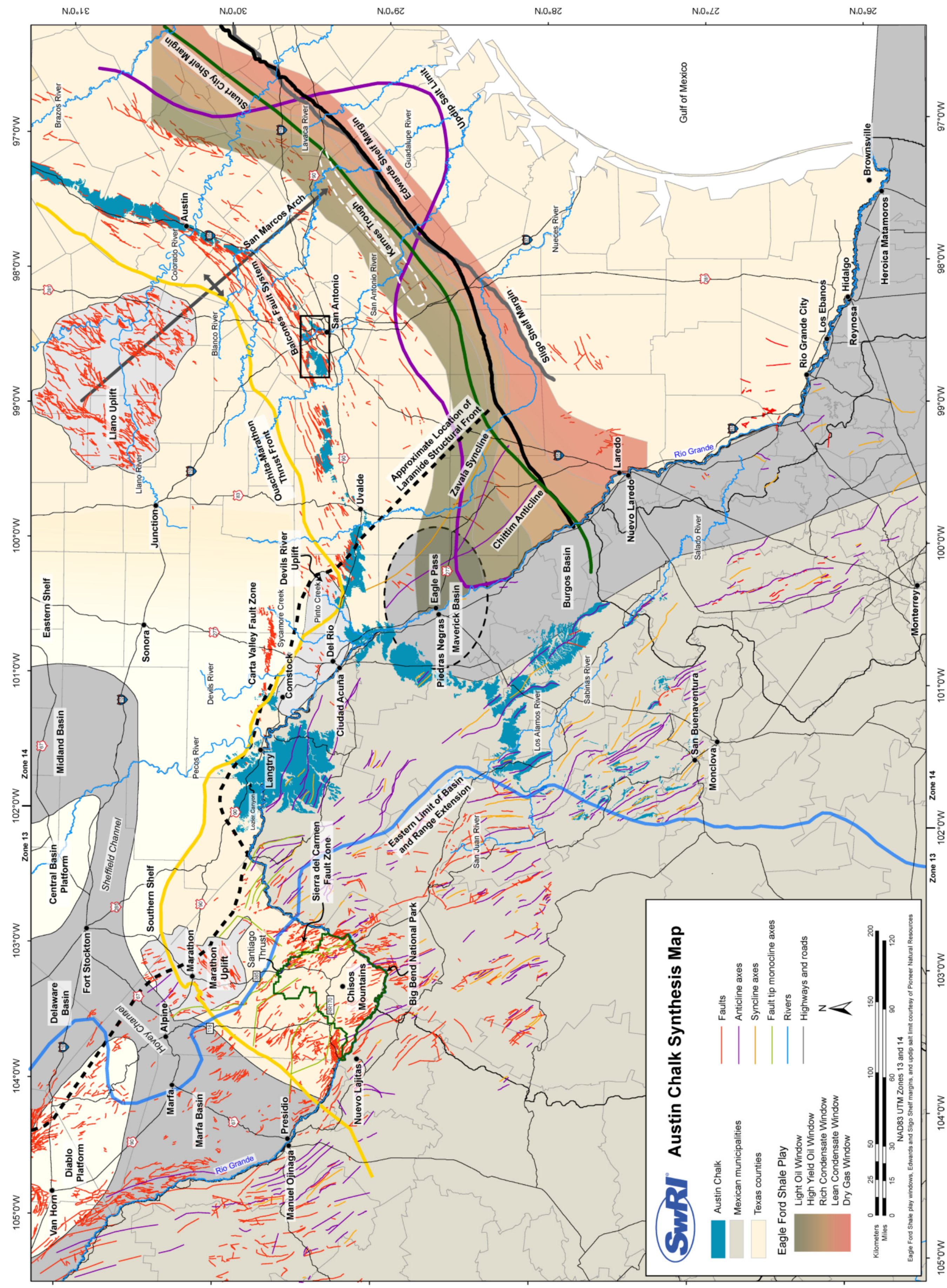
Natural deformation features, such as extension fractures (joints, veins), and faults in the Austin Chalk in South Texas are considered to be important to production of hydrocarbons and are likely to influence induced hydraulic fracturing. Deformation behavior, in general, is sensitive to the mechanical stratigraphy (e.g., Ferrill and Morris, 2008; Ferrill et al., 2017). The style and abundance of this brittle deformation also is likely to vary with the structural and tectonic setting, particularly in relation to Gulf of Mexico related extensional deformation (salt-related and non-salt-related), and potentially be influenced by contractional Laramide deformation. We investigated accessible outcrops of Austin Chalk in south-central Texas, including locations from a range of structural positions, especially in terms of proximity to mapped (seismic-scale) normal faults (Fig. 1). These different structural positions are similar to locations that are or may be exploited for oil and gas in the subsurface of South Texas. Deformation mechanisms and intensities were analyzed at a reconnaissance level at more than 30 locations to provide context and identify regional patterns with additional detailed investigations at select locations.

BACKGROUND

The Austin Chalk has been produced as a conventional fractured reservoir, producing hydrocarbons that have been thought


SwRI
Austin Chalk Synthesis Map
Austin Chalk
Mexican municipalities
Texas counties
Eagle Ford Shale Play
Light Oil Window
High Yield Oil Window
Rich Condensate Window
Lean Condensate Window
Dry Gas Window
Faults
Anticline axes
Syncline axes
Fault tip monocline axes
Rivers
Highways and roads
N
Kilometers
Miles
NAD83 UTM Zones 13 and 14
Eagle Ford Shale play windows, Edwards and Sligo Shelf margins, and updip salt limit courtesy of Pioneer Natural Resources
Gulf of Mexico
Stuart City Shelf Margin
Edwards Shelf Margin
Sligo Shelf Margin
Updip Salt Limit
Karnes Trough
San Marcos Arch
Balcones Fault System
Llano Uplift
Ouachita-Marathon Thrust Front
Approximate Location of Laramide Structural Front
Zavala Syncline
Chittim Anticline
Maverick Basin
Burgos Basin
Devils River Uplift
Carta Valley Fault Zone
Eastern Shelf
Midland Basin
Central Basin Platform
Sheffield Channel
Southern Shelf
Delaware Basin
Hovey Channel
Diablo Platform
Marfa Basin
Marathon Uplift
Santiago Thrust
Chisos Mountains
Big Bend National Park
Sierra del Carmen Fault Zone
Eastern Limit of Basin and Range Extension
Austin
San Antonio
Uvalde
Junction
Sonora
Del Rio
Ciudad Acuña
Comstock
Langtry
Eagle Pass
Piedras Negras
Laredo
Nuevo Laredo
Rio Grande City
Los Ebanos
Hidalgo
Reynosa
Brownsville
Heroica Matamoros
Monterrey
Monclova
San Buenaventura
Fort Stockton
Marathon
Alpine
Marfa
Presidio
Manuel Ojinaga
Nuevo Lajitas
Van Horn
Rio Grande
Zone 13
Zone 14

(FACING PAGE) Figure 1. Map of Austin Chalk outcrops (dark blue shaded area) in Central and West Texas. Black box in the San Antonio area shows focus area for Austin Chalk outcrop investigation here.

by many to have been sourced from the underlying Eagle Ford Formation (e.g., Grabowski, 1981; Haymond, 1991; Martin et al., 2011). Although referred to as "chalk," the Austin Chalk is heterolithic and includes limestone, chalk, marl, and mudstone, with differences in carbonate content, clay abundance and type, and organic content influencing the mechanical properties and resulting in mechanical layering of the formation (Young and Woodruff, 1985; Hovorka and Nance, 1994; Laubach et al., 2009; Corbett et al., 1987). Directional drilling has been used extensively to try to tap into fractured Austin Chalk since the 1980s. Traditionally, hydrocarbon source rocks are considered to consist of organic rich shale. Carbonate dominated rock like the Austin Chalk is typically not thought to contain sufficient organic content to generate economically important hydrocarbon volumes. However, some studies have shown that carbonate rocks contain more sapropelic organic matter, which yields a higher percentage of oil than the more humic organic matter in shales (Grabowski, 1981; Hunt and McNichol, 1984). The Austin Chalk in particular shows these characteristics, which makes this an attractive target for exploitation as a self-sourced reservoir (Grabowski, 1981; Hunt and McNichol, 1984). The Austin Chalk is drawing some attention as a "hybrid unconventional reservoir" on the basis that the Austin Chalk is to some extent self-sourced, and is also directly above the Eagle Ford Formation, which also has sourced hydrocarbons trapped in matrix porosity and fractures within the Austin Chalk beneath a shale topseal (Robinson, 1997). Directional drilling and induced hydraulic fracturing are being used to encounter natural fractures and generate new fractures to unlock these trapped hydrocarbons using the same general approach that is used in the Eagle Ford Formation. In addition, companies can take advantage of existing leases, wells, and surface infrastructure (e.g., wellpads, pipelines) to keep costs down and improve the economic viability of the play.

With this play concept in mind, fractures may provide storage for hydrocarbons and permeability necessary to deliver hydrocarbons to the wellbore, which are both beneficial characteristics. From this perspective, fractures would be generally considered positive features. More and better connected fractures could be beneficial in that they could (i) be drained of existing hydrocarbons and/or (ii) reactivated during hydraulic fracturing and penetrate into other natural fractures that could also be drained. On the other hand, natural fractures can provide pathways for the leakage of hydrocarbons out of the reservoir, either migrating updip or through a failed topseal. In the latter case, large and well-connected natural fractures (extension fractures and faults) can be detrimental to hydrocarbon retention in the Austin Chalk.

Previous work has shown that fractures are common in the Austin Chalk and that they are dominated by opening mode (primarily barren) joints, and that fractures in the Austin Chalk typically occur in two orthogonal sets of near vertical fractures (Friedman and McKiernan, 1995), although significant complexity in fracture networks has also been reported (Wiltschko et al., 1991; Corbett et al., 2009; Wilson et al., 2011). Faults have also been observed in the Austin Chalk, and have been found to (i) change dip through bed-scale mechanical layering (Nance et al., 1994), and (ii) include shear and dilational segments that record crack-seal textures (Nance et al., 1994; Lee et al., 1997; Lee and Wiltschko, 2000). Fault related folding described in the Austin Chalk and adjacent formations includes synthetic dip in fault-related monoclines (Ferrill and Morris, 2008; Corbett et al., 2009; Ferrill et al., 2012) and antithetic dip in hanging wall rollovers above listric normal faults (Nance et al., 1994; Corbett et al. 2009). Fracture intensity has been described as varying vertically as a function of mechanical stratigraphy (Corbett et al., 1987; Collins et al., 1992) and has been interpreted to be largely related to clay content (Bafia and Spencer, 1999). Joints have been observed to be terminated vertically at weaker (shale or marl) interbeds (Friedman et al., 1994; Rijken and Cooke, 2001), which is consistent with observations from the Eagle Ford Formation (Ferrill et al., 2014b). Although some fractures may be related to hydrocarbon generation (Berg and Gangi, 1999), most have been interpreted to be of tectonic origin from regional Gulf of Mexico related extensional deformation (e.g., Haymond, 1991).

FRACTURE CHARACTERIZATION

In our usage here, the term "fracture" includes all brittle deformation surfaces where cohesion has been lost and includes faults and extension fractures. The term "extension fracture" encompasses all opening mode (tensile, mode I) fractures, including joints and veins. The term "joint" refers to barren extension fractures. "Vein" refers to a cemented (e.g., with calcite or iron oxide cement) extension fracture. "Fault" refers to a shear fracture that exhibits evidence of slip in the form of slickenlines and/or measurable displacement.

Fracture Occurrence, Type, and Characteristics

Each outcrop of Austin Chalk that was investigated includes natural fractures. In all cases, extension fractures (product of tensile failure) are present, but in many cases normal faults (product of shear or hybrid failure) with displacements of millimeters to 10s of centimeters are also present. Observed extension fractures include barren joints, joints with bleached zones, joints with iron oxide staining, veins mineralized with iron oxide, veins mineralized with calcite, and dissolution cavities along fractures (Fig. 2). Fault characteristics include surfaces with grooves and striations, stylolitic suturing (i.e., slickolites), vein cementation, mineralized dilational jogs, and dissolution localized along fault (Fig. 3).

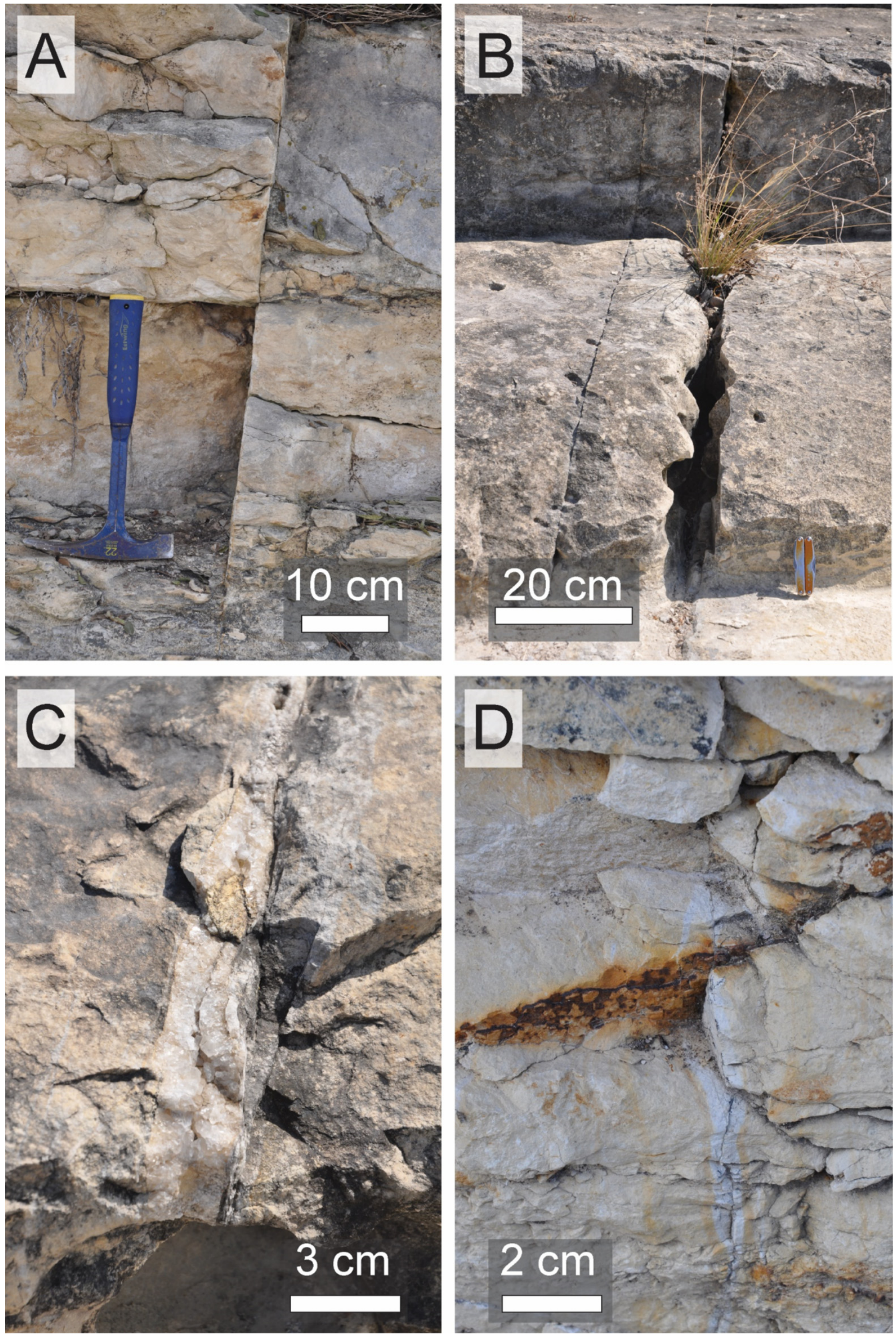
Extension Fracture Orientations

A map compilation of rose diagrams is used to summarize extension fracture orientation data from individual outcrops and localized clusters of outcrops throughout the study area (Fig. 4). Results show an overall pattern that includes a set of extension fractures that trends northeast-southwest, generally parallel to the faults in the Balcones Fault System, and/or another set that trends northwest-southeast, perpendicular to the dominant fault trend. Closer inspection reveals significant variation with well-developed orthogonal patterns in a few locations, two or more non-orthogonal sets in some locations, and only one dominant set present in other locations. Furthermore, the strike of dominant sets in some cases changes orientation by 10s of degrees over lateral distances on the order of 100s of meters or a few kilometers with changing structural position.

Fault Orientations

A map compilation of rose diagrams for measured fault strike data illustrates fault orientations throughout the study area (Fig. 5). The observed fault strike pattern is generally consistent with the regionally mapped Balcones Fault Zone trends, although substantial strike variability is observed. To some extent, the variability reflects the pattern of variability seen in the regional fault map. However, nearly 90° variation in fault strike is observed at two localities. This variability in fault strike likely represents local stress field evolution, related to transient stress fields developed during fault propagation and fault interaction.

Figure 2. Outcrop photographs illustrating extension fractures in the Austin Chalk: (A) Subvertical joint with minor iron-oxide staining (location AC–32), (B) subvertical joint (left of center) and dissolution-enlarged subvertical joint (right of center) (location AC–3, Culebra Creek), (C) vertical, 1.5 cm thick, coarse calcite vein (location AC–3, Culebra Creek), and (D) moderately dipping iron-oxide coated extension fracture (reddish brown coated surface inclined down to the left near center of photo) and vertical joint with bleaching suggesting movement of fluid along fracture (location AC–33).



Fracture Terminations

Observed fractures (i.e., joints, veins, and faults) in the Austin Chalk can have dimensions on the scale of many meters laterally. However, field observations indicate that fractures in chalk or limestone commonly terminate vertically at lithologic transitions—in particular at clay-rich claystone, mudrock, or marl beds (Fig. 6A). This observation holds for both extension fractures and faults, although several outcrops show that occasional fractures do cross these weak Austin Chalk interbeds. Allowing for those exceptions, fracture height tends to be largely controlled by vertical spacing between incompetent (clay rich) beds that are not brittle enough for fractures to propagate through.

Lateral fracture terminations are in many cases controlled by abutting of later-formed fractures against open joints (Fig. 6B), whereas later-formed fractures are observed to cut across mineralized (calcite or iron-oxide filled) veins. Consequently, lateral fracture length is largely controlled by relative fracture timing, with early formed fractures more likely to have long lateral trace lengths and later formed fracture lengths limited by spacing between earlier open fractures.

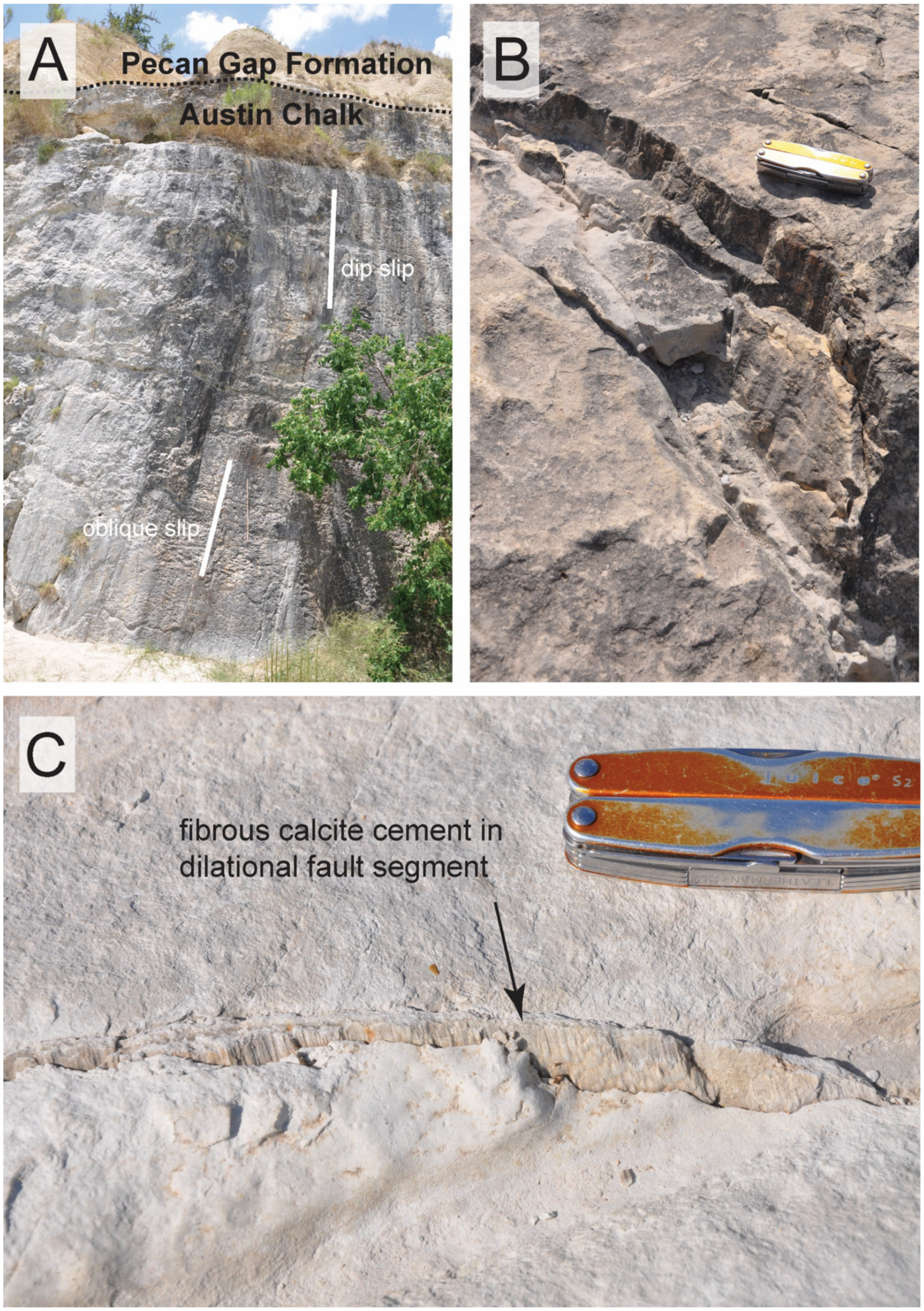


Figure 3. Outcrop photographs illustrating characteristics of small displacement faults in the Austin Chalk: (A) exposed footwall fault surface showing superimposed slickenlines indicating normal dip slip followed by normal oblique slip on fault (location AC–1, near Heroes Stadium at site of former Longhorn Quarry), (B) swarm of slip surfaces indicating dip slip motion (location AC–3, Culebra Creek), (C) fibrous calcite cement in dilational jog along small, approximately 1 cm displacement fault (location AC–3, Helotes Creek).

Fracture Pavement Mapping

Detailed mapping (using real-time differential GPS) of fracture networks exposed across saw cut benches within Helotes Creek immediately above the confluence with Culebra Creek (Location AC–3) was performed to explore the lateral extent, connectivity, and intersection relationships within the fracture network. The mapped fracture network, as well as plots based on detailed fault and extension fracture measurements at individual locations in and near the pavement mapping are presented in Figures 7 and 8. Plots of fault and extension fracture measurement locations (spot measurements) illustrate a 20° difference in dominant strike direction between faults and extension fractures. This difference suggests a rotation of the extension direction between timing of extension fracturing (joint development) and the subsequent normal faulting. Furthermore, this clockwise rotation of the principal southeastward extension direction is compatible with the development of the San Antonio relay ramp (Fig. 9) and the general concept of normal fault nucleation and propagation and local stress and extension direction rotation associated with the interaction between offset (en echelon) normal fault segments (e.g., Ferrill et al., 1999; Ferrill and Morris, 2001; Morris et al., 2014)—in this case the stepover of the main-displacement Balcones Escarpment Fault to the Haby Crossing Fault in northwest San Antonio.

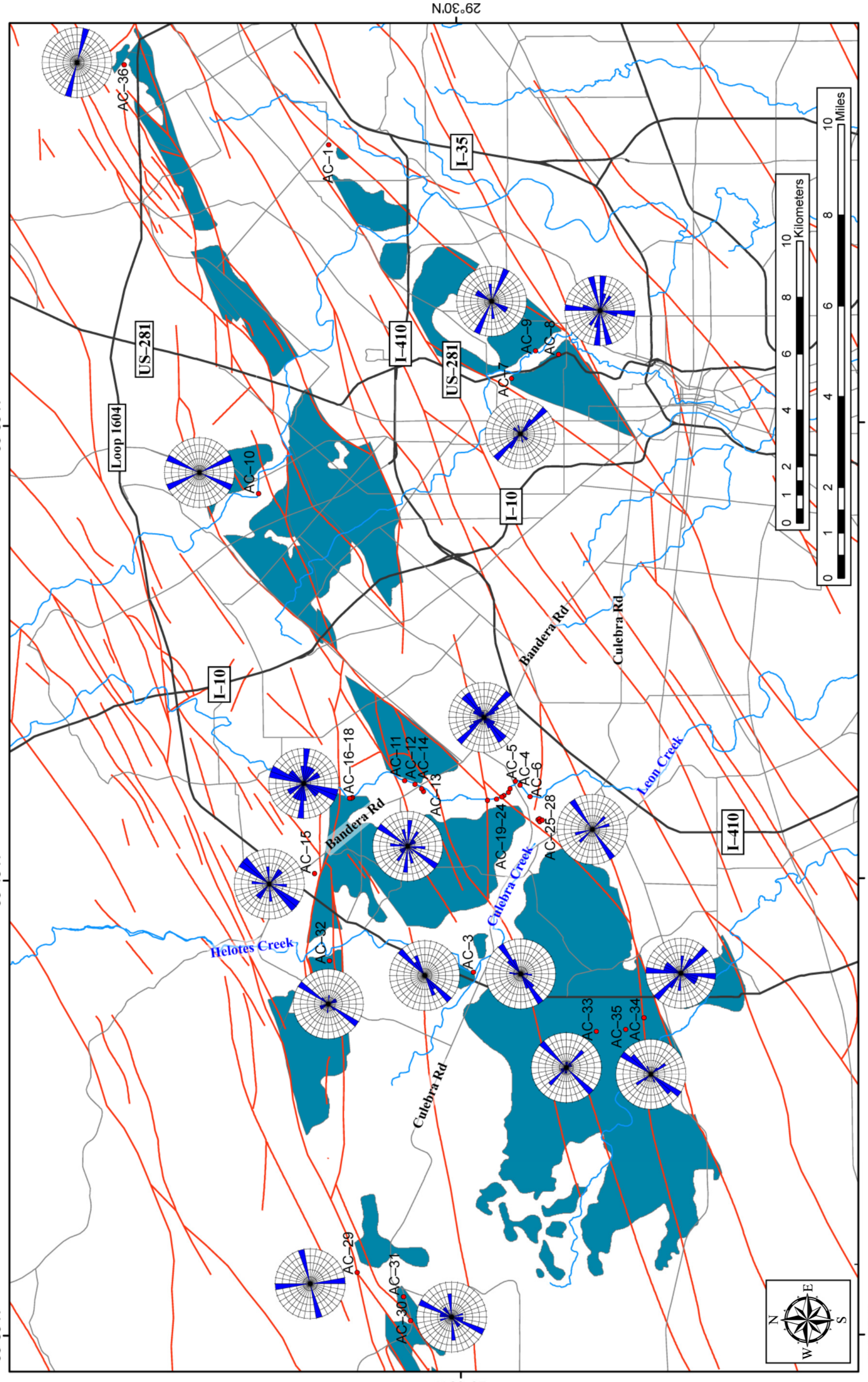


Figure 4. Map with Austin Chalk outcrop (blue shaded area), mapped fault traces (red lines) from the Geologic Map of Texas (Bureau of Economic Geology, 1992), and rose diagrams for extension fractures in this study area.

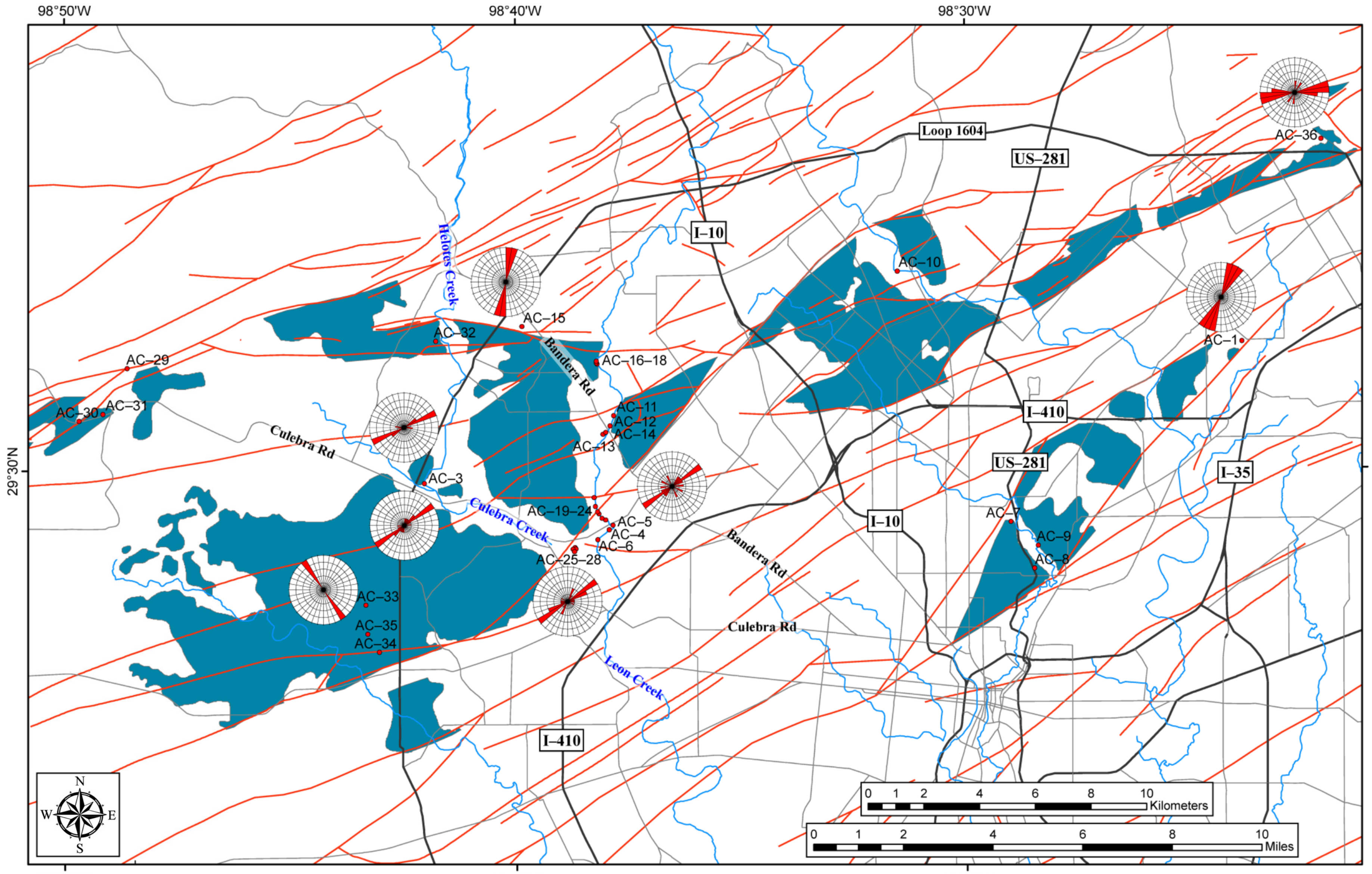


Figure 5. Map with Austin Chalk outcrop (blue shaded area), mapped fault traces (red lines) from the Geologic Map of Texas (Bureau of Economic Geology, 1992), and rose diagrams for faults measured in outcrops within the study area.

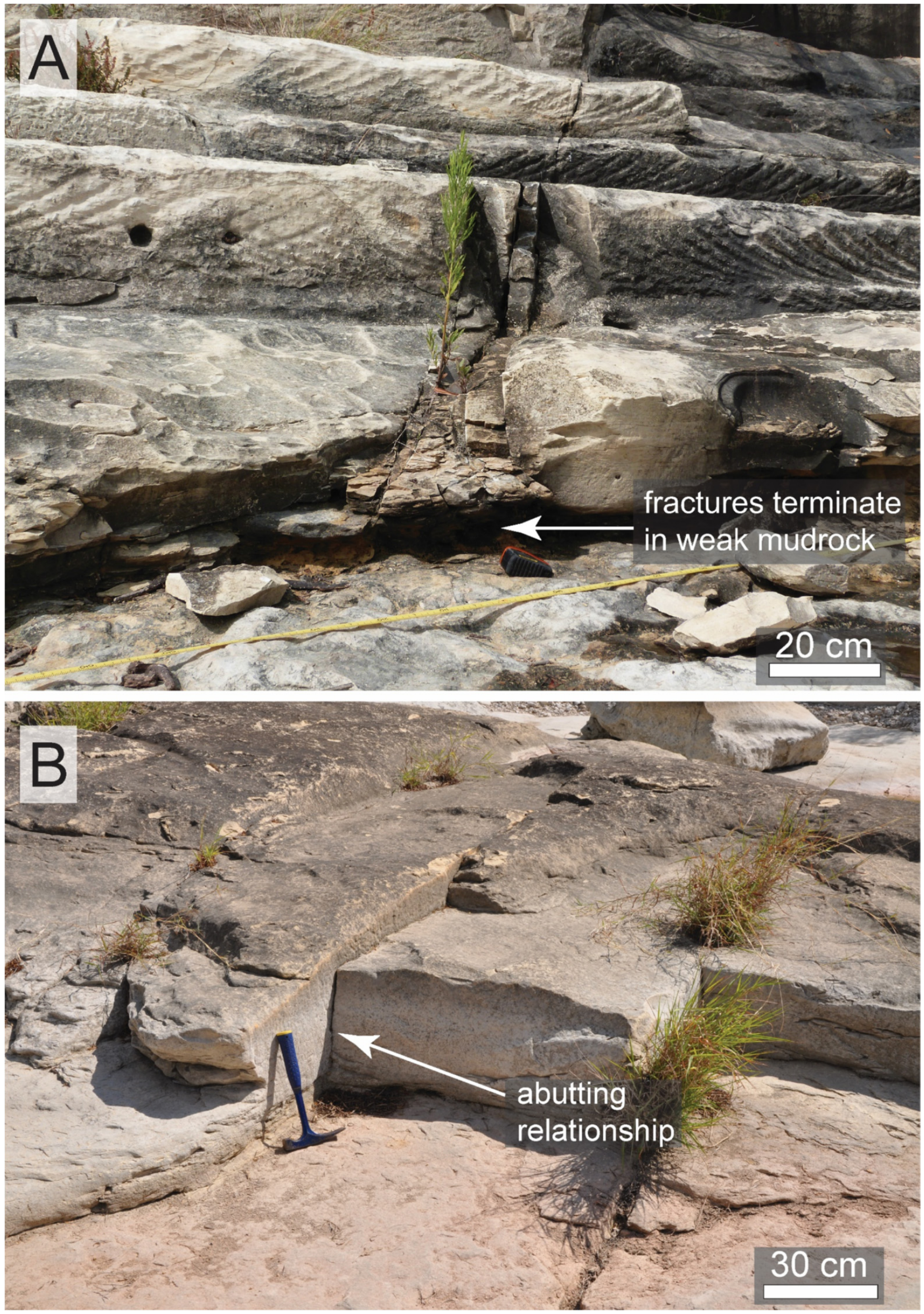


Figure 6. Austin Chalk outcrop photographs illustrating (A) extension fracture in chalk vertically terminating downward into mudrock layer (location AC–3, Culebra Creek), and (B) opening mode joint laterally terminating against earlier formed joint (location AC–22, Leon Creek).

DISCUSSION AND CONCLUSIONS

Investigated outcrops of Austin Chalk in south-central Texas (San Antonio area) are proximal to drilling and production from the Eagle Ford Formation and overlying Austin Chalk, and therefore represent relevant exposures for understanding deformation within the area of exploration and production interest. The structural style of the exposed Austin Chalk in this region is within the Balcones Fault System, which is the updip portion of the Gulf of Mexico marginal fault system, which influences the structural style of the Austin Chalk exploration and production area of South Texas (Bureau of Economic Geology, 1992; Collins, 2000). Results of reconnaissance field investigations in this project documented significant variability in failure modes (tensile versus shear), fracture orientations, fracture intensity (or spacing), and documented that incompetent beds within the Austin Chalk localize fracture terminations and in some cases caused fault (shear fracture) dip change (refraction). Fracture network characteristics are related to mechanical rock properties and structural position. These differences are potentially important factors for hydrocarbon and production from the Austin Chalk, and are particularly important for exploitation of the Austin Chalk as a partially self-sourced reservoir.

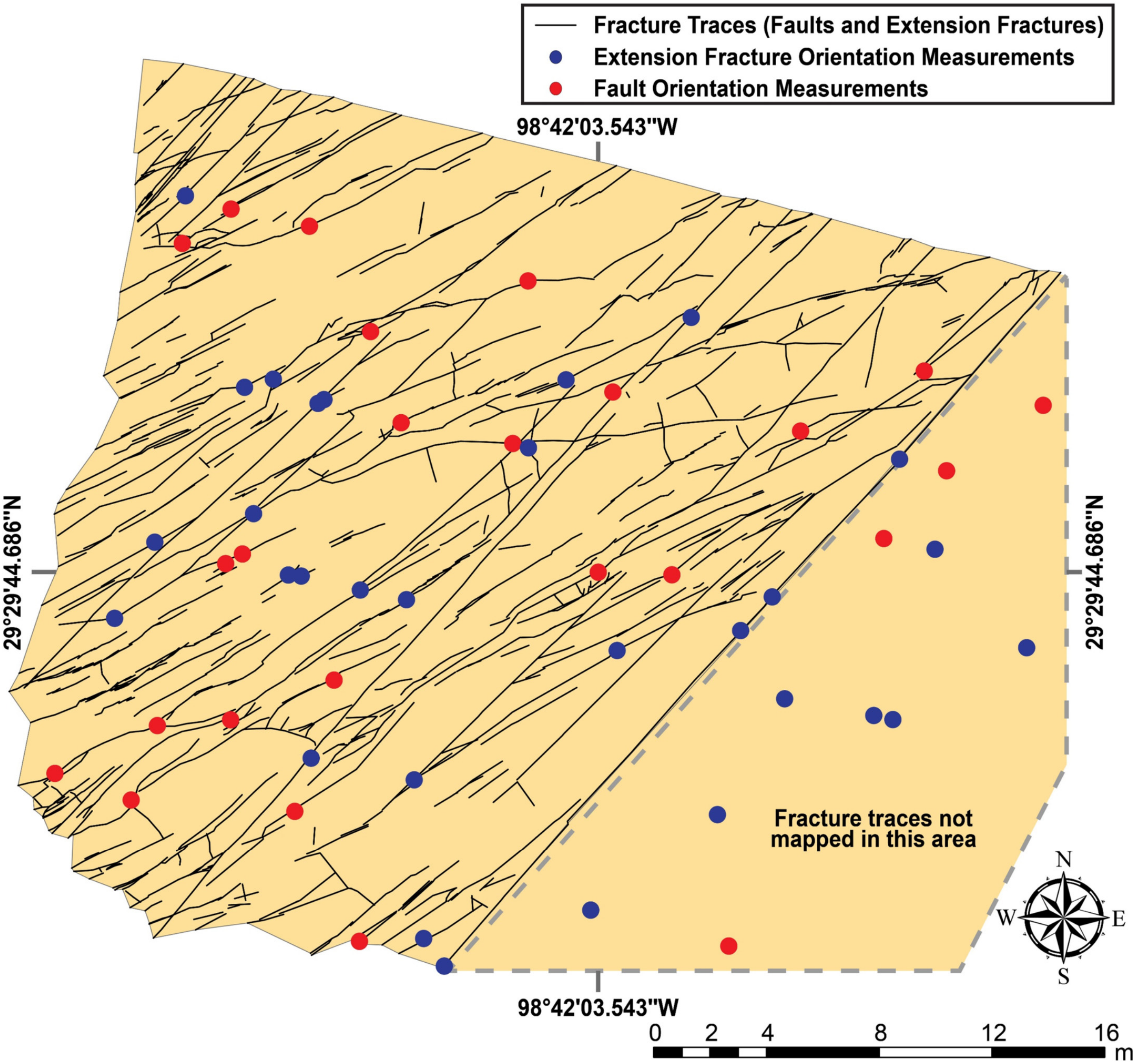


Figure 7. Fracture pavement map from Helotes Creek immediately upstream from the confluence with Culebra Creek with surveyed fracture traces shown as black lines within shaded region, extension fracture measuring locations indicated blue dots, and fault measurement locations indicated by red dots (location AC–3).

ACKNOWLEDGMENTS

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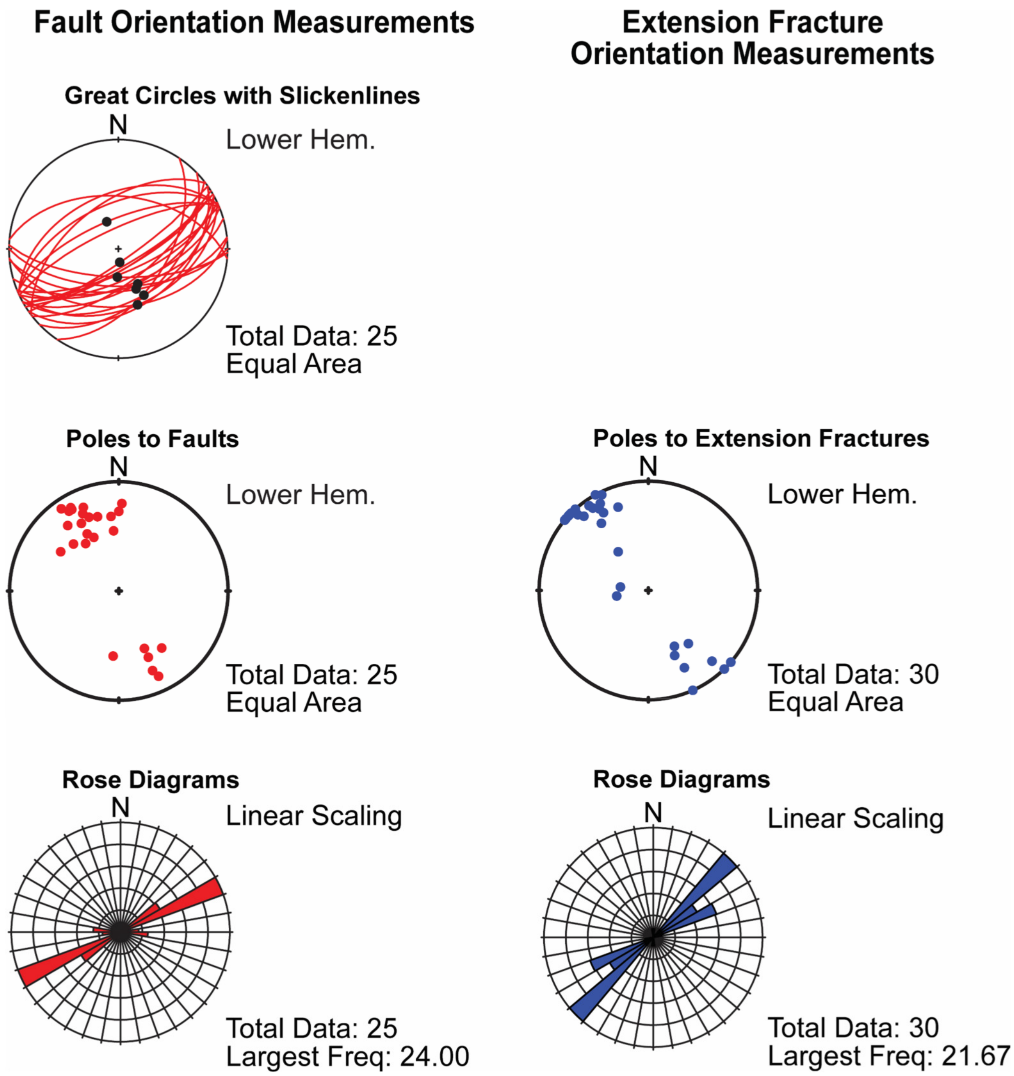

Figure 8. Plots of fault and fracture measurement locations (spot measurements) from fracture pavement area along Helotes Creek (measurement locations in Figure 7) illustrate differences in dominant strike directions between extension fractures and faults, consistent with a change in extension direction (location AC–3).

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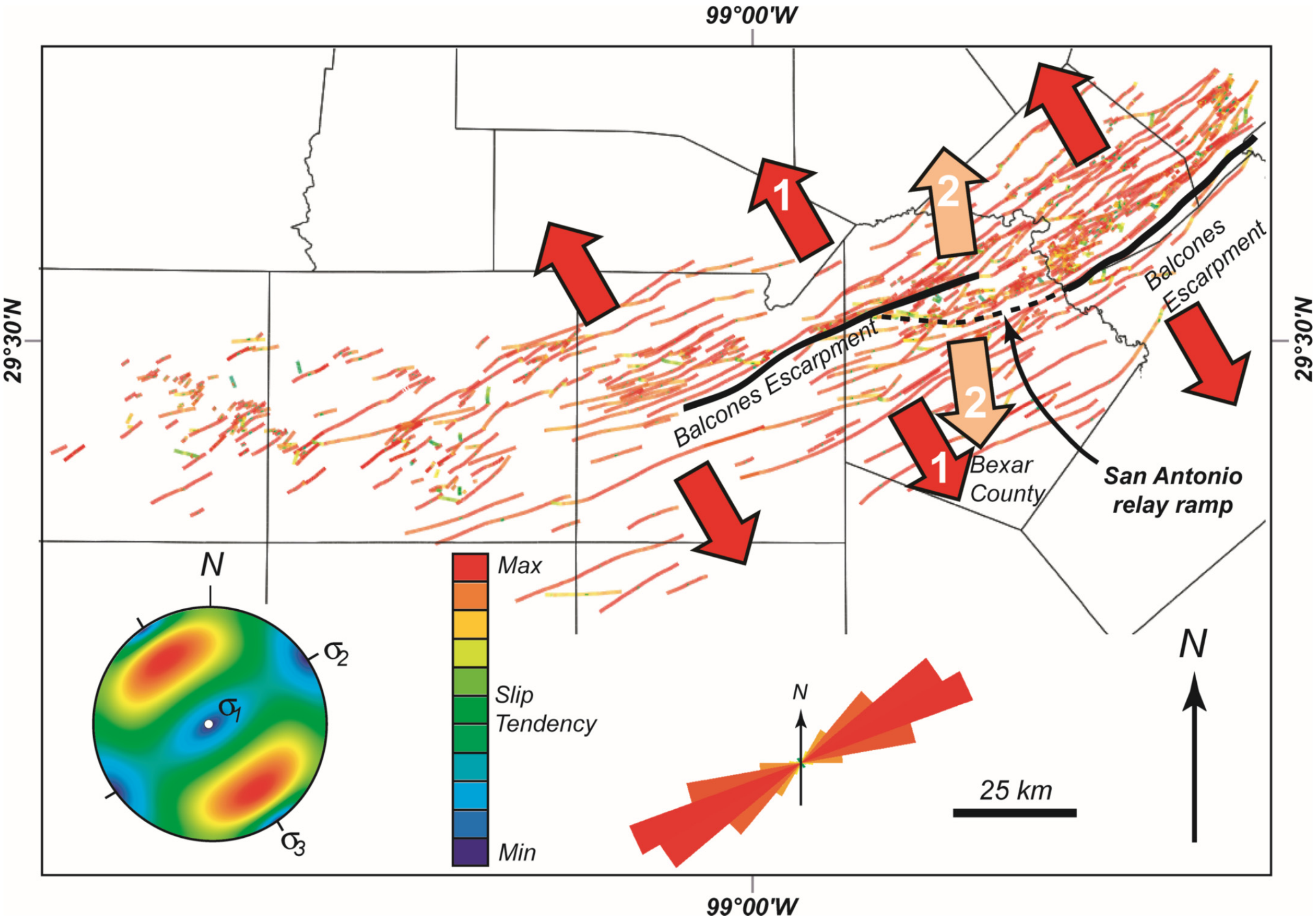

Figure 9. Fault slip tendency map with interpreted Tertiary stress field interpreted to have been active at the time of Balcones Fault System activity from Ferrill et al. (2004). Large red arrows indicate regional extension direction responsible for dominant fault orientations and displacement, and orange arrows (labeled 2) indicate local rotated extension direction associated with development of the San Antonio relay ramp (Collins and Hovorka, 1997; Ferrill et al., 2004; Morris et al., 2014). This locally reoriented extension direction explains the ENE–WSW strike of normal faults in the north San Antonio area, and orientations of some observed extension fracture and normal fault patterns in the study area.

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