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3D Interpretation, Structural Characterization, and Seismogenic Association of Faults in the Eagle Ford Region, South-Central Texas

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ABSTRACT

There is a well-known occurrence of increased felt seismicity and smaller seismic events in areas where oil field operations, such as wastewater disposal and hydraulic fracturing operations occur. The Eagle Ford shale play of south-central Texas has experienced an increase in the rate of felt seismicity from 2014–2019, temporally coincident with petroleum development in the region. By mid–2019, the rate of seismicity decreased alongside the reduction of well completions, thus prompting the drive to better understand the relationship between hydraulic fracturing operations and geologic conditions that contribute to the evolving hazard of this region.

This work aims to map and geomechanically characterize faults that delineate seismogenic regions, such as the Karnes fault zone, and aseismogenic regions of the Eagle Ford. A regional, integrated data set composed of published data, wells, earthquakes, and interpretations from operators provides input for a 3D structural framework. For fault mapping, key stratigraphic intervals have been mapped, fault segments identified from publications were validated and enhanced, 3D fault segment interpretations were integrated, and new faults were interpreted from vertical deviations in horizontal wells. Additionally, centroid moment tensors and well located earthquakes provide insights into earthquakes that are linearly distributed along fault planes and enable identification of active seismogenic faults.

Faulting mapped across the Eagle Ford trend is dominated by NE–SW striking normal faults, regional faults dipping towards the SE, and counter-regional faults dipping towards the NW. At least five locations are identified in the region that connects earthquakes to fault planes. Continued

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analysis will tie these earthquakes to their associated seismogenic structures and then can be assessed for their potential to be reactivated by hydraulic fracturing. Ultimately, this research will analyze how the 3D morphologic and stress state of seismogenic and aseismogenic fault systems relate to earthquakes by determining which faults are more sensitive, which faults have been seismogenic, and the uncertainties of these assessments.

INTRODUCTION

Increased felt seismicity has been observed in areas with unconventional oilfield operation activity, such as production through hydraulic fracturing (HF) operations and the disposal of wastewater (SWD). Recent research has followed the evolving earthquake rates in several oil and gas production and disposal areas of Texas, including the Eagle Ford shale play region of south-central Texas (Fig. 1). Over the time period of 2014–2019, there was an increase in the rate of felt seismicity that closely paralleled the increase in petroleum development that utilized HF (Fasola et al., 2019). The rate of felt seismicity decreased in mid–2019 through 2020 along with a decrease in petroleum development activity. There is a need to understand the spatial and temporal relationship of these earthquakes to HF operations because some of these active areas were not previously seismically active. Although there is research on the relationship between critically stressed faults and their spatial relationship to HF operations and earthquakes, the details of this topic are not fully understood. Therefore, studying the associated geologic conditions and the causal operational factors governing the evolving hazard of this region will support a better understanding of the relationship between HF operations and seismogenic fault reactivation. This understanding can help to guide mitigation recommendations or protocol in areas with similar co-seismic fault reactivation.

The Eagle Ford shale play area has been an extensive oil and gas production area since the 1950s and, significantly, this region has been the location of extensive HF for shale-gas development since around 2008 (Frohlich and Brunt, 2013). Studies in the Eagle Ford including, but not limited to, Fasola et al., 2019 and Frohlich and Brunt, 2013, have demonstrated a higher probability in producing earthquakes and earthquake clusters (notably 1973, 1993, and 2011) in relation to fluid injection compared to fluid withdrawal.

Another factor that adds complexity to this relationship is their proximity to both preexisting and unknown faults. Faults oriented for optimal slip, in a given stress field and located near production and disposal operations, may lead to fault reactivation and may be a cause of HF–induced seismicity (Fasloa et al., 2019). Understanding the spatial relationship, orientation, and in-situ stress conditions near faults in areas with HF operations is key to understanding the evolving hazard of fault reactivation and HF–induced seismicity in oil and gas production areas.

The Eagle Ford shale play area covers a large portion of South Texas, spanning from the Mexico border, northeast across Texas, and south and east of San Antonio (Fig. 1). The Upper Cretaceous Eagle Ford Formation is an organic-rich shale and calcareous mudrock (Ferrill et al., 2017). The Eagle Ford Formation lies in an area with both contractional and extensional faulting, and most faults trend subparallel to the northwest trending Lower Cretaceous shelf edge (Ferrill et al., 2017). The Eagle Ford area is an ideal place to study the relationship between faults, earthquakes, and HF because all three of these factors are evident (Fig. 1).

METHODS

A multidisciplinary data set was compiled to study the impact of hydraulic fracturing and seismogenic fault rupture in the Eagle Ford region of South Texas. The study area covers approximately 21,000 km^2 in south-central Texas with a focus in Gonzales, Wilson, Atascosa, Frio, McMullen, Live Oak, Bee, and DeWitt counties. Faults and key stratigraphic formations were integrated to generate a water-tight 3D structural framework model following the methods out-

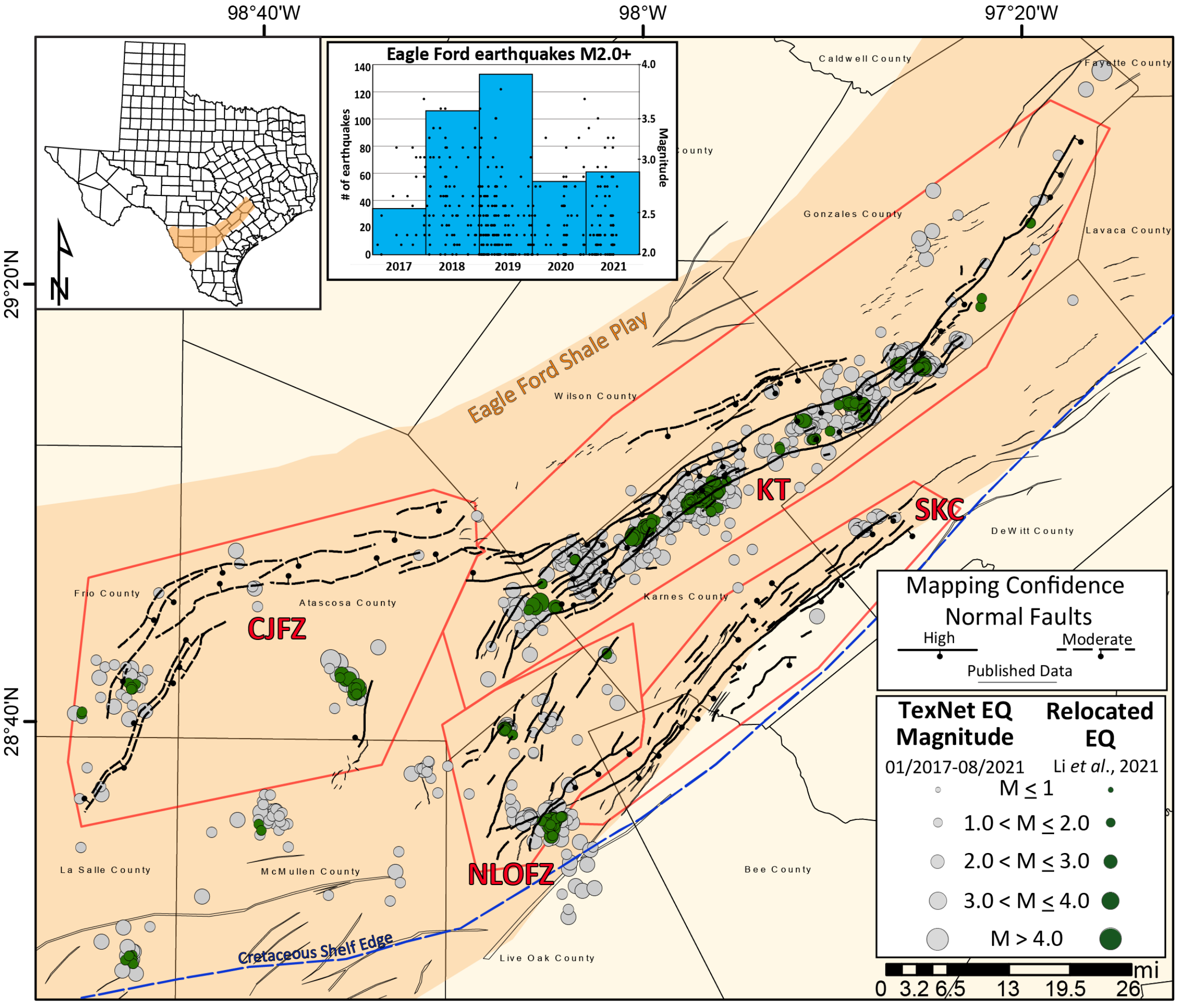

Figure 1. Regional view of Eagle Ford shale play region with faults mapped at the Buda horizon. This map includes the 4 study areas; earthquakes from the TexNet CISR catalog (inset) and relocated earthquakes from Li et al. (2021).

lined by Krantz and Neely (2016) (Fig. 2). Data used to create the model included maps and cross-section interpretations assembled from published literature, formation well tops interpreted by the authors and extracted from Geological Data Services (GDS, now IHS Markit) (IHS Energy, 2009), interpretations from thousands of digital and raster well logs from IHS LogNet, and earthquake hypocentral locations from multiple earthquakes (Li et al., 2021). Additionally, this data set benefited from fault interpretations provided by petroleum operators that were quality controlled by CISR scientists by utilizing 3D seismic data sets.

A high-quality fault interpretation in 3D is a critical element of the more integrated geomechanical analysis. Faults are classified by interpretation confidence based on veracity of data sources (stemming from 3D seismic data, relocated earthquakes, previously published data, formation well tops, etc.). High confidence faults have multiple data sources that validate their geometry while moderate confidence faults are classified by having varying degrees of uncertainty. Faults in the interpretation derived from higher quality inputs provided an analog for estimating the characteristics of faults that rely on constraints of lower quality.

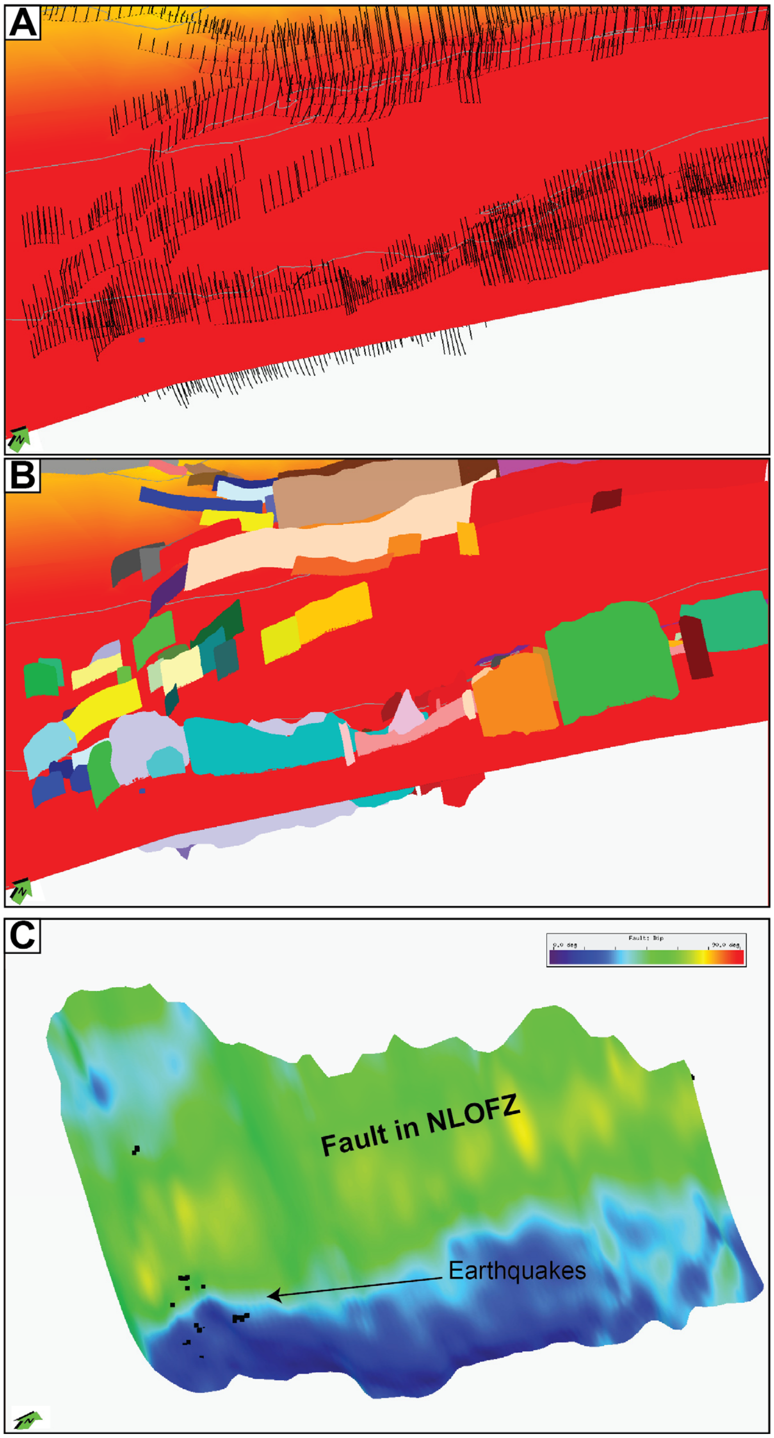

Figure 2. Fault interpretation and structural framework methodology following Krantz and Neely (2016) showing (A) view looking northwest with fault sticks intersecting Buda horizon (grey contours: 2500 ft); (B) same view from (A) but showing fault surfaces; and (C) zoom-in of a seismogenic fault located in the NLOFZ. Fault is colored by fault dip.

The density of horizontal wells (>13,000) in the Eagle Ford allowed for specialized horizontal well deviation fault mapping described in the landing zone interpretation methodology of Dommisse (2013) (Fig. 3). Specifically, faults picked using horizontal well deviations use the change in vertical deviation to locate faults. Wells are drilled updip and/or downdip from the heel to avoid or purposefully choose landing zones or structures in the subsurface. The regional dip of the Buda Formation was subtracted out of the well orientations to define smaller unmapped changes in these deviations.

In this geologic setting, earthquakes occur on existing faults and can therefore assist with fault interpretation. Earthquakes from the TexNet web catalog, 2017 to present, were used, along with the results of Li et al. (2021) to map seismogenic faults (Fig. 3). Li et al. (2021) employed the widely-used hypoDD earthquake relocation technique and describe the method. In contrast to the TexNet web catalog, where earthquakes are in broad, diffuse clusters, the work of Li et al. (2021) results form tight clusters and delineate specific faults or fault zones. These

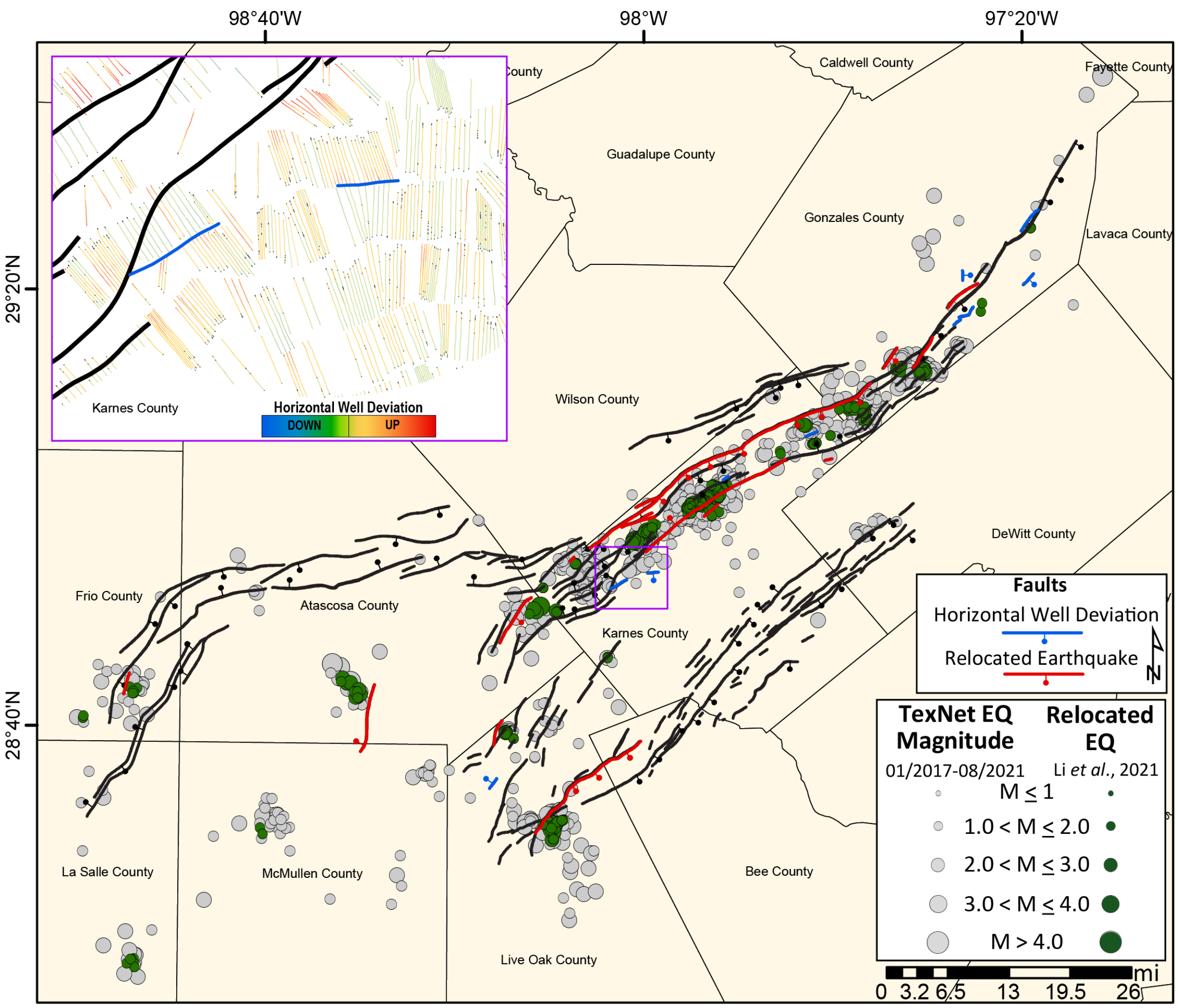

Figure 3. Map with 17 relocated earthquake faults (seismogenic) and 11 faults picked from horizontal wells. Inset shows the deviation (colored) from the heel of the horizontal well.

relocated events help to better define the Karnes Fault Zone (Karnes Trough [KT]), Charlotte-Jourdanton Fault Zone (CJFZ), and Northern Live Oak Fault Zone (NLOFZ) (Figs. 1 and 3).

RESULTS

A total of 169 normal faults are mapped in the Eagle Ford region and 71% are classified with high confidence (Fig. 1; Table 1). Total trace-length of mapped faults at the Buda horizon is ~1107 km and the mean fault length is 6 km. Generally, faults in the Eagle Ford region follow the regional trend of NE–SW strike (parallel to shelf margin and coastline) and 62% of faults dip towards the coast (SE). A majority of faults (82%) cut through Lower Cretaceous strata and extend to unconstrained depths, and 16% of faults are interpreted to extend shallower than the Carrizo/Wilcox formation. For analysis purposes, the faults are split into 4 areas of interest (AOI) based on regional location: KT, CJFZ, NLOFZ, and Southern Karnes County (SKC).

75 faults are mapped in the KT AOI (Atascosa, Wilson, Karnes, and Gonzalez counties), of which 61% are mapped with high confidence. Faults in KT have a mean length of 7 km. The mean strike for these faults is 058°. These faults dip from 15° to 81° and the mean dip is 51°. 60% of faults dip toward the southeast direction while 40% dip toward the northwest. The mean fault throw at the Buda horizon is 167 ft, with a maximum of 901 ft.

15 faults are mapped in CJFZ, of which 7% are mapped with high confidence. The mean fault length is 16 km. Similar to KT, faults in CJFZ have a mean strike of 058°. However, faults in the CJFZ display slight rotation in strike. Faults in westernmost CJFZ (La Salle and Frio counties) follow a regional subordinate NNE–SSW strike and CJFZ faults to the east (Atascosa County) rotate to the regional dominant NE–SW strike. The faults range in dip from 20° to 76° and have a mean of 58°. 53% of faults dip toward the northwest while 47% dip toward the southeast. The mean fault throw at the Buda horizon is 217 ft, the maximum is 711 ft.

30 faults were mapped in the NLOFZ (Live Oak, Bee, and Karnes counties), of which 80% are mapped with high confidence. The mean length of faults in NLOFZ is 4 km, which is less than the length of faults in KT and CJFZ. The mean strike of these faults is 050°. Faults in the NLOFZ display rotated strike similar to faults in the CJFZ: subordinate NNE–SSW striking faults in northern Live Oak County and dominant NE–SW striking faults to the south in central Live Oak and northern Bee counties. Fault dips range from 11° to 79° and the mean dip is 49°. 90% of NLOFZ dip toward the southeast. Mean throw at the Buda horizon is 145 ft and the maximum is 983 ft.

49 faults were mapped in the SKC region that lies in Live Oak, Bee, Karnes, and DeWitt counties; significantly, 100% of faults are mapped as high confidence segments. The mean fault length of the SKC faults is similar to those in NLOFZ at 4 km. Mean fault strike is 056°. Fault dip ranges from 25° to 70° and similarly to the KT faults, the mean dip is 51°. The mean fault throw is 80 ft, and the maximum is 288 ft.

From the 6 relocated earthquake sequences in the Eagle Ford region, 17 faults are interpreted as seismogenic (Figs. 2c and 3). Specifically, 2 are mapped in CJFZ, 13 are mapped in KT and 2 are mapped in NLOFZ. Generally, seismogenic faults follow the regional orientation

Table 1. Table of fault statistics.

Region	# of fault segments	Strike	Dip	Length (km)		Throw (ft)		Confidence	
		deg	deg	Average	Max	Average	Max	High	Low
CJFZ	15	058	58	16	33	217	711	1	14
KT	75	058	51	7	34	167	901	46	29
NLOFZ	30	050	49	4	24	121	977	24	6
SKC	49	056	51	4	36	80	288	49	0

trends and have a mean strike of 053°, a mean dip of 49°, and the majority (76%) of faults dip towards the coast (SE). Mean fault length of these faults is 9 km.

SUMMARY AND CONCLUSIONS

Overall, faults in the mapped region follow the regional trends expected in the Eagle Ford shale play, and significantly, there are several locations with active seismogenic faults. This has implications for fault reactivation and might indicate increased hazard in the seismically active regions. Seismogenic faults in proximity to such dense HF wells suggests further research is needed to better understand how changes in stress and pore pressure might cause new or previously unmapped faults to rupture. This research provides the foundation for further investigation into the spatiotemporal HF and earthquake relationships (injection induced earthquakes) in this region. Furthermore, analyzing the in-situ stress conditions, their relation to sensitive faults and earthquakes is key to understanding the evolving hazard in this region.

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