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Location and Felt Reports for the 25 April 2010 m_{bLg} 3.9 Earthquake near Alice, Texas: Was it Induced by Petroleum Production?

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Abstract This study examines seismograms and felt reports for the 25 April 2010 Alice, Texas, earthquake and explores its possible relationship with gas and oil production in the Stratton field. We identified *P* arrivals at seven broadband stations situated within ~100 km of the epicentral region and determined a location of 27.72° N, 97.95° W, about 11 km east of the location reported by the National Earthquake Information Center but coincident with the region of highest intensity (modified Mercalli intensity V–VI) felt reports. We compare arrivals for observed secondary *P* and *S* arrivals with predictions from a published Gulf Coast velocity model. At nearby stations, the secondary arrivals are much stronger than primary arrivals; the arrival times and the presence of high-amplitude phases traveling at the Love-wave velocity of the uppermost model layer suggest the focal depth was shallow, 3 km or less. This places the 2010 hypocenter approximately along the mapped trace of the Vicksburg fault zone and at the depth of the Frio formation, the principal productive member in the Stratton field, which has produced at least 2.7 trillion cubic feet of gas and about 100 million barrels of oil since production commenced in 1938. We conclude it is plausible, although not proven definitively, that production in the Stratton field contributed to the occurrence of the 2010 Alice earthquake and an earlier similar earthquake that occurred on 24 March 1997.

Introduction

On 25 April 2010 at 2:10 UTC (Saturday evening, 8:10 p.m. local time), a felt earthquake occurred near Alice, Texas (Fig. 1), a community about 75 km west of Corpus Christi. The National Earthquake Information Center (NEIC) determined the epicenter as 27.71° N, 97.85° W (20 km east of Alice; see Table 1) and the magnitude as m_{bLg} 3.9. Earthquakes are highly unusual in this part of south Texas. The only previous earthquake cataloged here occurred on 24 March 1997; this m_{bLg} 3.8 earthquake was also felt in and near Alice (Bilich *et al.* 1998), although its U.S. Geological Survey (USGS)-determined epicenter lay approximately 20 km west of the USGS epicenter for the 2010 event.

There are several highly productive gas and oil fields within the felt areas of the Alice earthquakes, and we will consider the possibility that petroleum production induced these events. The first section of this paper presents results from a felt-report survey for the 2010 earthquake; the second section analyzes seismograms recorded by several nearby EarthScope Transportable Array stations and determines a more accurate epicenter for it. The third section compares the 2010 results with the Bilich *et al.* (1998) analysis of the 1997 earthquake and clears up several puzzles about the earlier event: our analysis suggests that both earthquakes had nearly identical epicenters, and these epicenters coincided with the region of highest Mercalli intensities for both events. The fourth section summarizes regional geology and the history of petroleum production near the epicentral region. Finally, in the discussion section we address whether it is plausible that petroleum production in the nearby Stratton field induced the Alice earthquakes.

Felt Reports from the 2010 Alice Earthquake

In December 2010 one of this paper's authors (M. B.) visited the Alice area and interviewed numerous local residents about their experiences during the April 2010 earthquake. He also visited or made telephone calls to local police and sheriff's departments and to individuals who had contributed felt reports to the Bilich *et al.* (1998) study of the 1997 Alice quake.

These investigations indicate the total felt area of the 2010 earthquake was approximately 1350 km^2 (Fig. 2). Throughout much of this region the felt reports were consistent with modified Mercalli intensities (MMI) of III. Typical reports included feeling a dizzy sensation, items on tables or walls shaking and rattling, hanging items swaying, and/or hearing the sound of a faint explosion. People interviewed

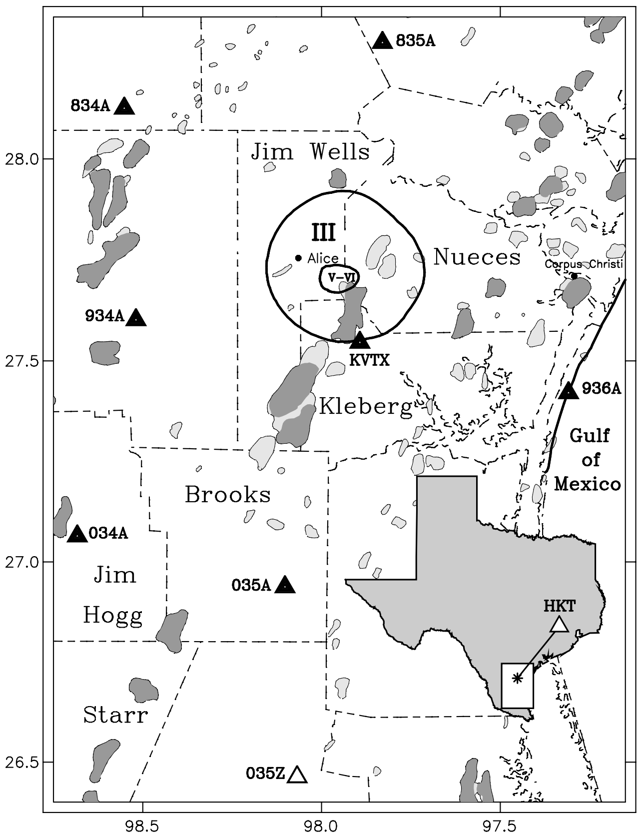

Figure 1. Map of the Alice, Texas, region. Areas labeled III and V–VI indicate modified Mercalli intensities (MMI) reported for the 25 April 2010 earthquake (see Fig. 2). Locations of major oil fields (dark shaded areas) and gas fields (light shaded areas) are from Galloway *et al.* (1983) and Kosters *et al.* (1989). Triangles show locations of broadband seismograph stations that recorded the 2010 earthquake, with filled triangles indicating stations used to determine the preferred location in Table 1. The geographic extent of the area mapped, location of seismic station HKT, and the ray path from 2010 epicenter to HKT are indicated on the outline of Texas at the lower right.

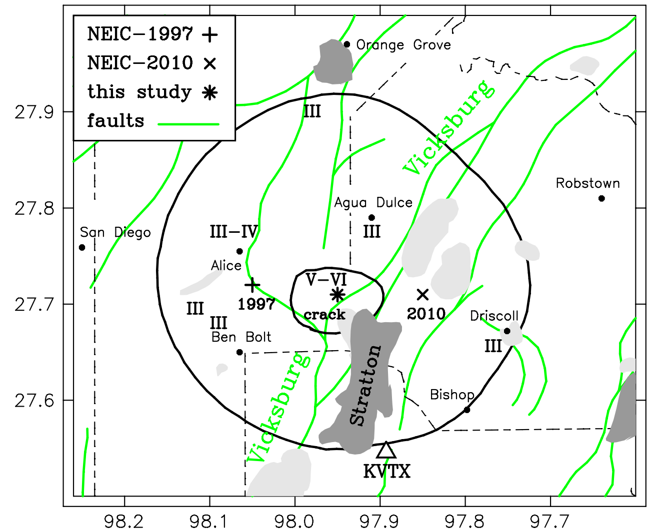

Figure 2. Felt reports for the 25 April 2010 Alice earthquake. Labels of MMI levels III and III–IV indicate locations where individuals provided felt information. Three individuals within the MMI V–VI isoseismal region reported experiencing MMI V or VI during the 2010 earthquake. Location labeled "crack" indicates the reported location of a mile-long northeast–southwest crack following 1997 earthquake (see text). The symbols +, X, and *, respectively, indicate the NEIC epicenters for the 1997 and 2010 earthquakes and the location determined in this study (Table 1). Mapped faults are from Ewing (1990). The color version of this figure is available only in the electronic edition.

in the towns of San Diego, Orange Grove, Robstown, and Bishop did not report feeling the earthquake.

The highest intensities, corresponding to MMI V or VI, occurred within an approximately 65-km^2 sparsely populated region about 10–15 km southeast of Alice:

- *Respondent KC:* A hanging light swayed back and forth so forcefully it touched the ceiling. The entire house shook, and there was a loud rumbling sound, like a large airplane flying very low overhead. Two children, ages 4 and 5, became frightened. Knick-knacks and pictures fell and broke. There was a loud humming noise coming from a vibrating well pipe that extends about 25 m into the ground.
- *Respondents TB and WB*: Cabinet doors swung open. Deer head mounts on the east wall all shifted in the same direction toward the north. A 50 gal aquarium on the north wall had water splashed on the floor all around it, with more water on the east side.
- *Respondents KH and JH:* Objects fell from shelves and furniture moved about. Bushes and trees rattled. Shaking lasted about 2–3 s and frightened members of the household.
- *Respondents BD and JD:* A man sleeping in a recliner was awakened, and he thought an airplane had hit the house. Pictures fell off the walls, and the whole house shook for about 5 s.

Table 1
Earthquakes Discussed in This Paper

Date (yyyy/mm/dd)	Time (hh:mm:ss.ss in UTC)	Latitude (° N)	Longitude (° W)	Depth	m_{bLg}	MMI Maximum
NEIC Locations						
1997/03/24	22:31:34.56	27.72	98.05	5	3.8	V
2010/04/25	02:10:42.77	27.71	97.85	5	3.9	III
This Study's Preferred Hypocenters						
1997/03/24	22:31:31.4	27.72	97.95	1.5	3.8	V–VI
2010/04/25	02:10:39.9	27.72	97.95	1.5	3.9	V–VI

Location of the 2010 Alice Earthquake

Fortuitously, the 2010 Alice earthquake occurred when the EarthScope Transportable Array was in Texas, and thus seven broadband stations within about 1° of the reported epicenter recorded it. Unfortunately, these records do not look like regional seismograms in textbooks, which possess impulsive *P* and *S* arrivals having large amplitudes followed by smaller-amplitude codas. Instead, records of the Alice earthquake typically exhibit several distinct phases having different frequencies, with these often being preceded by one or more smaller, sometimes barely identifiable arrivals. Especially for *S* phases, this made it difficult to identify the earliest arrivals with confidence. The unusual character of the Alice records may come about because the crustal structure along the Gulf Coast, with 10–15 km of sediments overlying basement (e.g., Mickus *et al.*, 2009), is markedly different than in most continental regions (Peel *et al.*, 1994).

We thus located the 2010 earthquake using only *P* arrivals and the four-layers-over-a-half-space crustal model (Keller and Shurbet, 1975; see Table 2) developed specifically for this region along the Gulf Coast. To minimize systematic mislocation caused by model errors or by regional variations in crustal structure, we used only seven stations: the closest station KVTX, and six EarthScope stations surrounding the epicenter, all within 1°. With these data, the epicenter determined using a standard iterated least-squares procedure was 27.72° N, 97.95° W (root mean square [rms] residual = 0.25 s; gap = 107°). This lies near the center of the MMI V–VI isoseismal region (Fig. 2) and is 11 km west of the NEIC-determined epicenter.

For this epicentral location, inspection of the waveforms suggests that the plethora of arrivals that we had difficulty identifying correspond to refracted waves traveling in the various layers in the Keller–Shurbet crustal model (Table 2). Thus, the large vertical (*Z*)-component arrivals at about 9 s at stations KVTX and 65 s at 035Z correspond to *P* waves traveling in the topmost layer 1 (Fig. 3a); earlier, smaller arrivals at KVTX correspond to waves traveling in layers 2 and 3 (Figs. 3a and 4); still earlier arrivals at 035Z correspond to deeper layers. For north-component data (Fig. 3b), model predictions for *S* arrivals also indicate that many of the larger arrivals correspond to waves traveling in layers as predicted by the Keller–Shurbet model.

Table 2

Crustal Model 3 (Keller and Shurbet, 1975), Used in This Paper for Locating Earthquakes

Layer	*P* Velocity (km/s)	*S* Velocity (km/s)	Thickness (km)
1	2.2	1.27	3.0
2	3.8	2.19	6.0
3	5.3	3.06	9.0
4	6.5	3.58	13.5
half-space	7.8	4.43	-

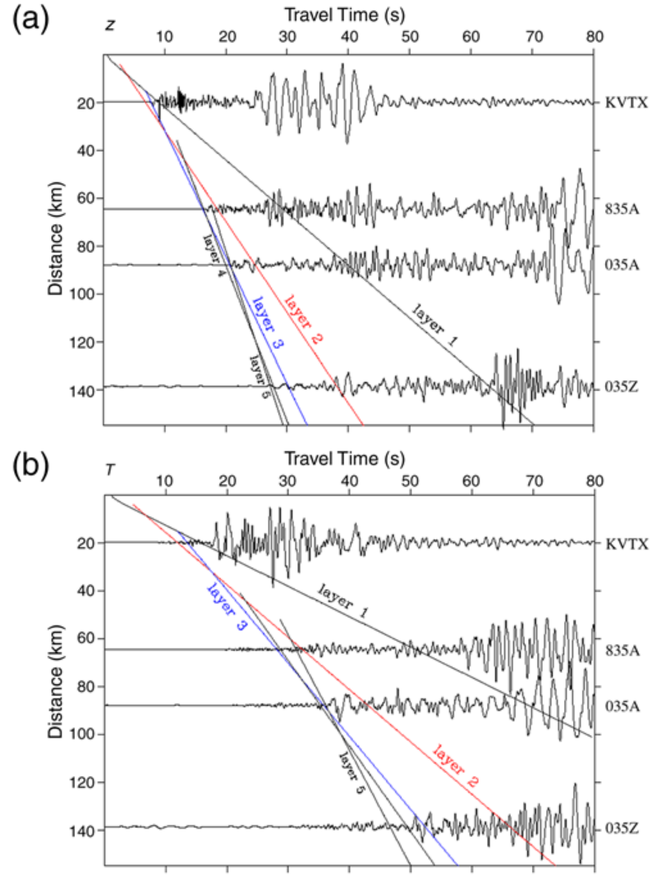

Figure 3. Record section of (a) *Z*-component arrivals and (b) transverse-component arrivals for the 2010 Alice earthquake for stations along a north–south transect approximately parallel to the coast of the Gulf of Mexico. For a source at 27.72° N, 97.95° W, and 1.5-km depth, lines indicate predicted *P*- and *S*-arrival times for phases traveling in each layer of crustal model 3 (Keller and Shurbet, 1975), determined using a tripartite array of stations surrounding the Alice epicenters. Note that initial *P* arrivals are weak at most stations, with subsequent stronger arrivals coinciding approximately with predicted later-arriving phases. The color version of this figure is available only in the electronic edition.

This analysis also suggests that the focal depth is shallow. Unless the focus lies within the lowest-velocity model layer and is thus 3 km or less, one would not observe arrivals corresponding to seismic waves traveling in layer 1.

Comparing the 1997 and 2010 Earthquakes

Seismograms at Hockley, Texas

The seismic station at Hockley, Texas (HKT; $\Delta = 2.90°$), was the closest station to record both the 1997 and 2010 earthquakes and the closest station anywhere recording the 1997 event. Although the HKT east-component seismograph was malfunctioning during the 2010 event, broadband *Z*- and north-component records for the 1997 and 2010 earthquakes are virtually identical, with peaks, troughs, and amplitudes of waveforms for the two events

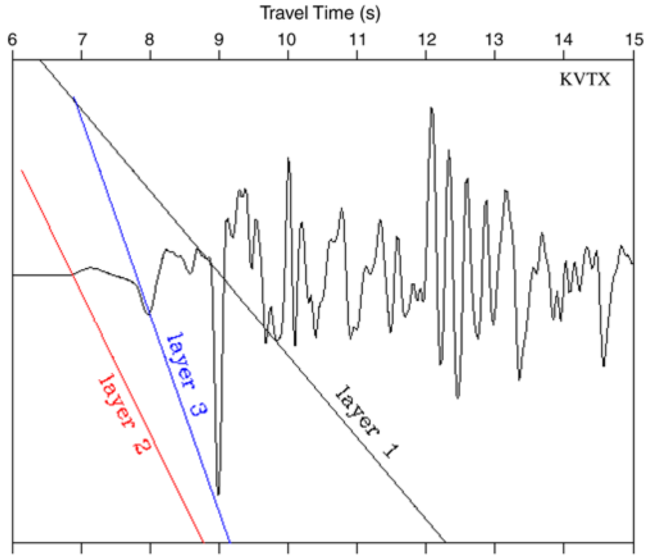

Figure 4. The *Z*-component arrival at Kingsville, Texas (KVTX, $\Delta = 19.8$ km). Lines indicate predicted *P* arrivals using the crustal model 3 (Keller and Shurbet, 1975; see Table 2) for a hypocenter at 27.72° N, 97.95° W, and depth 1.5 km. The first arrival corresponds to a weak phase traveling in layer 2, whereas the later, stronger arrivals are from phases in layers 3 and 1. The presence of strong phases at stations KVTX, 835A, and 035Z at times consistent with a path in layer 1 suggest a shallow hypocenter occurring within layer 1. The color version of this figure is available only in the electronic edition.

matching for nearly ten minutes following the *P* arrival at ~53 s after the origin (Figs. 5 and 6).

The sizes of the 1997 and 2010 earthquakes are approximately the same. Their USGS-reported m_{bLg} magnitudes (3.8

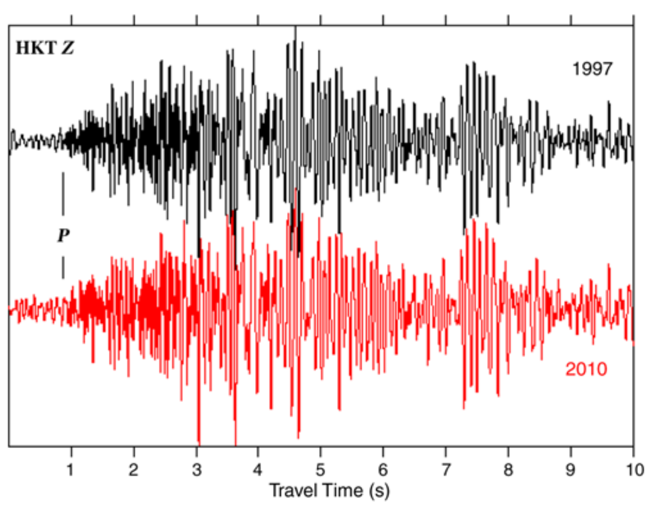

Figure 5. Vertical (*Z*) component seismograms for the 1997 and 2010 Alice earthquakes recorded at Hockley, Texas (HKT; $\Delta = 2.90°$), the closest station to record both events. The plotted records have been high-pass filtered with a corner at 10 s. Note that the *P* arrival is emergent and that there is considerable energy arriving with travel times exceeding 5.5 min (i.e., with speeds slower than ~1.0 km/s). The color version of this figure is available only in the electronic edition.

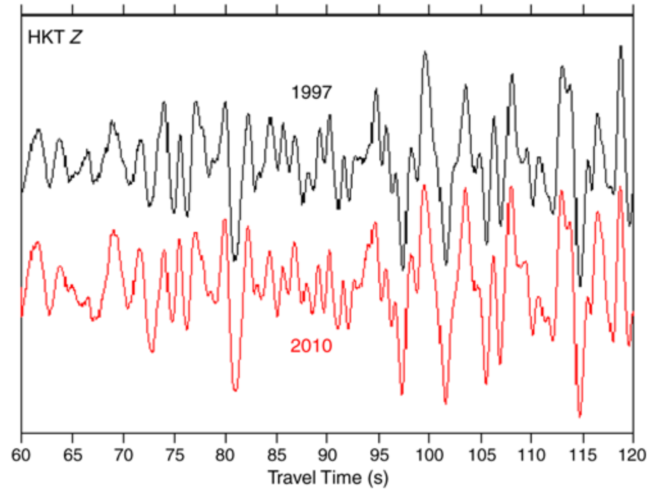

Figure 6. Detailed comparison of waveforms recorded at HKT for the 1997 and 2010 Alice earthquakes. Here, the plotted sample is the *Z*-component record for travel times of 60–120 s, which includes the coda of *P* and expected arrival time of *S*. For both *Z*- and north-component records, this and similar comparisons demonstrate that the waveforms are virtually identical for travel times of 55–500 s or greater, thus suggesting that the 1997 and 2010 earthquakes originated from the same or nearly the same hypocenter. The east-component seismograph at HKT was not working at time of 2010 earthquake. The color version of this figure is available only in the electronic edition.

and 3.9) are virtually identical, and at HKT their maximum peak-to-peak amplitudes on the *Z* and north components agree within a few percent, with the 1997 earthquake slightly larger on *Z* and the 2010 slightly larger on the north.

On the 1997 HKT seismogram there was a large and puzzling arrival observed on the transverse component (Fig. 7; also see Bilich *et al.*, 1998). This phase, the largest on any component, consists of 10 cycles having a predominant period of ~6.0 s.

We interpret this phase as an S_H wave trapped in the uppermost sedimentary layer. If β_1 and β_2 are the shear velocity in the two uppermost layers, S_H waves will propagate as trapped waves (Love waves) within the upper layer if the phase velocity V_{phase} for S_H waves with angle of incidence θ satisfies the equation

$$V_{\mathrm{phase}} = \beta_1 / \sin\theta < \beta_2. \quad (1)$$

That is, the velocity V_{phase} of wave fronts travelling along the boundary is less than the shear velocity in the second layer, and thus there is total reflection at the boundary. However, energy in the wave travels horizontally more slowly than β_1 and depends on angle of incidence θ; so the group velocity V_{group} for the trapped wave is

$$V_{\mathrm{group}} = \beta_1 \sin\theta. \quad (2)$$

Therefore, eliminating θ in equation (1) gives the condition allowing a trapped wave to occur as

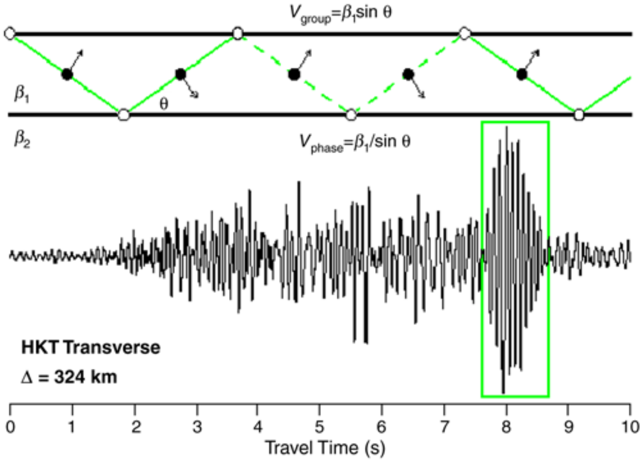

Figure 7. Surface-layer Love wave at HKT. For the 1997 Alice earthquake, the largest phase at HKT (indicated with a box) is transversely polarized and has a travel time of about 7.5 min (453 s), or a group velocity of about 0.7 km/s. S_H wave fronts with angles of incidence θ in a surface layer with velocity β_1 can be trapped as a Love wave if wave fronts interfere constructively and their phase velocity $\beta_1/\sin\theta$ is less than the shear velocity β_2 in the next layer. In the figure, the change from solid to dashed lines at the free surface indicates that the phase reverses upon reflection there. The phase velocity corresponds to the motion of the open circles along the boundaries; energy in the wave fronts travels along ray paths in the direction of the arrows and thus the group velocity parallel to the surface is $\beta_1 \sin\theta$. We interpret the phase in the box as a trapped wave in a surface layer. This is consistent with the hypothesis that along the Alice–HKT path (see Fig. 1) there is a thick sedimentary layer with low shear velocities ($\beta_1 \sim 1.2$ km/s) and suggests the Alice earthquake had a shallow focal depth within this layer. The color version of this figure is available only in the electronic edition.

$$\beta_1 < (\beta_2 V_{group})^{1/2}. \quad (3)$$

The phase of S_H waves reverses as they are reflected at the free surface. Thus wave fronts will interfere constructively when their wavelength λ, the distance along the boundary between successive wave fronts having the same orientation and phase, is

$$\lambda = 4L/\tan\theta, \quad (4)$$

where L is the layer thickness. This will occur when the period T is

$$T = \lambda/V_{phase} = 4L\cos\theta/\beta_1. \quad (5)$$

HKT lies 322 km from Alice, and the phase marked in Figure 7 begins ~453 s following the origin; this corresponds to an unusually low group velocity V_{group} of 0.71 km/s. For the Keller–Shurbet model (Table 2), β_2 is 2.19 km/s; equation (3) thus gives $\beta_1 < 1.25$ km/s. This is almost identical to Keller–Shurbet's β_1 of 1.27 km/s. Moreover, if we use this group velocity and Keller–Shurbet's β_1 to find θ using equation (2) and use a top-layer thickness L of 3.0 km, equation (5) gives the period T as 7.8 s, which is slightly greater than the 6.0 s observed for the marked phase in Figure 7.

The large amplitude of the large phase in Figure 7 supports the assertion that the 1997 earthquake had a shallow focal depth within the uppermost layer. For flat-layered crustal models, very little S_H energy from sources below the uppermost layer boundary will enter the wave guide and propagate as trapped waves. Thus the presence of this large transverse phase suggests there is a shallow sedimentary layer along the Alice–HKT Gulf Coast path, and this layer has a shear velocity contrast with respect to deeper layers similar to that in the Keller–Shurbet model.

Felt Reports

For the 1997 and 2010 earthquakes, the locations and geographic extent of their MMI III and MMI V–VI felt areas are highly similar (compare Fig. 2 in this paper and fig. 3 in Bilich *et al.*, 1998). Although the mapped 2010 isoseismals are marginally larger, the differences are within the uncertainties of the felt-report surveys.

The MMI V–VI felt region is sparsely populated, and all but one of the 2010 respondents also reported experiencing the 1997 Alice earthquake. In addition, two of these individuals provided felt-report information concerning the 1997 earthquake that was not incorporated in Bilich *et al.* (1998):

- *Respondent WB:* The 1997 earthquake damaged the concrete foundation of WB's barn and shifted the entire structure to the north. Shortly after the earthquake, he noticed an approximately one-mile-long crack extending southwest to northeast in fields about 2.5 km south of his residence (crack location: 27.69° N, 97.97° W). He estimated the crack's widest point to be approximately 6 inches; he attempted to measure the depth of the crack but was unsuccessful because it was too deep. WG noted that he had farmed this land his entire life and this crack, one long continuous feature, was unlike cracks caused by the drying up of the ground due to lack of water, which tend to form a polygonal pattern.
- *Respondent JC:* An e-mail from JC stated that "The quake back in the spring of 1997 was the worst I have ever experienced. It was two parts. First I thought a plane had crashed on the roof as the house seemed to drop. Then across the room, about 30 feet, I saw things begin to fall from shelves and then a wave went under my feet and things fell and cabinets flew open. This quake caused cracks in our brick wall and sent cracks through cement walks everywhere." JC also recalled that some time after the 1997 earthquake, they pulled up the floor carpet to install tiles and realized that the tremors did more damage than first thought because the floor foundation had cracks.

Locations

The observation that the 1997 and 2010 earthquakes produced nearly identical seismograms at HKT (Figs. 5 and 6) suggests that both earthquakes originated from the same or almost the same hypocenter. This is also supported by the fact that the highest-intensity felt reports were from the same locations for both earthquakes. Our preferred location for both earthquakes (Table 1) is approximately in the center of the MMI V–VI felt region.

Both the 1997 and 2010 earthquakes appear to have shallow focal depths, less than a few km. A shallow focal depth is required to fit initial and later-arriving *P* and *S* arrivals for the 2010 earthquake at stations within 1° (Figs. 3 and 4) and to explain the occurrence of the large transverse arrival at HKT for the 1997 earthquake (Fig. 7).

Inspection of Figures 3–7 helps explain why the NEIC-reported locations for the 1997 and 2010 earthquakes differed significantly and were both about 11 km from this study's preferred location (Table 1). In 1997, body-wave arrivals at HKT, the only reporting station within 5°, were emergent or unreadable and traveled parallel to the Gulf Coast along a path with crustal structure dissimilar to conventional crustal structure models. An ~10-km location error is unsurprising if it depends on emergent arrivals and arrivals at stations at distances exceeding 5°.

In 2010 there were seven EarthScope Transportable Array stations within ~1° of the Alice epicenter. Nevertheless, the earliest *P* and *S* arrivals were difficult to identify, probably because of a shallow focal depth and the unusual Gulf Coast crustal structure. Moreover, at the EarthScope stations the strongest body-wave arrivals were later arrivals. An ~10-km location error is unsurprising if one wrongly identifies late-arriving phases as initial arrivals or determines locations using an improper crustal model.

Regional Geology and Petroleum Production

The Vicksburg Fault Zone

The Vicksburg fault zone extends from the Texas–Mexico border northeastward across Starr, Jim Hogg, Brooks, Jim Wells, Kleberg, and Nueces counties (Figs. 1 and 2). According to Swanson and Karlsen (2009, p. 17), "A major deltaic progradation… in the early Oligocene created the Vicksburg fault zone, which is a narrow fault zone characterized by vertical displacement of the underlying section. The Vicksburg fault zone forms the up-dip limit of significant structural deformation of the Frio formation. The Frio fault zone, down-dip of the Vicksburg fault zone, is a broad, deep listric system that consists of 5 to 10 major normal faults spaced 5 to 10 km apart, with intervening rollover anticlines." These anticlines and normal faults, with offsets down to the east (Kerr, 1990), act as traps for gas and oil, which formed in fluvial environments.

Since 1928 there has been extensive gas and oil production along the Vicksburg fault zone. According to Smith (2009), fields along the Vicksburg trend had produced 1.12 billion barrels of oil between 1928 and 1994 and 5.98 trillion cubic feet of gas from 1970 to 1993. For both gas and oil, there are discrepancies in production figures quoted by different authorities. For gas this is partly because, prior to about 1950, much of the gas associated with oil production was flared and thus not recovered. For both gas and oil, different organizations use different procedures when accounting for total volumes. Nevertheless, all authorities report that there have been high rates of production from Vicksburg fields for more than 80 years, and, although rates are decreasing, production is still ongoing.

Stratton Field

One of the more productive fields along the Vicksburg fault zone is the Stratton field, which abuts the MMI V–VI felt area of the Alice earthquakes (Fig. 2). The Stratton field began producing in 1938 from the Frio formation at a depth of 6500 feet (2000 m). Subsequently most of the production has been from reservoirs at depths of 3000–10,000 ft (1–3 km; see Fig. 8 and Swanson and Karlsen, 2009). There are more than 100 producing reservoirs in the Stratton field; most are sand-rich channel-fill and splay deposits interstratified with floodplain mudstones; because of their fluvial origin, individual reservoirs are typically only 5–10 m thick and all are less than 1–2 km in aerial extent (Kerr, 1990; Kerr and Jirik, 1990; Combes, 1993; Hardage *et al.*, 1994). Levey, Finley, and Sippel (1994) state that the period from 1950 through 1968 was the primary development phase of the Stratton field. Peaks in annual gas production occurred during the mid-1950s and early 1970s, when production exceeded 80 billion cubic feet per year (Fig. 9).

Various sources indicate that the Stratton field has produced more than 2.7 trillion cubic feet of gas and 100 million barrels of oil since production began in 1938. These sources include the Texas Railroad Commission, which regulates petroleum production (but not railroads) in Texas, Levey, Finley and Sipple (1994), and Slatt (2006). The Stratton field is still active although both gas and oil production have steadily decreased since about 1973 (Fig. 9). Since 1990 a significant fraction of the new wells completed in the Stratton field have been in the northernmost portion of the field, in Nueces and Jim Wells Counties, just east of our preferred epicenters for the 1997 and 2010 earthquakes.

Discussion

Location of the Alice Earthquakes

Following the Bilich *et al.* (1998) study of the 24 March 1997 Alice earthquake, several questions remained unanswered: (1) why the NEIC-reported locations for this event did not coincide with the highest-intensity felt area; (2) why *P* and *S* arrivals at HKT were emergent and difficult to identify with confidence; and (3) why the highest-amplitude wave trains observed at HKT arrived so late and

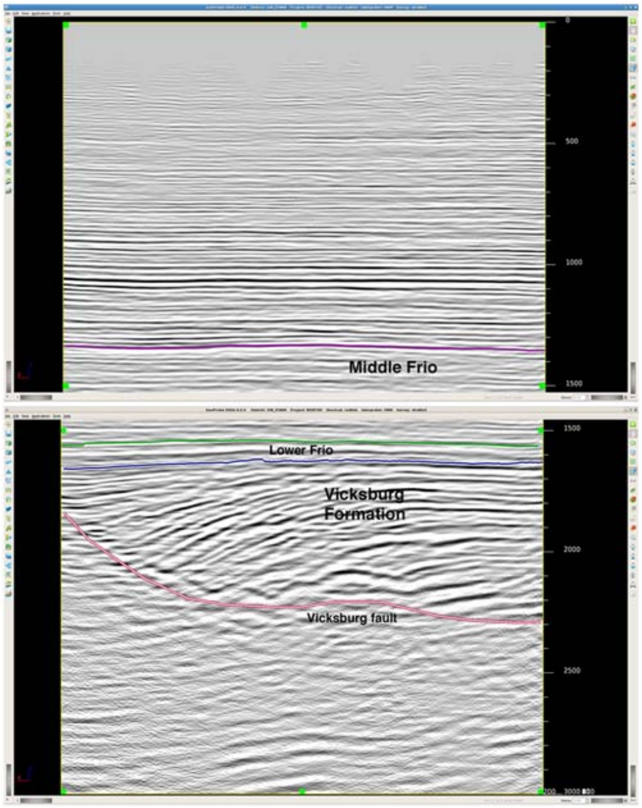

Figure 8. West–east reflection seismic line from a 3D dataset over Stratton Field (Levey, Finley, and Sippel, 1994; Levey, Hardage, *et al.*, 1994), showing generalized structure and stratigraphy. The seismic line is approximately 3 km long and is situated about 3 km south of the preferred epicenters of the 1997 and 2010 earthquakes. The vertical axis indicates two-way travel time in ms. The principal stratigraphic horizons are interpreted and labeled on the figure: the gently deformed middle (~1350 ms) and lower (~1550 and 1650 ms) Frio formation overlies the growth-faulted lower Frio and Vicksburg formation section, above the master Vicksburg expansion fault (1800–2300 ms). The Vickburg fault is a regional north-northeast-striking buried growth-fault zone, subparallel to the present coastline and extending at least 100 miles northeast from the Mexico–U. S. border. Most of the gas production in the Stratton field is from middle Frio sandstone reservoirs at depths of 1.5–2.0 km. The color version of this figure is available only in the electronic edition.

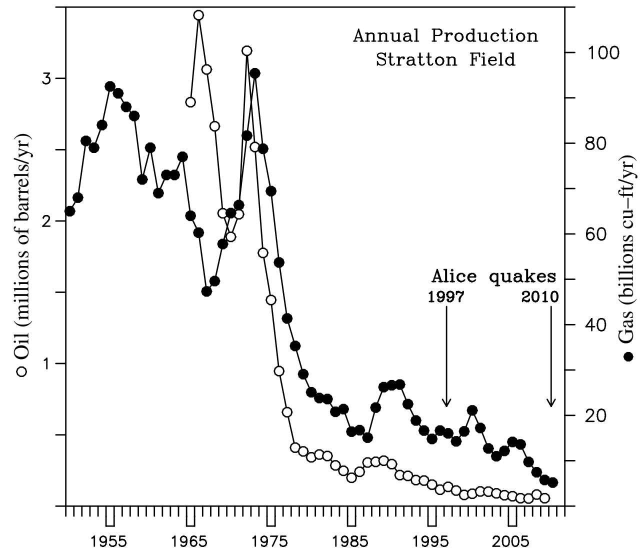

Figure 9. Annual gas and oil production in the Stratton field. Note that both the 1997 and 2010 Alice earthquakes occurred well after the highest production levels were reached in the 1965–1975 period. Data are from Levey, Finley and Sippel (1994) updated with information from the Texas Railroad Commission.

were so highly dispersed (e.g., Fig. 7). In this paper, we can answer these questions because numerous stations of the EarthScope Transportable Array were deployed within 100 km of Alice and recorded the nearly identical earthquake that occurred on 25 April 2010.

Our first major conclusion is that the epicenter of the 2010 Alice earthquake was approximately at 27.72° N, 97.95° W. This location coincides with the center of the MMI V–VI felt area, lies approximately along the mapped trace of the Vicksburg fault zone, and is situated within 3 km of the northwestern boundary of a major petroleum field, the Stratton field.

Our second conclusion is that the 1997 and 2010 Alice earthquake shared identical or nearly identical epicenters and mechanisms. This is supported by the observation that peaks and troughs over many minutes matched for their seismograms at station HKT. This suggests that the mile-long surface crack observed following the 1997 quake was situated within 3–4 km of the epicenter, with an orientation approximately parallel to the Vicksburg fault zone.

Our third conclusion is that the 1997 and 2010 earthquakes both had shallow focal depths, probably 3 km or less. For the 2010 earthquake, a shallow focal depth is required to explain multiple *P* and *S* body-wave arrivals; these must originate within a layered crustal structure similar to that reported for this area by Keller and Shurbet (1975). For this focal depth and somewhat unusual velocity structure, the earliest-arriving phases at regional distances are often weak and difficult to identify properly, complicating location using standard methods. This explains the discrepancy between the NEIC-reported locations and the highest-intensity regions for the 1997 and 2010 earthquakes. For the 1997 earthquake, a shallow focal depth and the presence of a thick, very-low-velocity layer in the upper crust of the Gulf Coastal plain also explain the high-amplitude, late-arriving arrivals at HKT (Fig. 7). The 1997 observation of a surface crack is consistent with a shallow focal depth, as is the relatively small area of the highest-intensity felt regions for both the 1997 and 2010 earthquakes (e.g., Blake, 1941).

Petroleum Production Caused the Alice Earthquakes? Arguments in Favor

Most seismologists agree that human activities sometimes cause or trigger earthquakes in hydrocarbon fields (e.g., see review by Suckale, 2009), and several observations support the assertion that the Alice earthquakes may represent such a phenomenon. Earthquakes of tectonic origin are almost nonexistent along the Gulf Coastal plain within 80 km of the Gulf of Mexico (Frohlich and Davis, 2002). In this study we have established that the Alice earthquakes did occur at the boundary of the highly productive Stratton field that coincides with the mapped trace of the Vicksburg fault zone. Our evidence indicates the earthquakes had shallow focal depths (< 3 km) that coincide with the depths of production for the Stratton field.

The volumes of fluid displaced by oil and gas production in the Stratton field are considerable. Over the field's lifetime, the 100 million barrels of oil produced correspond to a volume V_O of 16×10^6 m^3. The aerial extent A of the field as mapped by Galloway *et al.* (1983) is about 100 km^2 (see Fig. 2); thus the oil produced is equivalent to a pool covering the entire field with thickness V_O/A of 16 cm. Similarly, two trillion cubic feet of natural gas occupy a volume of 56×10^9 m^3; if liquefied, this volume is reduced by a factor of 600 to about V_G of 100×10^6 m^3. This corresponds to a pool with thickness V_G/A of 1.0 m.

With the limited information available, detailed modeling of stress changes caused by fluid withdrawal in the Stratton field is unlikely to be very useful. Much of the detailed information about subsurface structure, well pressures, etc. is proprietary or simply unavailable because of changes in policy and procedures over the long history of the field. Moreover, according to Smith (2009), "Pressure in the diverse reservoirs [of Vicksburg fault zone fields] has been maintained by gas injection, water injection, waterflood, and polymer flood." For the Stratton field, Levey, Finley and Sippel (1994, p. 7) note that during the 1950–1970 period of primary development, "gas was cycled in several reservoirs to provide pressure support to maximize production from oil completion." Thus any thorough modeling would need to allow for the possibility either or both fluid injection and production are responsible for the Alice earthquakes.

There are notable similarities between the Alice earthquakes and some other earthquakes in Texas that occurred at the boundaries of gas and oil fields. For example, the 9 April 1932 Wortham–Mexia earthquake occurred along the southeast–northwest–trending Mexia fault zone, which forms structural traps for several large and highly productive oil fields, including the Mexia and Wortham fields (Sellards, 1933; Frohlich and Davis, 2002). Total oil production in the Mexia field to the end of 1931 exceeded 90 million barrels. Felt reports for the Wortham–Mexia earthquake suggest it was shallow, as it was felt with intensity MMI VI in Wortham, where it shook down bricks from chimneys, but went unnoticed in Fairfield, 30 km away. Finally, the geological report noted the quake induced a crack that extended across the concrete highway between Wortham and Mexia (Sellards, 1933).

Petroleum Production Caused the Alice Earthquakes? Arguments Against

Oil and gas production is a huge industry in Texas. Frohlich and Davis (2002) digitized maps of oil and gas fields from Galloway *et al.* (1983) and Kosters *et al.* (1989), determined that 5% of Texas' area lay within an oil or gas field, and calculated that the median distance between randomly chosen locations in Texas and an oil or gas field was 15.5 km. Thus the occurrence of an earthquake near or within a field is not in itself strong evidence for a causal relationship.

The relationship between timing of seismic activity and production in the Stratton field is much more tenuous than in some other cases of induced seismicity, such as the Denver earthquakes (Hsieh and Bredehoeft, 1981), the Snyder earthquakes in west Texas (Davis and Pennington, 1989), or the 2008–2010 Dallas–Fort Worth earthquakes (Frohlich *et al.*, 2010; 2011). Gas and oil production in the Stratton field has declined significantly since 1972 (Fig. 9). It is not obvious why earthquakes should occur in 1997 and 2010, 25–40 years after peak withdrawal rates, when rates were less than 15% of peak values.

Finally, earthquakes of apparently tectonic origin do occasionally occur along the Gulf Coast (e.g., Brasseaux and Lock, 1992), although they are rare. For example, in Louisiana, earthquakes on 19 October 1930 near Napoleonville and on 16 October 1983 near Lake Charles (Stevenson and Agnew, 1988) were both about 60 km inland from the Gulf of Mexico and had reported magnitudes of 4.2 and 3.8, respectively. Thus both their magnitudes and distances from the Gulf Coast were approximately the same as the Alice earthquakes.

What Is to Be Done?

If we hope to understand the relationship between seismicity and activities associated with gas and oil production, what is presently lacking are systematic investigations of gas and oil fields that compare fields where earthquakes do not occur with fields where they do. We seismologists tend to investigate earthquakes when they occur and take note when their epicenters lie in or near producing fields, as with the Alice and Wortham–Mexia earthquakes, or near salt-water disposal (SWD) injection wells, as with the 2009–2010 Dallas–Fort Worth and Cleburne earthquakes (Frohlich *et al.*, 2010; 2011; Howe *et al.*, 2010). However, felt earthquakes are not observed near the vast majority of producing oil fields, gas fields, and SWD wells in Texas; thus seismological studies concluding that fluid injection or gas and oil production cause earthquakes (e.g., Pennington *et al.*, 1986; Davis *et al.* 1995) are biased toward the exceptional events where earthquakes occur, rather than typical situations where they do not.

Because drilling for gas and oil production is expensive, for many fields there have been extensive geological studies and geophysical surveys prior to or during production. These potentially could provide far more detailed information about subsurface conditions in the hypocentral area than is typically available for tectonic earthquakes. Unfortunately much of this information is proprietary and thus unavailable for analysis or publication without the express cooperation of the companies producing a field and/or the subcontractors who conducted the surveys.

For example, for the 2008–2010 Dallas–Fort Worth epicenters (Frohlich *et al.*, 2010; 2011), proprietary geophysical survey data confirmed the approximate location for the fault trace of a nearby fault that appeared on the Ewing (1990) state of Texas tectonic map. Some geophysical survey information is in the public domain for the Stratton field (e.g., see Hardage *et al.*, 1994; Levey, Hardage, *et al.*, 1994), but the fact that this is unusual will complicate efforts to make systematic comparative studies with other fields in similar environments.

Finally, the EarthScope Transportable Array provides an opportunity to more thoroughly investigate both induced and background seismicity in areas like Texas. In many central U. S. states there are few seismograph stations, and earthquakes with magnitudes smaller than about 3.5 are not routinely reported unless they occur in urban areas. In most states, including Texas, there are no commercial or government agencies tasked with systematically inspecting seismograms to identify unreported events. The passage of the Transportable Array, providing publicly available broadband data from stations operated for two years on a grid with 70-km spacing, should make it possible to identify for earthquakes as small as about M 2.5, both those that occur naturally and those possibly associated with petroleum operations.

Data and Resources

All seismograms analyzed in this study are archived at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center and freely available to all. Information concerning well locations and gas and oil production in the Stratton field is archived by the Texas Railroad Commission and available on their public web site.

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References

Bilich, A., S. A. Clark, B. Creighton, and C. Frohlich (1998). Felt reports from the Alice, Texas, earthquake of 24 March 1997, *Seismol. Res. Lett.* **69,** 117–122.

Blake, A. (1941). On the estimation of focal depth from macroseismic data, *Bull. Seismol. Soc. Am.* **31,** 225–231.

Brasseaux, C. A., and B. E. Lock (1992). The Opelousas earthquakes of 1823 and 1870, Louisiana history, *J. Louisiana Hist. Assoc.* **33,** 317–324.

Combes, J. M. (1993). The Vicksburg formation of Texas: Depositional systems distribution, sequence stratigraphy, and petroleum geology, *Am. Assoc. Petrol. Geol. Bull.* **77,** 1942–1970.

Davis, S. D., and W. D. Pennington (1989). Induced seismic deformation in the Cogdell oil field of west Texas, *Bull. Seismol. Soc. Am.* **79,** 1477–1495.

Davis, S. D., P. Nyffenegger, and C. Frohlich (1995). The 9 April 1993 earthquake in south-central Texas: Was it induced by fluid withdrawal? *Bull. Seismol. Soc. Am.* **85,** 1888–1895.

Ewing, T. (1990). Tectonic map of Texas, scale 1:750,000, Univ. Texas Bureau of Economic Geology.

Frohlich, C., and S. D. Davis (2002). *Texas Earthquakes*, Univ. Texas Press, Austin, Texas, 275 pp.

Frohlich, C., C. Hayward, B. Stump, and E. Potter (2011). The Dallas–Fort Worth earthquake sequence: October 2008 through May 2009, *Bull. Seismol. Soc. Am.* **101,** doi 10.1785/0120100131.

Frohlich, C., E. Potter, C. Hayward, and B. Stump (2010). Dallas-Fort Worth earthquakes coincident with activity associated with natural gas production, *TLE* **29,** 270–275, doi 10.1190/1.3353720.

Galloway, W. E., T. E. Ewing, C. M. Garrett, N. Tyler, and D. G. Bebout (1983). *Atlas of Major Texas Oil Reservoirs*, Univ. Texas Bureau of Economic Geology, Austin, Texas, 139 pp.

Hardage, B. A., R. A. Levey, V. Pendleton, J. Simmons, and R. Edson (1994). A 3-D seismic case history evaluating fluvially deposited thin-bed reservoirs in a gas-producing property, *Geophysics* **59,** 1650–1665.

Howe, A. M., C. T. Hayward, B. W. Stump, and C. Frohlich (2010). Analysis of recent earthquakes in Cleburne, Texas, *Seismol. Res. Lett.* **81,** 379.

Hsieh, P. A., and J. S. Bredehoeft (1981). A reservoir analysis of the Denver earthquakes—A case study of induced seismicity, *J. Geophys. Res.* **86,** 903–920.

Keller, G. R., and D. H. Shurbet (1975). Crustal structure of the Texas Gulf Coastal plain, *Geol. Soc. Am. Bull.* **86,** 807–810.

Kerr, D. R. (1990). Reservoir heterogeneity in the middle Frio formation: Case studies in Stratton and Agua Dulce fields, Nueces County, Texas, *Trans. Gulf Coast Assoc. Geol. Soc.* **40,** 363–372.

Kerr, D. R., and L. A. Jirik (1990). Fluvial architecture and reservoir compartmentalization in the Oligocene middle Frio formation, South Texas, *Trans. Geol. Soc. Gulf Coast Assoc. Geol. Soc.* **40,** 373–380.

Kosters, E. C., D. G. Bebout, S. J. Seni, C. M. Garrett, L. F. Brown, H. S. Hamlin, S. P. Dutton, S. C. Ruppel, R. J. Finley, and N. Tyler (1989). *Atlas of Major Texas Gas Reservoirs*, Univ. Texas Bureau of Economic Geology, Austin, Texas, 161 pp.

Levey, R. A., R. J. Finley, and M. A. Sippel (1994). *Quantifying secondary gas resources in fluvial/deltaic reservoirs: A case history from Stratton field*, South Texas, Rept. Investigations No. 221, Univ. Texas Bureau of Economic Geology, 38 pp.

Levey, R. A., B. A. Hardage, R. Edson, and V. Pendleton (1994). *3-D Seismic and Well Log Data Set Fluvial Reservoir Systems—STRATTON Field South Texas*, Univ. Texas Bureau of Economic Geology. Austin, Texas, 30 pp. and CD-ROM.

Mickus, K., R. J. Stern, G. R. Keller, and E. Y. Anthony (2009). Potential field evidence for a volcanic rifted margin along the Texas Gulf Coast, *Geology* **37,** 387–390, doi 10.1130/G25465A.1.

Peel, F. J., C. J. Travis, and R. Hossack (1995). Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: A preliminary analysis, in *Salt Tectonics: A Global Perspective*, M. P. A. Jackson, D. G. Roberts, and S. Snelson, Am. Assoc. Petrol. Geol. Bull. Memoir 65, pp 153–175.

Pennington, W. D., S. D. Davis, S. M. Carlson, J. Dupree, and T. E. Ewing (1986). The evolution of seismic barriers and asperities caused by the depressuring of fault planes in oil and gas fields of south Texas, *Bull Seismol. Soc. Am.* **76,** 939–948.

Sellards, E. H. (1933). The Wortham-Mexia, Texas, earthquake, *Contributions to Geology, Univ. Texas Bull.*, No. 3201, Univ. Texas Bureau of Economic Geology. Austin, Texas, 105–112.

Slatt, R. M. (2006). *Stratigraphic Reservoir Characterization for Petroleum Geologists, Geophysicists and Engineers*, Elsevier, Amsterdam, The Netherlands, 592 pp.

Smith, J. S. (2009). Vicksburg fault zone fields, *Handbook of Texas Online*, Texas State Historical Association, available at http://www.tshaonline.org/handbook/online/articles/dovhs (last accessed October 2011).

Stevenson, D. A., and J. D. Agnew (1988). Lake Charles, Louisiana, earthquake of 16 October 1983, *Bull. Seismol. Soc. Am.* **78,** 1463–1474.

Suckale, J. (2009). Induced seismicity in hydrocarbon fields, *Adv. Geophys.* **51,** 55–106, doi 10.1016/S0065-2687(09)05107-3.

Swanson, S. M., and A. W. Karlsen (2009). USGS assessment of undiscovered oil and gas resources for the Oligocene Frio and Anahuac Formations, onshore Gulf of Mexico Basin, USA, Search and Discovery Article 10178, http://www.searchanddiscovery.com/documents/2009/10178swanson/index.htm (last accessed December 2011), 44 pp.

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