Possible cause for an improbable earthquake: The 1997 M_w 4.9 southern Alabama earthquake and hydrocarbon recovery

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ABSTRACT

Circumstantial and physical evidence indicates that the 1997 M_w 4.9 earthquake in southern Alabama may have been related to hydrocarbon recovery. Epicenters of this earthquake and its aftershocks were located within a few kilometers of active oil and gas extraction wells and two pressurized injection wells. Main shock and aftershock focal depths (2–6 km) are within a few kilometers of the injection and withdrawal depths. Strain accumulation at geologic rates sufficient to cause rupture at these shallow focal depths is not likely. A paucity of prior seismicity is difficult to reconcile with the occurrence of an earthquake of M_w 4.9 and a magnitude-frequency relationship usually assumed for natural earthquakes. The normal-fault main-shock mechanism is consistent with reactivation of preexisting faults in the regional tectonic stress field. If the earthquake were purely tectonic, however, the question arises as to why it occurred on only the small fraction of a large, regional fault system coinciding with active hydrocarbon recovery. No obvious temporal correlation is apparent between the earthquakes and recovery activities. Although thus far little can be said quantitatively about the physical processes that may have caused the 1997 sequence, a plausible explanation involves the poroelastic response of the crust to extraction of hydrocarbons.

INTRODUCTION

On October 24, 1997, an unprecedented M_w 4.9 earthquake shook southern Alabama. This event, preceded on May 4, 1997, by a magnitude 3.1 foreshock and followed by more than 17 aftershocks in the subsequent three months, occurred in the nearly aseismic Gulf Coastal Plain (Fig. 1). The main-shock normal-fault mechanism (Chang et al., 1998) is consistent with a regional north-south extensional stress field (Nunn, 1985). A system of Miocene and older faults in the epicentral region is associated with the development of major salt deposits and hydrocarbon traps (Tew et al., 1993; Montgomery et al., 1997). The close proximity of the earthquakes to oil and gas production fields suggests a relationship between them (see, e.g., Pennington et al., 1986; Cox, 1991).

The characteristics of the earthquakes are derived from main-shock seismograms recorded at regional distances (Chang et al., 1998), aftershock seismograms recorded on portable seismographs deployed in the epicentral region from October 25, 1997, to January 15, 1998, and intensity surveys (Fig. 2). Hydrocarbon recovery activities are reported to the Alabama State Oil and Gas Board as monthly volumes of oil, gas, and water extracted, and as monthly average injection wellhead pressures and volumes of water and brine. We examine the available evidence with respect to previously established criteria to determine the likelihood that seismicity is related to recovery activities (Davis and Frohlich, 1993; Segall, 1989; Nicholson and Wesson, 1990, 1992).

SPATIAL AND TEMPORAL RELATIONSHIPS

Evidence for a causal relationship between hydrocarbon recovery and the 1997 Alabama earthquake sequence includes their spatial coincidence and the fact that the sequence was unprecedented (Fig. 1). Aftershock epicenters and Modified Mercalli intensity (MMI) observations indicate a main shock location within, or at the perimeters of, the active Big Escambia Creek, Little Rock, and Sizemore Creek production fields (Fig. 2), which have been operated since the mid-1970s. Of the four known earthquakes that occurred prior to 1997 in southern Alabama, two on the Mississippi border have been related to waste disposal injection (Nicholson and Wesson, 1990). The

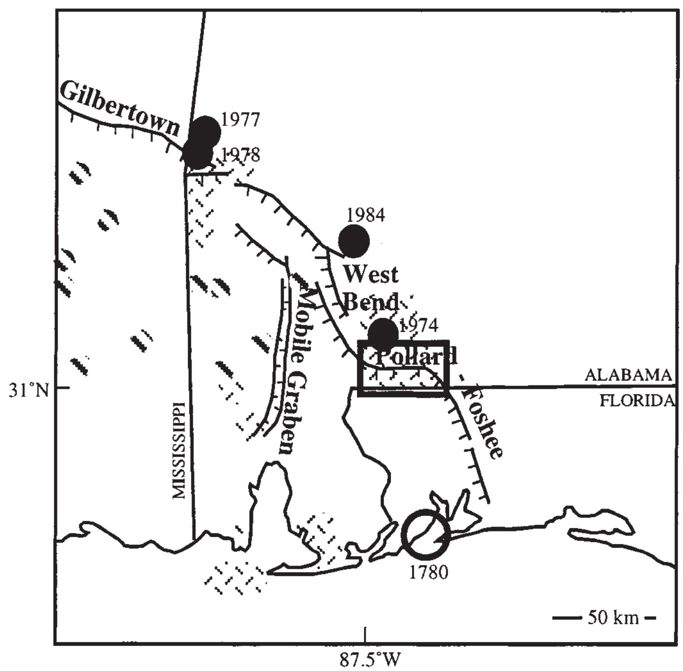

Figure 1. Schematic map of study area showing system of Miocene and older faults (modified from Montgomery et al., 1997). Labeled lines indicate normal faults; ticks are on down-dropped side. Patterned areas indicate approximate areas covered by oil and gas fields in southern Alabama only. Jagged-line patterns indicate salt domes of Mississippi interior salt basin. Black circles show epicenters and dates of earthquakes reported prior to 1997; all have estimated magnitudes between 3.0 and 3.5. Rectangle outlines approximate epicentral region shown in Figure 2. Occurrence of 1780 event (open circle) is uncertain (see text).

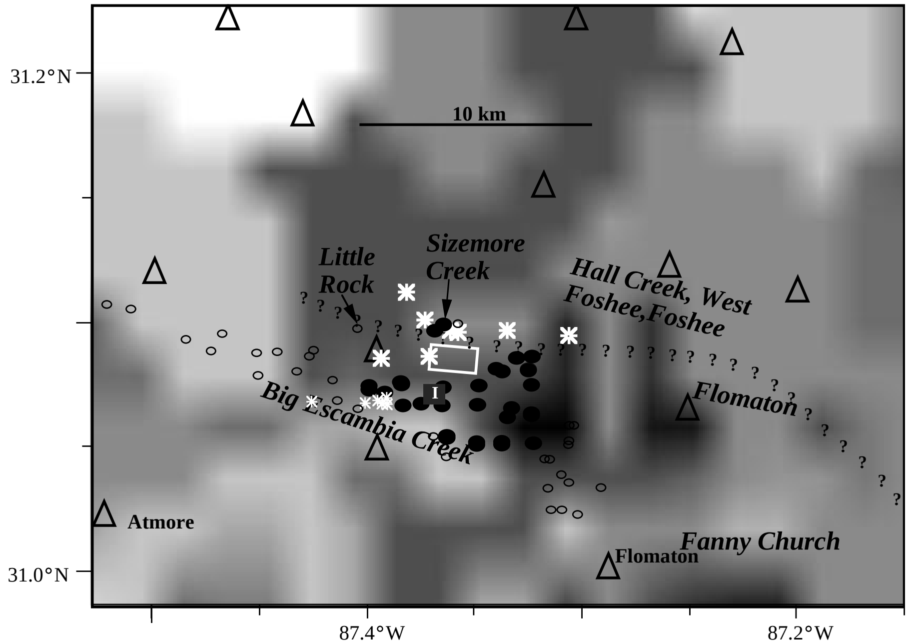

Figure 2. Map of epicentral region showing spatial relationship between earthquake epicenters and wells. Large white asterisks indicate aftershocks located with data from three or more stations; small white asterisks indicate aftershocks located with data from only two stations and fixed surface depth; rectangle is projection of approximate main-shock rupture area; ovals indicate locations of producing wells (solid black ovals correspond to wells represented in Fig. 4); square with I marks location of two injection wells within ~5 km of probable main shock; triangles mark locations of portable seismic stations installed after main shock. Question marks indicate probable location of main fault in region (part of Miocene Pollard-Foshee fault system). Shaded background shows smoothed, interpolated intensity estimates (black = modified Mercalli intensity [MMI] VIII, white = MMI III; modified from data compiled by D. Raymond, 1997, personal commun.). Although absolute intensity values may be somewhat uncertain, they reliably indicate relative severity of earthquake effects (at much higher resolution than in Fig. 3). Note that observational gap exists between highest intensities westward to locations of injection wells. Region of high intensities could extend into this gap, even though interpolated values do not. Main-shock location, although uncertain by several kilometers, is consistent with intensity data, aftershocks, and location of major preexisting fault system. Italicized names denote active production fields in region. Atmore and Flomaton are towns.

historic record contains one MMI IV earthquake in 1780 near Pensacola, Florida (Fig. 1); however, reports of a hurricane at the same time make this record suspect (Stover and Coffman, 1993). Preexisting faults may have been reactivated during the 1997 sequence, making the events not truly random and of possible tectonic origin. However, the production fields occupy only a small fraction of the regional fault system, making chance occurrence of earthquakes only on the segments near the fields unlikely.

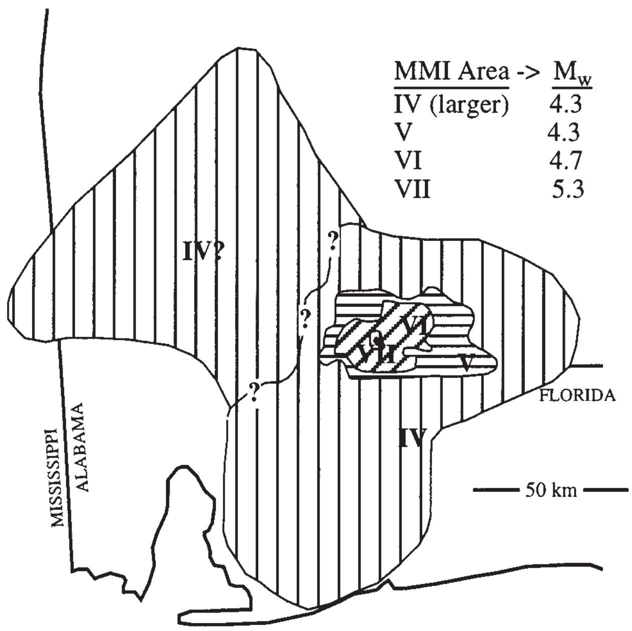

Figure 3. Map showing smoothed, contoured Modified Mercalli intensity (MMI) estimates for October 24, 1997, M_W 4.9 main shock (provided by D. Raymond). MMI IV region is uncertain, and on the basis of a few observations, could include large area to northwest. Magnitudes are computed from each isoseismal area using formulas of Johnston (1996).

The depths of well activities and the earthquake hypocenters are within a few kilometers of one another. Modeling of regional waveforms, surface-wave radiation patterns, and stacked depth phases constrain the main shock focal depth to 4.5 ± 1 km (Chang et al., 1998). The intensity pattern is consistent with a shallow focal depth (Fig. 3), although high seismic wave attenuation may also explain the pattern (Johnston, 1996). Aftershock focal depths range between 2 and 6 km. Extraction wells reach ~4.5 km, tapping the producing horizons of the Smackover Formation limestone and Norphlet Formation sandstone. The only two injection wells in the fields bottom at 2.1 km in the Tuscaloosa Group sandstone and shale (Burroughs, 1997). The close proximity of wells to the hypocenters obviates the need for fractures to provide connectivity; however, the field-bounding Pollard-Foshee fault system (Tew et al., 1993) may facilitate the migration of fluids or pore pressures. The main-shock focal mechanism (strike 90°, dip 60° down to south; Chang et al., 1998) is consistent with the presumed strike and dip of this fault system.

Davis and Frohlich (1993) suggested that a causal relationship between injection and seismicity is indicated if the earthquakes follow the onset or cessation of injection by a few days. Other case histories provide constraints on plausible time lags between earthquakes and changes in injection or extraction practices. Seismicity probably related to injection in the El Dorado, Arkansas, area of the Gulf Coastal Plain began within a few months after increases in injection pressures (by several MPa) and in injected volumes. In other cases, earthquakes lag changes in injection or extraction volumes or rates by several years (Nicholson and Wesson, 1992).

No clear temporal correlation is apparent between the 1997 Alabama earthquakes and volumes of oil and gas extracted, or in the volumes and average monthly pressures in each of the injection wells (Fig. 4). Extracted volumes did not change by more than a factor of two in the five years or so prior to 1997, nor has the variability been much greater over the lifetimes of the fields. The injected volumes have remained similarly stable in well 77242 over its lifetime, and have dropped by several orders of magnitude in well 74112 in the past decade. In the five or so years preceding the 1997 earthquakes, the pressures dropped in well 77242 by ~5 MPa and in well 74112 they frequently fluctuated and increased by a factor of ~10 (Fig. 4). Such increases might be rapid enough to increase pore pressures, leading to significant pressure increases at depth.

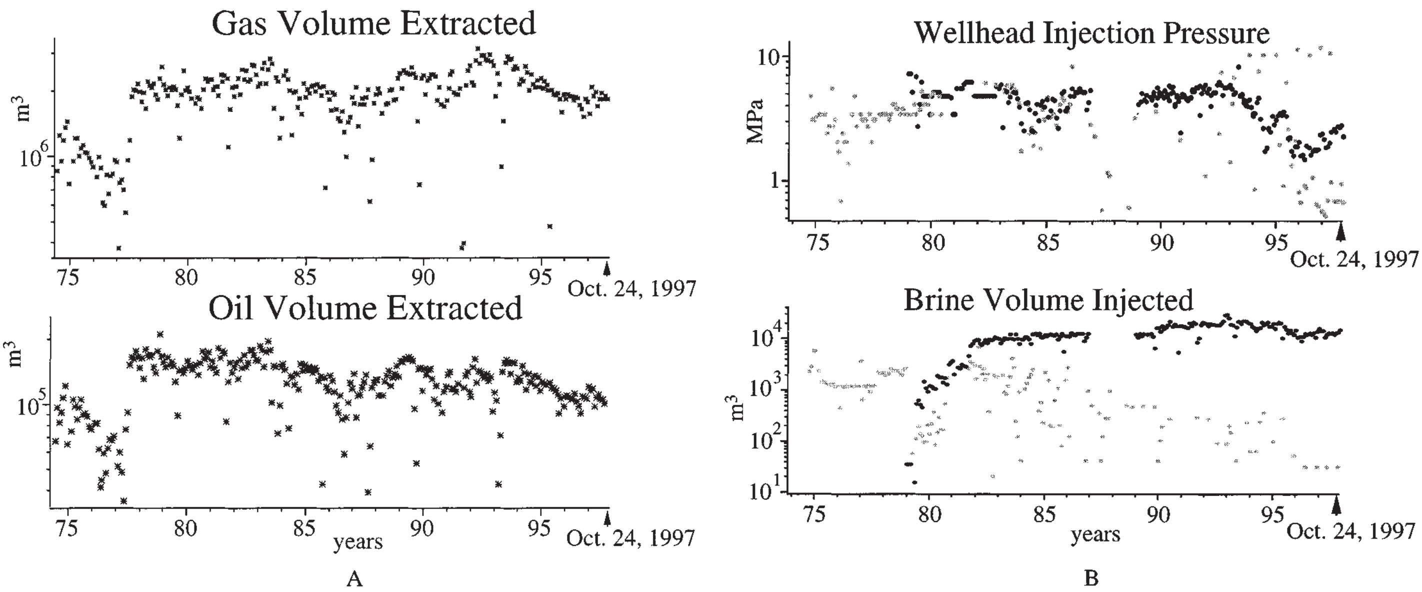

Figure 4. Monthly volumes and pressures reported to Alabama State Oil and Gas Board for wells in epicentral region (solid black ovals in Fig. 2). Time ticks denote January 1 of years marked. Distance to which well data were considered relevant is based on studies of recovery-related seismicity in other regions. A: Volumes of gas and oil extracted. Water is also extracted, but volumes are orders of magnitude lower and thus are not included here. B: Average wellhead injection pressures for injection wells 77242 (black symbols) and 74112 (gray symbols) (top) and corresponding volumes of brine injected.

The significance of these pressure and volume time histories is difficult to assess quantitatively without knowing the material properties governing fluid and pressure transmission and the poroelastic behavior (Segall, 1989). Nonetheless, theoretical predictions show that for sufficiently impermeable materials, poroelastic stresses may increase steadily even in the absence of marked production changes (Paul Segall, 1998, personal commun.). A study of the oil-producing Smackover Formation in southern Alabama indicates that porosity and permeability vary significantly (Kopaska-Merkel and Hall, 1993), and the 1997 epicenters were in an area of relatively low permeability. In addition, the overlying Tuscaloosa Group consists of interbedded sands and clays, the latter of which constitute aquicludes that form barriers against the migration of injected waste (Alverson, 1970).

PHYSICAL CONSIDERATIONS

Several mechanisms relate extraction and injection to earthquake activity, although the modeling required to test them requires specific information on material properties, recovery-related parameters, and the ambient stress field at hypocentral depths. The most common mechanism invokes Coulomb failure, in which increased pore pressures reduce the effective normal stress, moving a fault closer to failure. Although the ambient stresses at depth are unknown in southern Alabama, Mohr circle calculations of Nicholson and Wesson (1990) and of Cox (1991) for the Gulf Coastal Plain show that pore pressures increases of less than ~5 MPa can cause slip on optimally oriented preexisting faults. These calculations assume conditions (i.e., fluid pressure and stress gradients) likely to be similar to those in southern Alabama. Monthly injection pressures in the epicentral area have exceeded ~5 MPa, although it is not clear how to account for the transient high pressures in well 74112 (Fig. 4).

The permeability surrounding the wellhead strongly influences whether injection-induced stress perturbations effectively dissipate. Theoretical calculations suggest that geologic heterogeneities, particularly relatively permeable fault zones, can significantly amplify such perturbations near the fault (Lee and Wolf, 1998). Although the locations and orientations of individual faults of the Pollard-Foshee fault system are not well known, some may act to focus the wellhead stress perturbations. McGarr (1976) proposed that mass injection could result in extensional strains, stored as elastic strain energy and released in normal faulting. However, the volumes extracted exceed those injected by orders of magnitude. Thus, if invoked, this mechanism must act in the immediate vicinity of the injection wells.

In the shallow porous rocks found in the southern Alabama fields, poroeelasticity theory would predict that extraction causes contraction above and below the reservoir with surrounding expansion (Segall, 1989). A causal relationship between the 1997 main shock and extraction is plausible if the main shock occurred at the perimeter of the producing fields, which is possible given location uncertainties (Fig. 2). Segall and Fitzgerald (1998) suggested that lateral variations in permeability, which seem likely in the faulted and deformed crust of the study area (Tew et al., 1993; Montgomery et al., 1997), might generate steep pore pressure gradients and horizontal stresses sufficient to cause extensional fracturing in low-permeability regions. The normal-fault focal mechanism eliminates from consideration the mechanism suggested by McGarr (1991), in which mass removal results in volumetric contraction stored as elastic strain and released in reverse-fault earthquakes. Pennington et al. (1986) suggested that extraction may facilitate seismic failure by changing the stability regime from stable sliding to stick-slip. This mechanism does not seem plausible for the 1997 events if loading were purely tectonic, because it requires the strain energy released by the earthquakes to have accumulated since production began and thus implies extraordinarily high natural strain rates.

The depths and magnitude distribution of the 1997 Alabama earthquakes are atypical of most natural events. Most crustal earthquakes occur below several kilometers depth, probably because shallow sediments are too weak to store accumulating tectonic strain. Yet, the main shock rupture probably occurred <~1 km below the sediment-basement interface at ~5 km (Burroughs, 1997), and perhaps above it. Some of the aftershocks occurred within the sedimentary units above the basement. Earthquakes in these layers may have resulted from rapid pore-pressure changes and strain rates or chemical changes (Kisslinger, 1976).

The magnitude of the earthquake and lack of smaller prior earthquakes also are anomalous among naturally occurring earthquake sequences. If the M_w 4.9 Alabama earthquake resulted from tectonic processes alone and if seismicity rates are assumed to follow a Gutenberg-Richter relation with a typical b-value equal to one, then there should be about 10 M ~3.9 earthquakes and about 100 M ~3 earthquakes. (The best catalog for the central and eastern U.S. is consistent with this relation and b-value; Frankel, 1995.) Even accounting for large location uncertainties, earthquakes in this magnitude range would not have gone undetected since the late 1970s, when reliance on instrumental data for detection and location began. That only a few earthquakes, none with M >3.5, were documented prior to 1997 is thus inconsistent with a paradigm of natural seismicity.

CONCLUSIONS

Circumstantial evidence favoring a causal relationship between hydrocarbon recovery and the 1997 earthquake sequence in southern Alabama is persuasive, although a mechanism involving tectonic loading cannot be eliminated. A purely tectonic origin is difficult to reconcile with strain accumulation at geologic rates in shallow sedimentary units above the basement, where M >3 aftershocks and possibly the M_w 4.9 main shock were located. A tectonic origin also implies an uncommon frequency-magnitude relationship, given the paucity of smaller earthquakes prior to October 24, 1997. Despite this evidence, however, no clear temporal correlation between hydrocarbon recovery and the 1997 sequence has been established.

More definitive constraints on the causes of this unusual earthquake sequence will require additional detail about the local material properties and stresses, and modeling of the media response to recovery activities. However, the normal-fault mechanism, extensional regional stress regime, fluid and gas volumetric data, and the previous work of others provide constraints. If injection is related to the sequence, either by raising the pore pressure or by elastic volumetric straining, it must act very locally, because extracted volumes exceed those injected by orders of magnitude. If extraction is the mechanism, the normal fault source may be consistent with models that account for poroelastic stresses.

ACKNOWLEDGMENTS

We thank Paul Segall, Dorothy Raymond, David Simpson, Rob Wesson, and an anonymous reviewer for their helpful comments; T. Bice, D. Carver, E. Cranswick, and the Incorporated Research Institutes for Seismology for field support; the State Oil and Gas Board of Alabama, particularly R. Raymond and J. Hall; D. Raymond of the Alabama Geological Survey for intensity survey results and insight about the local geology and tectonics; and O. Eckhoff, M. Hopper, M. Meremonte, A. Barnes, J. Collier, and S. Rhea. CERI Contribution 364.

REFERENCES CITED

Alverson, R. M., 1970, Deep well disposal study for Baldwin, Escambia, and Mobile Counties, Alabama: Geologic Survey of Alabama Circular 58, 49 p.

Burroughs, D., 1997, The petroleum industry in Alabama, 1994: Tuscaloosa, Alabama State Oil and Gas Board Oil and Gas Report 3-R, 138 p.

Chang, T. M., Ammon, C. J., and Herrmann, R. B., 1998, Faulting parameters of the October 24, 1997 southern Alabama earthquake: Seismological Research Letters, v. 69, p. 175–176.

Cox, R. T., 1991, Possible triggering of earthquakes by underground waste disposal in the El Dorado, Arkansas area: Seismological Research Letters, v. 62, p. 113–122.

Davis, S. D., and Frohlich, C., 1993, Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment: Seismological Research Letters, v. 64, p. 207–224.

Frankel, A., 1995, Mapping the seismic hazard in the Central and Eastern United States: Seismological Research Letters, v. 66, p. 8–21.

Johnston, A. C., 1996, Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity: Geophysical Journal International, v. 124, p. 381–411.

Kisslinger, C., 1976, A review of theories of mechanisms of induced seismicity: Engineering Geology, v. 10, p. 85–98.

Kopaska-Merkel, D. C., and Hall, D. R., 1993, Reservoir characterization of the Smackover Formation in southwest Alabama: Geologic Survey of Alabama Bulletin 153, 111 p.

Lee, M., and Wolf, L. W., 1998, Analysis of fluid pressure propagation in heterogeneous rocks: Implications for hydrologically induced earthquakes: Geophysical Research Letters, v. 25, p. 2329–2332.

McGarr, A., 1976, Seismic moments and volume changes: Journal of Geophysical Research, v. 81, p. 1487–1494.

McGarr, A., 1991, On a possible connection between three major earthquakes in California and oil production: Seismological Society of America Bulletin, v. 81, p. 948–970.

Montgomery, S. L., Baria, L. R., and Handford, C. R., 1997, Frisco City sandstone: Upper Jurassic play in southern Alabama: American Association of Petroleum Geology Bulletin, v. 81, p. 1595–1611.

Nicholson, C., and Wesson, R. L., 1990, Earthquake hazard associated with deep well injection—A report to the U.S. Environmental Projection Agency: U.S. Geological Survey Bulletin 1951, 74 p.

Nicholson, C., and Wesson, R. L., 1992, Triggered earthquakes and deep well activities: Pageoph, v. 139, p. 561–578.

Nunn, J. A., 1985, State of stress in the northern Gulf Coast: Geology, v. 13, p. 429–432.

Pennington, W. D., Davis, S. C., Carlson, S. M., DuPree, J., and Ewing, T. E., 1986, The evolution of seismic barriers and asperities caused by the depression of fault planes in oil and gas fields of south Texas: Seismological Society of America Bulletin, v. 76, p. 939–948.

Segall, P., 1989, Earthquakes triggered by fluid extraction: Geology, v. 17, p. 942–946.

Segall, P., and Fitzgerald, S. D., 1998, A note on induced stress changes in hydrocarbon and geothermal reservoirs: Tectonophysics, v. 289, p. 117–128.

Stover, C. W., and Coffman, J. L., 1993, Seismicity of the United States 1568–1989 (revised): U.S. Geological Survey Professional Paper 1527, 417 p.

Tew, B. H., Mink, R. M., Mancini, E. A., Mann, S. D., and Kopaska-Merkel, D. C., 1993, Regional geologic framework and petroleum geology of the Smackover formation, Alabama and Panhandle Florida coastal waters area and adjacent federal waters area: Geological Survey of Alabama Bulletin 154, 60 p.

Manuscript received June 22, 1998
Revised manuscript received October 22, 1998
Manuscript accepted January 5, 1999